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Techniques of Water-Resources Investigations
of the United States Geological Survey

Chapter A17

ACOUSTIC VELOCITY METER SYSTEMS

By Antonius Laenen

Book 3
APPLICATIONS OF HYDRAULICS

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PREFACE

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The unit of publication, the Chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. Chapter A17 of Book 3 (TWRI 3-A17) deals with acoustic velocity meter systems.

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ACOUSTIC VELOCITY METER SYSTEMS

By Antonius Laenen

Abstract

Acoustic velocity meter (AVM) systems operate on the principles that the point-to-point upstream traveltime of an acoustic pulse is longer than the downstream traveltime and that this difference in traveltime can be accurately measured by electronic devices. An AVM system is capable of recording water velocity (and discharge) under a wide range of conditions, but some constraints apply:

1. Accuracy is reduced and performance is degraded if the acoustic path is not a continuous straight line. The path can be bent by reflection if it is too close to a stream boundary or by refraction if it passes through density gradients resulting from variations in either water temperature or salinity. For paths of less than 100 m, a temperature gradient of 0.1° per meter causes signal bending less than 0.6 meter at midchannel, and satisfactory velocity results can be obtained. Reflection from stream boundaries can cause signal cancellation if boundaries are too close to signal path.
2. Signal strength is attenuated by particles or bubbles that absorb, spread, or scatter sound. The concentration of particles or bubbles that can be tolerated is a function of the path length and frequency of the acoustic signal.
3. Changes in streamline orientation can affect system accuracy if the variability is random.
4. Errors relating to signal resolution are much larger for a single threshold detection scheme than for multiple threshold schemes.

This report provides methods for computing the effect of various conditions on the accuracy of a record obtained from an AVM. The equipment must be adapted to the site. Field reconnaissance and preinstallation analysis to detect possible problems are critical for proper installation and operation of an AVM system.

Introduction

An acoustic velocity meter (AVM) measures the velocity of flowing water by means of a sonic signal, which moves faster downstream than upstream. Meters of this type are useful in measuring discharge at streamflow sites where the relation between discharge and stage varies with time because of variable backwater conditions and also where stream slopes are too flat to permit measurements accurate enough for slope computations.

The AVM is a nonmechanical, nonintrusive device that is capable of measuring lower velocities than can be measured with a current meter. It can provide a continuous and reliable record of water velocities over a wide range of conditions, but several constraints apply.

AVM systems range from a simple velocity meter to complex computerized systems that compute and transmit real-time discharges. At some installations, a single signal path is adequate; at others, multiple signal paths are required.

The purpose of this report is to provide a manual on the installation and operaton of AVM's, including (1) theory of operation, (2) selection of equipment and suitable measuring site, (3) method of installation, (4) calibration, (5) operation, and (6) constraints that apply to their successful use.

Overview

Summary information under each of the following eight topics is intended to answer questions commonly asked about AVM systems, including their suitability for use at a particular site.

Theory—AVM systems work on the principles that the point-to-point traveltime of sound is longer upstream than downstream and that traveltimes can be measured accurately by electronic devices. Measurement of velocity is along an acoustic path set 30-45° diagonal to streamflow. Commercial systems that measure streamflow use the time-of-travel method to determine velocity. Fluctuations in the speed of sound due to changes in water density gradients are compensated for by methods used to calculate the velocity.

Limitations—AVM accuracy and performance are limited by four factors: (1) the location of the acoustic path with respect to water surface and streambed, which provide reflective surfaces for multipath interference, (2) density gradients (usually caused by different temperatures or salinities), which cause the acoustic path to bend, (3) concentrations of sediment, air bubbles, organic materials, and organisms, all which attenuate the acoustic signal, and (4) streamflow variability, which causes the angle between the acoustic path and the flow to change.

Availability—Two types of equipment are available for use in measuring velocity: (1) a simple one- or two-path microprocessor-based preprogrammed system that will output velocity only and (2) a more complex and versatile multipath minicomputer- or microprocessor-based keyboard-programmable system that can serve as a complete discharge-data aquisition unit. At present all systems require an AC power source. The use of acoustic-crossed paths will help define any changes in streamflow orientation. A responder adaptation, discussed later in the report, will eliminate the need for a hard-wire cross-channel link.

Accuracy—For many streamflow situations, single-path AVM systems can attain accuracies of 3 percent and multipath systems can obtain accuracy to within 1 percent. AVM system error can be attributed to three sources: (1) Timing error as defined by the resolution of traveltime. This resolution is approximately ±0.03 m/s for systems using signal-quality checks and approximately ±0.1 m/s when quality checks are not employed. (2) Angularity error as defined by the orientation of the streamflow to the acoustic path. For every one degree of uncertainty in path angle there is approximately 1 percent uncertainty in velocity measurement. (3) Deflection error as defined by acoustic ray bending. For paths less than 300 m, error is usually less than 3 percent.

Site selection—A review of system limitations and equipment requirements is necessary before site selection. Find a stream reach where velocity distribution is nearly regular and somewhat confined and where the channel is stable or can be measured for cross-section change. Reconnoiter the stream for existing structures to mount acoustic transducers. Obtain cross-section sounding information and note obstructions that might reflect the signal near the acoustic path. Obtain temperature, specific conductance, sediment concentration, and air-entrainment information.

Analysis—(1) Analyze the acoustic path for multipath interference. For every 100 m of acoustic path, approximately 1 m of depth is required to prevent multipath interference. The acoustic path should be at least one-half meter below the water surface in slow moving water to prevent signal bending from solar heating. (2) Signal bending will affect system accuracy. Avoid situations where the acoustic signal is bent so drastically that it reflects from either the water surface or the streambed, or both. (3) Analyze the acoustic path for signal attenuation. The normal sediment concentration that can be safely tolerated by most AVM systems is approximately 2,000 mg/L, but this is dependent on system frequency, particle size, and path length. Avoid situations where air entrainment can be a problem.

Calibration—AVM system calibration can be accomplished by current-meter measurement or by theoretical computation based on a logarithmic vertical velocity distribution.

Operation and maintenance—AVM systems are relatively sophisticated electronic devices that have proven to operate well but require specialized maintenance. Important in the system's performance is the availability of properly trained personnel. In-house electronic expertise is an invaluable asset. Spare parts and proper test equipment are necessary in achieving minimal downtime.

Theory of Operation

Most commercial AVM systems that measure streamflow use the time-of-travel method to determine velocity along an acoustic path set diagonal to the flow. This method is described in detail in a report by Laenen and Smith (1983), in which the general formula (fig. 1) for determining line velocity is defined as:

$$V_L = \frac{B}{2\mathrm{COS}\Theta}\left[\frac{1}{t_{CA}} - \frac{1}{t_{AC}}\right] \qquad (1)$$

where

V_L = line velocity, or the average water velocity at the depth of the acoustic path, and

Θ = angle of departure between streamflow and the acoustic path.

t_{AC} = traveltime from A to C (upstream),

t_{CA} = traveltime from C to A (downstream), and

B = length of the acoustic path from A to C.

The acoustic propagation rate is not a necessary element in equation 1 and fluctuations in the propagation of sound resulting from changes in water temperature or any other factors affecting water density have no effect on the computation of water velocity.

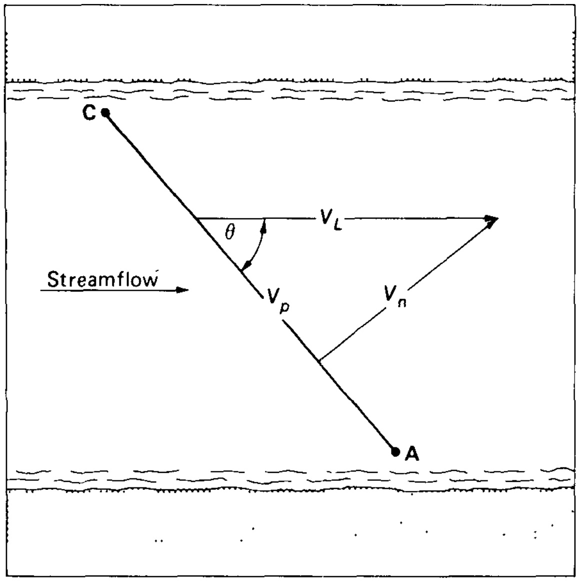


Figure 1.—Velocity component used in developing traveltime equations.

Electronic delays encountered in equipment and cables are very small and, except for very short acoustic paths, are insignificant when compared to total traveltime. These delays are normally included in the measurement of upstream and downstream traveltimes. For long and unequal runs of connecting cable (between transducer and electronic signal processor) delays in either direction are very close to the same because transmitted and received signals travel essentially the same electrical path.

In the measurement of traveltime a sonic transducer is triggered by a single spike of excitation voltage and responds by oscillating for a short time at the frequency of the piezoelectric crystal encased in its face. The oscillation is dampened by the physical constraints of the system as the pulse is converted to a pressure wave and transmitted into the water. When the pulse (now traveling through the water) is received by the second transducer, it is converted back to electrical energy. Figure 2 is a voltage representation of what would normally be viewed on an oscilloscope attached to the transducer. The transmit pulse is a representation of the transmit oscillation which is affected by feedback from the crystal-water interface and the received pulse is a representation of what has been transmitted acoustically.

In the measurement of traveltime, the time between the start of the transmit pulse and the start of the receive pulse is measured in both the upstream and downstream direction (fig. 2). Normally, threshold detection of the first cycle of the arriving pulse is used to determine the completion of a traveltime measurement. The simplest form of threshold detection is the triggering of a counter gate when the incoming pulse reaches a selected voltage level. A variety of schemes have been used to ensure that the proper signal, and not random noise (electrical or acoustical background or static), activates the system timing.

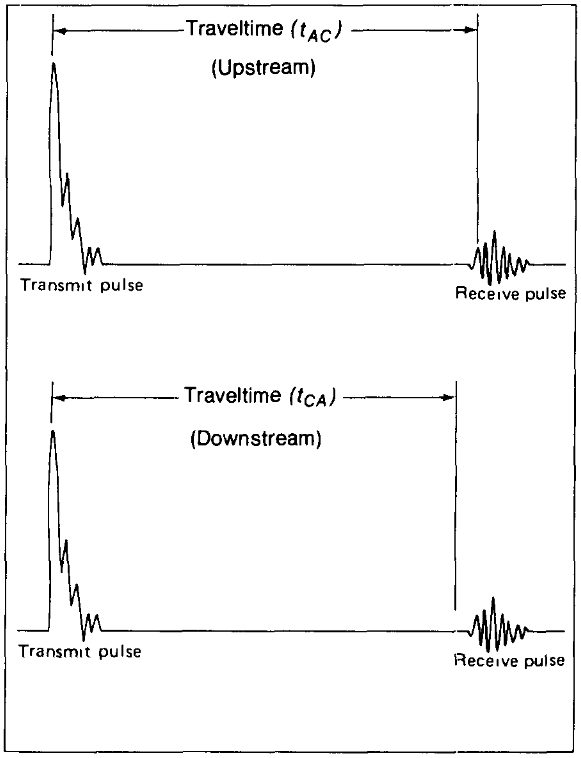


Figure 2.—Voltage representation of transmit and receive pulses at upstream and downstream transducers.

In most systems the received signal is monitored by one or more voltage threshold levels, and signals of an amplitude not meeting these levels are not used. In addition, various schemes are employed for comparing each measured traveltime with the preceding measurement, and data that depart by some fixed amount are disregarded. Some systems also have an automatic gain control to fix signal levels.

Quality checks are necessary because the acoustic transmission may be attenuated, distorted, or reflected by density gradients, high concentrations of suspended sediment or air bubbles, high concentrations of marine animals or vegetation, or the presence of boats or other large objects in the acoustic path.

Associated Limiting Phenomena

Although AVM systems will operate well in a wide variety of situations, their performance is influenced by phenomena that affect the propagation of the acoustic signal. System boundaries (water surface and streambed) provide reflective surfaces for multipath interference. Temperature differentials and other changes that affect the density of the water will cause signal bending. The presence of suspended sediment, air bubbles, organic materials, and living organisms cause signal attenuation.

The AVM's performance is also affected by the hydraulic situation in which it is placed. Streamflow direction in a cross section may change with time and discharge. Other flow patterns such as large eddies may cause anomalous conditions that cannot be compensated for even by multiple-path AVM systems.

Interference

When a nondirectional transducer emits a sonic pulse, sound spreads out in all directions; however, many transducers are designed to concentrate most of the sound in a narrow beam that spreads out conically from the source. Figure 3 shows a two-dimensional power diagram of the radiation pattern for a transducer with a 4-degree beam width. Beam width is determined at the 3-dB power level (sometimes referred to as the half-power point). AVM transducers are normally designed with 5- to 20-degree beam widths. The receiving transducer intercepts only a small portion of the transmitted sound; specifically the energy transmitted along the most direct and reflected routes between transducers.

If a streamflow system had no physical boundaries (water surface or streambed), there would be only one route to the receiving transducer, and a single, distortion-free signal (fig. 2) would be received. However, all streams have boundary conditions, and transmitted pulses are reflected by and received from these boundaries. If a boundary is close, the reflected signal will arrive at almost the same time and will interfere with the direct signal. This is known as multipath interference.

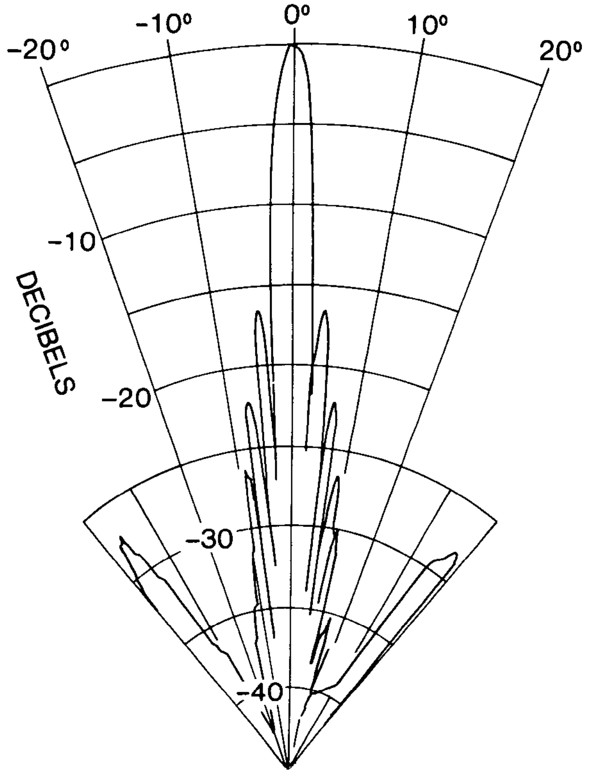


Figure 3.—Radiation pattern from typical narrow-beam transducer (Muir, 1974)

Because of multipath interference, transducers must be located some minimum distance from a reflecting surface. Lowell (1977) postulated that a reflected signal arriving at a receiver within one wavelength of the direct signal will interfere with the first pulse of the signal. The required clearance distance (D_c) can be computed if one wavelength of the carrier frequency is added to the direct path length and equated with the length of the reflected signal path (fig. 4) as follows:

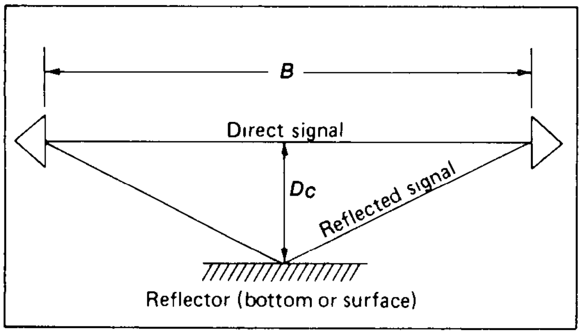


Figure 4 —Direct and reflected paths in defining multipath interference (Lowell, 1977) (See text for explanation of symbols.)

$$B + \lambda = 2\sqrt{\left(\frac{B}{2}\right)^2 + D_c} \quad , \qquad (2)$$

where

B = distance between transducers,
D_c = clearance distance, and
λ = wavelength, defined as c/F

where

c = velocity of sound, and
F = frequency.

Solving for D_c,

$$D_c = \sqrt{\frac{2\lambda B \times \lambda^2}{4}} \quad , \qquad (3)$$

since B, assume $\lambda^2 = 0$

then

$$D_c \cong \sqrt{\frac{\lambda B}{2}} \quad . \qquad (4)$$

The purpose of computing clearance distance is to place the acoustic path at a level in the cross section that avoids the destruction of the first cycle of the received waveform, which is the only part of the waveform used by existing AVM systems to detect traveltime.

Multiple signals caused by reflection have been observed at all operational AVM locations. Figure 5 shows a typical example of received waveforms as viewed with an oscilloscope. The first waveform is the direct (straight line) signal, the second waveform is from a bottom reflection, and the third waveform is a surface-reflected signal. Clearance distance is more than adequate for the direct signal because the reflected signals are displaced in time by much more than one cycle of the carrier frequency. Note that the second and third waveforms are superimposed slightly and that there is a phase shift where they superimpose. Also note that the first cycle of the second waveform is inverted compared to the first waveform. This inversion results when the signal is reflected. Surface reflections can be of nearly the same magnitude as the direct signal because very little energy is lost or scattered when surface conditions are calm. However, when the surface is rough and is not a good reflector, scattering occurs and no reflected signal may be detected.

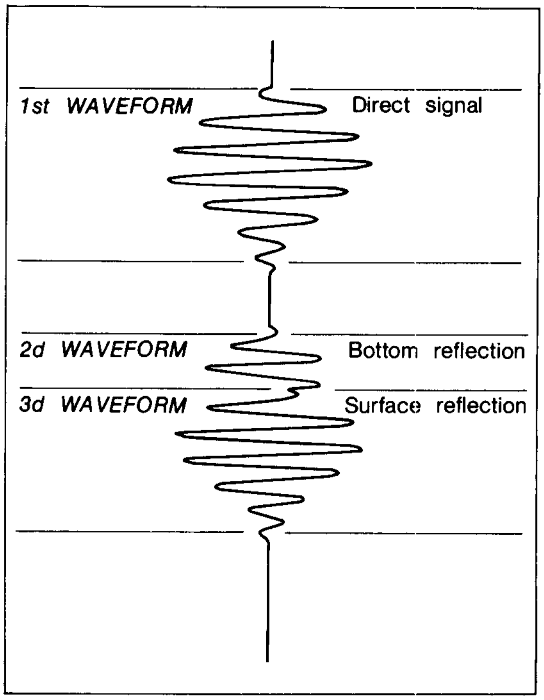


Figure 5 —Voltage representation at a transducer of the direct and reflected received pulses.

Bottom reflections are normally more consistent than surface reflections but are of lesser amplitude. Attenuation occurs because the bottom surface tends to either absorb or scatter the signal. For example, cobble and boulder bottoms will tend to scatter the signal, while soft mud bottoms will absorb the signal. Sandy stream bottoms have the best reflective qualities.

Refraction

One of the factors that can cause signal loss at a receiving transducer is refraction of the acoustic beam (or ray) by a density gradient. The velocity of sound in water is affected by density changes. Density gradients exist because of variations in water temperature, dissolved constituents, and suspended matter. The acoustic beam will bend as it travels through a medium with a density gradient perpendicular to its direction.

Figure 6 shows how the velocity of sound varies with temperature for distilled water and seawater (salinity = 35 g/L). The velocity of sound in ocean water is expressed by the following empirical relation (Clay and Medwin, 1977):

$$c = 1449.2 + 4.6T - 0.55T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35.0) + 0.016d, \quad (5)$$

where

c = velocity of sound (m/s),
T = water temperature (°C),
S = salinity (g/L), and
d = depth (m).

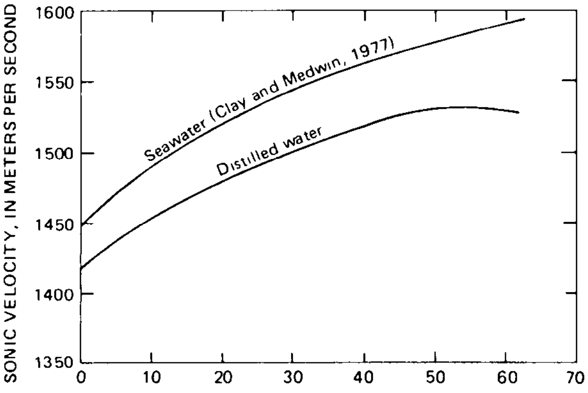


Figure 6.—Sonic velocity in water (Laenen and Smith, 1983)

Sound velocity determined by equation 5 differs slightly from sound velocity determined by tables given in the *Handbook of Chemistry and Physics* (Chemical Rubber Company, 1980); however, the equation is essentially the same for temperatures between 10 and 50 °C.

Refraction, as illustrated in figure 7, will occur in the presence of either vertical or horizontal density gradients. Snell's law (Clay and Medwin, 1977) can be used to trace the acoustic ray in a stratified medium. The direction a signal takes as it goes from medium 1, to 2, to 3, ... , to n are as follows:

$$\frac{\mathrm{SIN}\Theta_1}{c_1} = \frac{\mathrm{SIN}\Theta_2}{c_2} = \frac{\mathrm{SIN}\Theta_3}{c_3} = \ldots . \frac{\mathrm{SIN}\Theta_n}{c_n} \quad (6)$$

For a constant density gradient (g), the radius of curvature (R) of the acoustical ray (from Clay and Medwin, 1977) can be defined as follows:

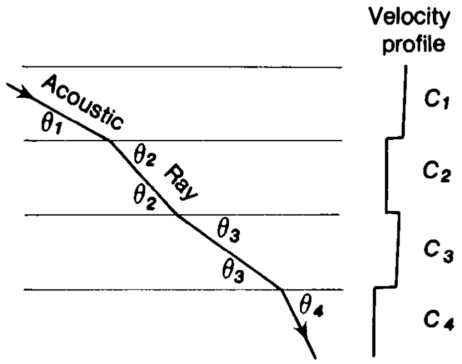


Figure 7.—Vector components used to develop Snell's law of refraction in a layered medium (Urick, 1975).

$$R = \frac{c}{g} = \frac{c_1}{\left[\dfrac{c_1 - c_2}{d_1 - d_2}\right]}, \quad (7)$$

where

c_1 = velocity of sound at the initial depth (d_1),
c_2 = velocity of sound at depth (d_2);

The deflection (D) from figure 8 of the ray for a distance (x) traveled is

$$D = R - \sqrt{R^2 - x^2} \quad . \quad (8)$$

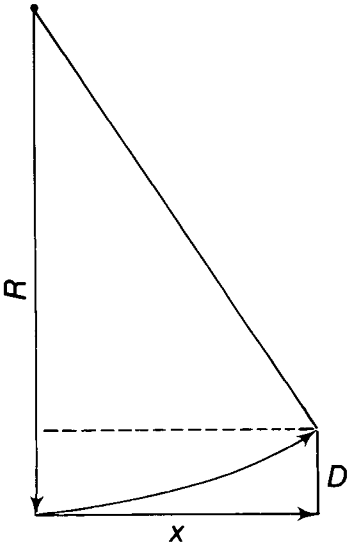


Figure 8.—Vectors used in defining ray bending in a constant density gradient medium.

Temperature gradients of 0.1 °C/m or more generally occur only in the top one-half meter of slow-moving or ponded water. Because temperature gradients are usually less than 0.1

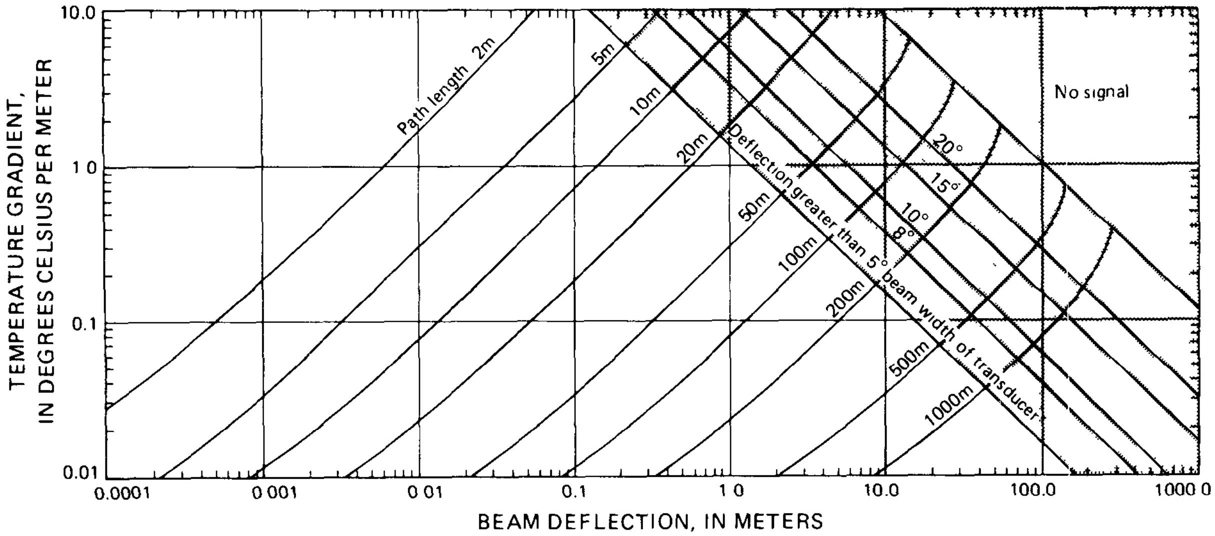


Figure 9.—Beam deflection from linear-temperature gradients for selected path lengths. Transducer directivity or beam width determined at the 3-dB level of the transmitted signal pattern. The signal is propagated beyond the beam width but at a weak level. In the shaded area the deflection is so great that signals cannot be received directly for any transducer beam width (Laenen and Smith, 1983).

°C/m in most streams, thermal gradients will generally not affect acoustic reception or accuracy nor produce any signal loss for acoustic paths less than 300 m, if transducers are located at least one-half meter below the water surface.

Figure 9 depicts a family of curves developed from equations 7 and 8. These curves can be useful in determining if known temperature gradients can cause deflections great enough to prevent signal reception. For example, if an AVM system equipped with 5-degree beam width transducers were used in a stream with a maximum vertical temperature gradient of 0.1 °C/m and the acoustic path is 200 m, then the deflection of the center of the acoustic beam would be approximately 5 m; however, the receiving transducer would still intercept a signal of acceptable magnitude. Using the same gradient of 0.1 °C/m and increasing the path distance to 500 m, the deflection of the beam would be approximately 35 m and the receiving transducer would not intercept an acceptable signal. Any deflection greater than approximately 22 m (0.07 °C/m temperature gradient) would probably pre-

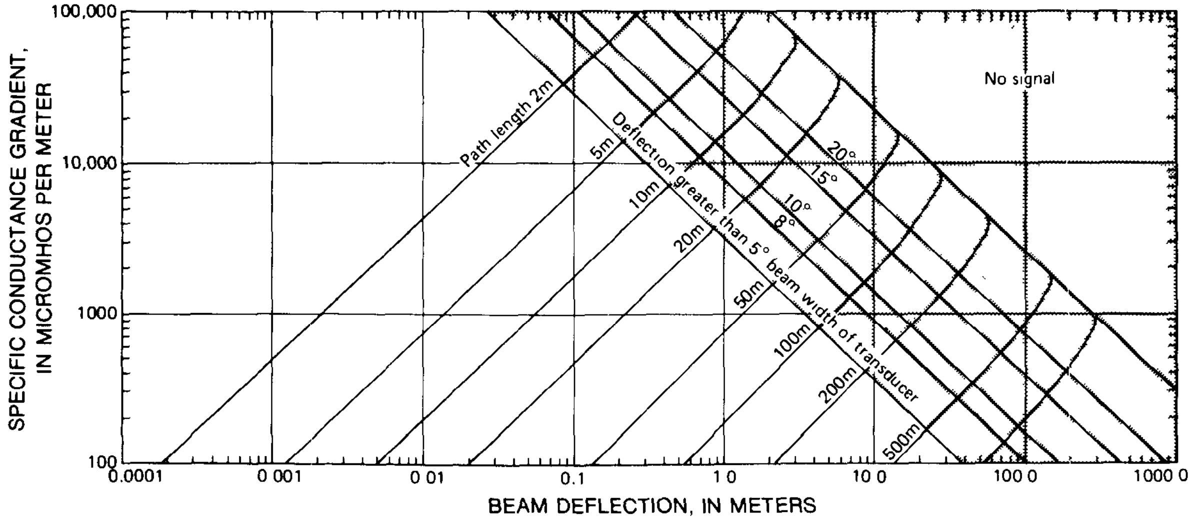


Figure 10.—Beam deflection from linear "specific-conductance" gradients for selected path lengths. Transducer directivity or beam width determined at the 3-dB level of the transmitted signal pattern. The signal is propagated beyond the beam width but at a weak level. In the shaded area the deflection is so great that signals cannot be received directly for any transducer beam width (Laenen and Smith, 1983).

vent acoustic signal reception. As another example, if transducers of the same 5-degree beam width were used for a 200-m path, a temperature gradient of about 0.2 °C/m would cause the beam to deflect approximately 9 m and the receiving transducer would intercept a weak signal (transmitted outside the primary beam width).

Figure 10 is similar to figure 9 and can be used to assess refraction caused by salinity gradients. Salinity is frequently documented by measurement of specific conductance, which is converted to salinity by the following relation:

$$S = \left(\frac{SC}{1 + 0.04T}\right)^{1.08}, \qquad (9)$$

where

S = salinity (g/L),
SC = specific conductance (μmhos), and
T = temperature (°C).

Salinity gradients commonly occur in estuaries and, in contrast with temperature gradients, are sometimes so large that proper acoustic reception cannot occur. Where thermal or salinity gradients are expected to cause problems as depicted in figure 11, a detailed on-site investigation should be made for the collection of temperature or conductivity data and to be used in ray-tracing programs for the definition of expected accuracy and performance.

Normally, the increase in path length as a result of ray bending is slight; however, the difference between the sampled vertical velocity and that which occurs along a straight line path between transducers may be large. This difference can significantly decrease the precision of an AVM system.

Attenuation

Acoustic signals are attenuated by absorption, spreading, and scattering. Attenuation or signal loss from these sources are added to determine the adequacy of the received signal strength for proper AVM performance. Attenuation is measured in nepers (n) or decibels (dB). The decibel is a unit used to express the ratio between two amounts of power and is expressed as:

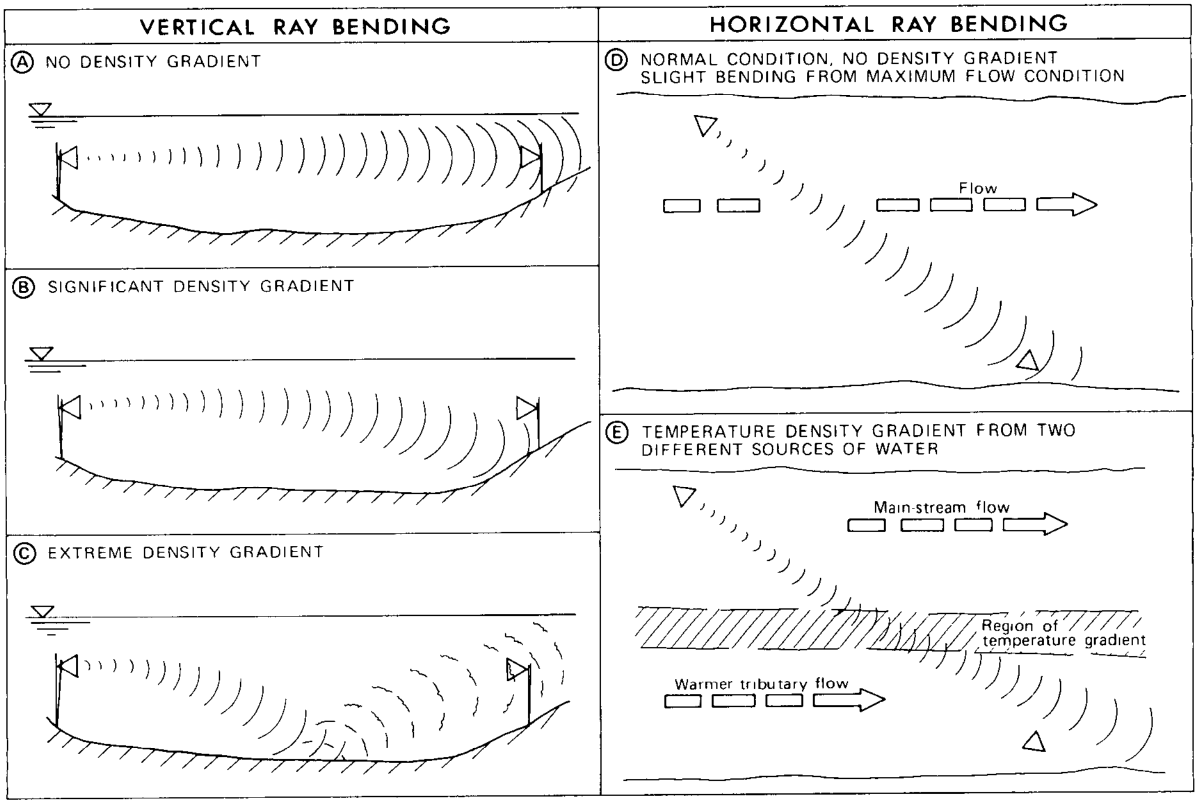


Figure 11.—Signal bending caused by different water-density gradients (Laenen and Smith, 1983)

$$\alpha = 10 \log \left(\frac{P}{P_r}\right) \quad , \qquad (10)$$

where

α = attenuation (in dB),
P = observed power (power out), and
P_r = reference power (power in).

Because sound intensity is proportional to the square of the sound pressure, the ratio becomes:

$$\alpha = 20 \log \left(\frac{\rho_o}{\rho_s}\right) \quad , \qquad (11)$$

where

ρ_o = observed sound pressure,
ρ_s = sound pressure at the source (or reference)
(dB can be converted to nepers by multiplying by 0.1151).

Transmission losses are normally calculated using voltage observations.

For AVM systems currently operated by the Survey, it has been found that the allowable attenuation for 100-kHz systems is about 14 nepers, and for 200-kHz systems about 12 nepers. Information on AVM's used in the United Kingdom indicate that for 500-kHz systems the allowable attenuation is about 10 nepers (Herschy, 1978).

Absorption involves the conversion of acoustical energy into heat. In distilled water, absorption is affected by frequency; in seawater, absorption is additionally affected by the energy consumed in the ionic relaxation of magnesium sulfate ($MgSO_4$). Figure 12 shows attenuation curves for seawater and distilled water.

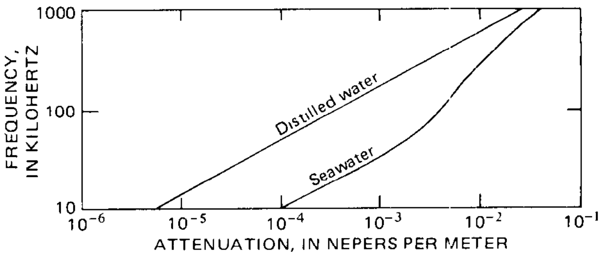


Figure 12.—Attenuation caused by absorption (Urick, 1975) To convert nepers to decibels multiply by 8.688.

Spreading loss is weakening of a signal as it spreads outward geometrically from the source. It varies with the square of the distance and can be expressed as follows for a spherical spreading loss:

$$\alpha = 20 \log \left(\frac{B}{B_r}\right) \quad , \qquad (12)$$

where

α = attenuation (dB),
B = distance, and
B_r = reference distance.

Scattering losses are caused by suspended sediment entrained air, or other suspended particles such as algae or plankton, all of which also absorb sound. Scattering losses are normally the dominant losses in streamflow situations. Figure 13 shows attenuation as related to sediment-particle diameter for specific frequencies (from equation by Urick, 1975). Table 1 shows conservative values of sediment concentrations that may be tolerated by AVM systems for selected transducer frequencies and

Table 1—Estimates of tolerable sediment concentrations for AVM system operation, based on attenuation from spherical spreading and from scattering from the most critical particle size
[Sediment concentrations in milligrams per liter]

Selected transducer frequency (kHz)	Path distance (m)							
	5	20	50	100	200	300	500	1,000
1,000	6,300	1,200	400	——	——	——	——	——
500	——	3,500	1,200	530	230	——	——	——
300	——	7,900	2,800	1,300	560	350	——	——
200	——	11,000	4,000	1,800	830	520	280	——
100	——	——	10,000	4,600	2,200	1,400	770	350
30	——	——	——	——	8,800	5,700	3,200	1,500

path lengths. The assumptions used to estimate the values in table 1 are based on attenuation as calculated by equation 12 and attenuation from the high point of the graph in figure 13. It should be noted that the lower the frequency the greater sediment concentration that can be tolerated; however, the lower the frequency transducer used, the greater the resolution error, the more power required to drive it, and the more costly the transducer.

A gas bubble of the same diameter as a rigid sediment particle can attenuate the acoustic signal as much as 400 times more than the particle if the bubble resonates (Clay and Medwin, 1977). Resonation occurs when the bubble is approximately the same diameter as the signal wave length.

Other nonrigid bodies such as algae or plankton will also resonate to frequencies of appropriate wavelength and cause more attenuation than similar concentrations of rigid particles.

Because little is known about bubble populations in streams, onsite measurements of signal attenuation should be made at sites where air bubbles or other nonrigid bodies are thought to cause problems.

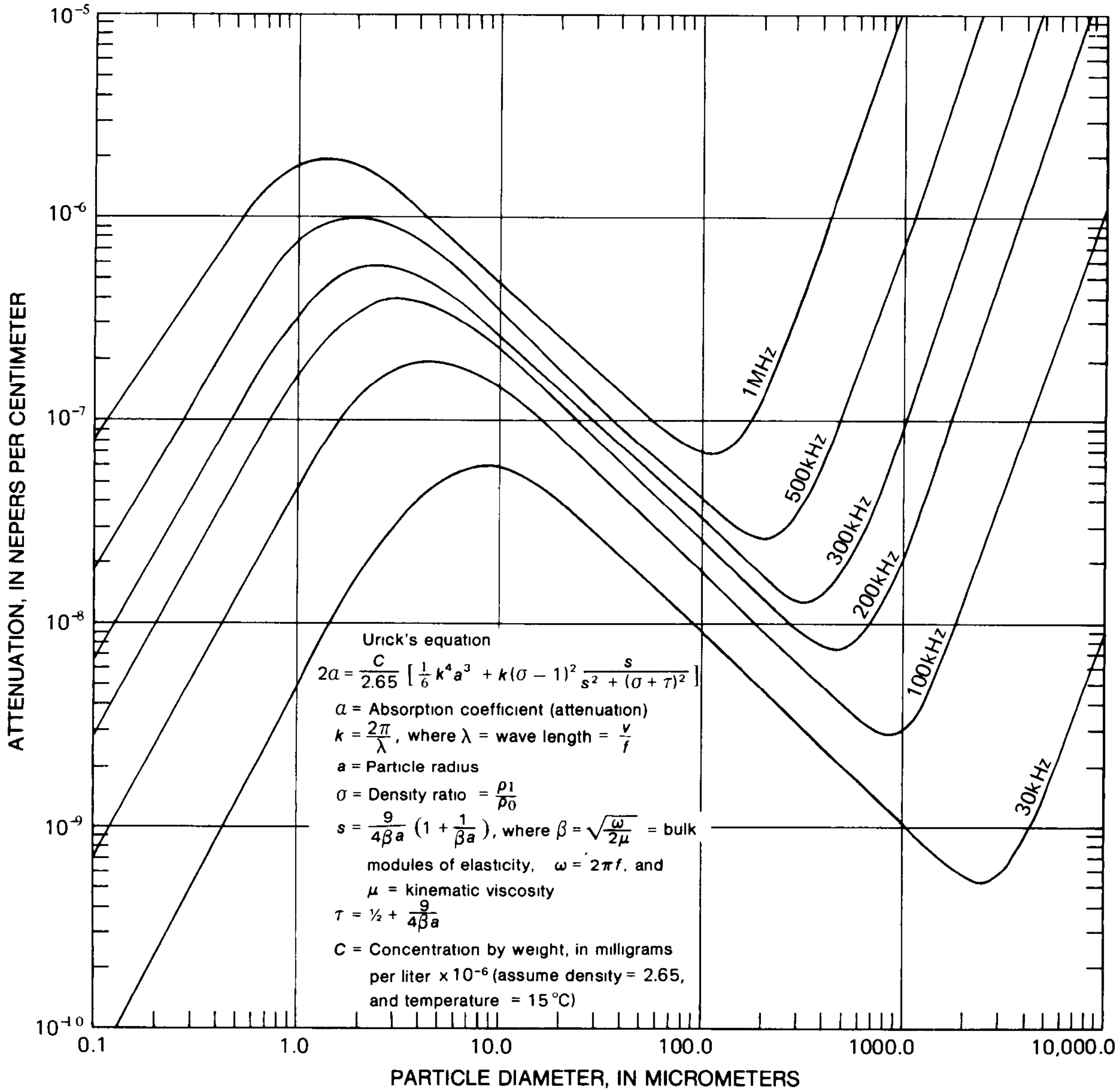


Figure 13.—Attenuation from sediment particles for selected frequencies for a sediment concentration of 1 mg/L. To determine total attention from sediment, results must be weighted by particle size and then multiplied by concentration (Laenen and Smith, 1983). To convert nepers to decibels multiply by 8.688.

Streamflow Orientation

Single-path AVM systems have a transducer located near each bank on a diagonal across the stream. The angle between the acoustic path and the average direction of streamflow is normally from 30° to 60°. To determine the ratio of line velocity (parallel to the streamflow) with respect to path velocity (along the acoustic path), it is necessary to determine the angle between these two vectors. For every one degree error made in the measurement of this vector angle, there is approximately one percent error in the velocity ratio, for angles near 45° (Smith, 1969). The path angle may be difficult to measure in the field, and it may vary with time or stream discharge.

Any single-path system should initially be rated by current-meter measurement to define the relation of path velocity to the mean velocity of the stream. If measurements cover the range of discharge, then the rating usually masks any error made in the measurement of path angle and compensates for it. However, if streamflow angle varies with respect to the acoustic path, current-meter measurements may not be adequate to define the relation of path velocity to the mean velocity. A crossed-acoustic path (or an acoustic path measuring the opposite diagonal) will usually provide the information necessary to compensate for an error in angularity either from initial measurement or from a changing streamflow angle.

Neither single-path nor cross-path methods can be used to compute velocity where large eddies persist in the stream. Stream reaches with extreme turbulence or other poor hydraulic measuring conditions should be avoided when locating a potential site.

Available Equipment

Currently (1983), six manufacturers market AVM systems that have demonstrated the capability of measuring flow in stream channels (Laenen and Smith, 1983). In order to be reliable and versatile in the field, an AVM should have either a minicomputer- or microprocessor-based programmable capability. The rapid advance in silicon memory-chip technology has lowered the cost and increased the capabilities of equipment utilizing these advanced components. This rapid pace of electronic component development also means that equipment obsolescence is probable within 10 years.

At present, there are basically two magnitudes of complexity in streamflow-measuring AVM equipment: (1) a simple one- or two-path microprocessor-based preprogrammed system that will output a velocity only (stage to be logged separately) and (2) a more complex multipath minicomputer- or microprocessor-based keyboard-programmable system that has real-time input-output and discharge computational versatility.

Simple System

The advantages of a simple system are: fewer components, less complication, and lower cost. In most situations where instantaneous discharge is not a requirement and data processing can be accomplished elsewhere, the simple system should be used. It can be considered, for all practical purposes, a

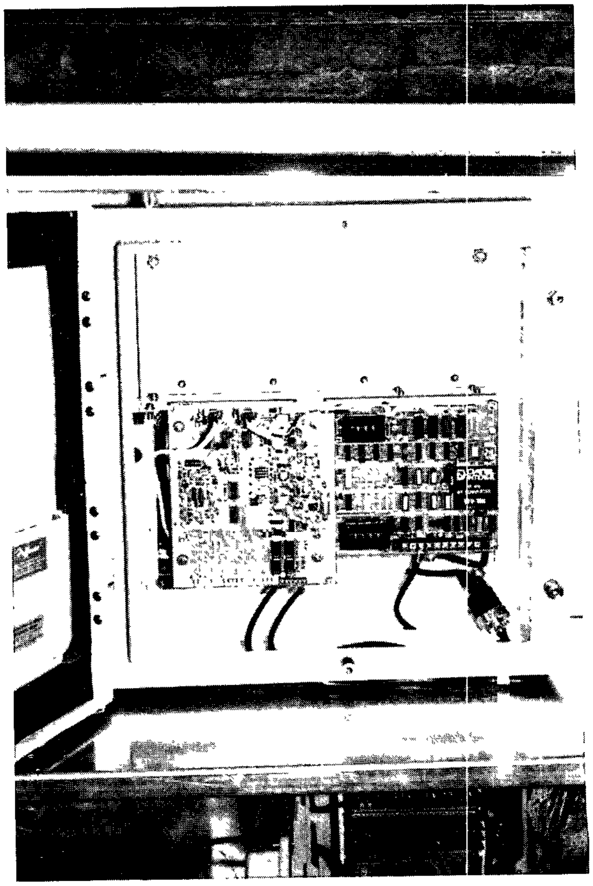


Figure 14.—Simple microprocessor system

velocity probe; however, it is a probe that can integrate the velocity over the width of the stream. The digital or analog voltage output of the system can be logged or transmitted by conventional methods. Stage, the other component necessary for the measurement of discharge, will have to be measured by some other device and logged in separately. A simple AVM system in a weatherproof enclosure (note the size of the equipment with respect to the electric plug) is depicted in figure 14.

The primary disadvantage of a simple system is that it is not real-time oriented and the output will still have to be processed with stage information to determine discharge. Other disadvantages of simple systems are that they are basically single path and require AC voltage to operate, but these disadvantages are not insurmountable. Manufacturers will modify circuitry to accommodate user requirements. Some systems are designed to operate with multiple-path inputs; however, there is only one velocity output, which cannot be separated (data from the individual paths are weighted and averaged to determine the output velocity). Systems normally interrogate acoustically at the rate of 100 times or more per minute. A reduction in the number of interrogations will reduce the power requirements nearly proportionately. However, any initial engineering costs needed to implement modifications could be somewhat high.

Versatile System

Keyboard-programmable minicomputer or microprocessor systems have the advantage of manipulating the input velocity and stage data into real-time data in almost any form. Velocity data from multiple paths can be independently stored, weighted by stage relation, combined with cross-section data to compute discharge, averaged at selectable time intervals, logged, and (or) telemetered. The versatile system is a complete discharge-data aquisition system. At present, this is the most efficient system to operate in a multiple-path configuration.

Disadvantages of versatile equipment over the simple systems are more complexity, more maintenance, and more expense. Although the use of a minicomputer as a central processor is probably an ultimate aim in data collection, it is also the most costly, both in installation and maintenance. Figure 15 is a photograph of the minicomputer and associated teletype used for on-site recording. Keyboard-programmable microprocessor systems (fig. 16) offer fewer problems than minicomputer systems. In addition to higher initial costs and more intensive maintenance, versatile systems require considerable power and some environmental pro-

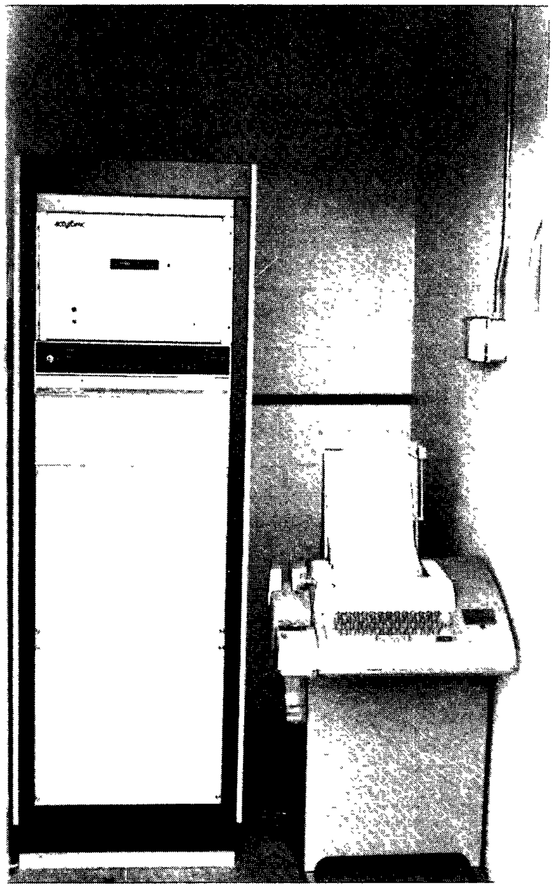


Figure 15.—Versatile minicomputer system.

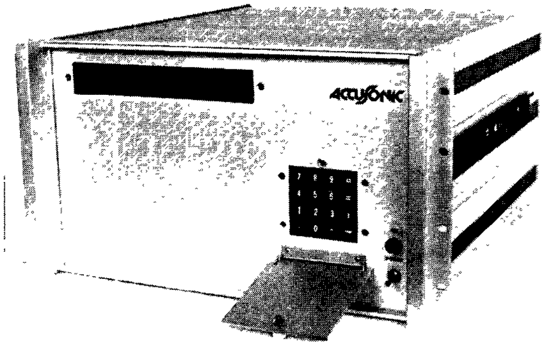


Figure 16.—Versatile microprocessor system. Photograph by Ocean Research Equipment, Inc.

tection. Versatile systems also require an AC voltage source.

Additional acoustic paths will increase accuracy, but the increase is not proportional to the number of paths. Single-path AVM systems operated by the Survey and rated by current-meter measurements have shown accuracies of about ±3 percent. The addition of more acoustic paths in the vertical will not normally increase the accuracy significantly except where: (1) velocity distributions are known to deviate from the normal, (2) the cross section is highly irregular, and (3) streams have a large range in stage such that the acoustic path defines only the low end of the vertical velocity profile at high stages. In this case, a second acoustic path, which is out of water at low flows, will significantly increase accuracy at the higher flow.

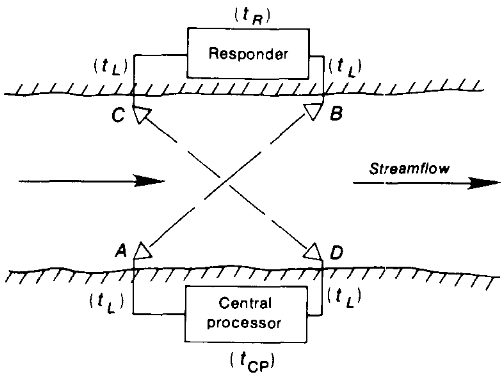
The new adaptable hydrologic data aquisition system (AHDAS) now being developed for the Survey should make simple systems nearly as flexible as the versatile systems described above.

Cross-Path Adaptation

If streamflow in a cross section is subject to direction change, then two acoustic paths crossing at approximately right angles will improve the accuracy of the computed flow. Either simple or versatile systems can utilize this cross-path adaptation. Installation of crossed paths makes it possible to measure in less-than-ideal hydraulic sections, for example, at or near a stream bend or a constriction. The adaptation also makes it possible to eliminate or reduce the number of current-meter measurements required for calibration because the most critical factor in line velocity measurement, the path angle, is compensated for.

Responder Adaptation

All AVM systems require some form of communication link between transducers and the central processor. Normally, the transducers are connected via a combination of submarine and overhead cabling. Where a cable link is impractical between the far-side transducer and the central processor, an electronic responder may be used instead. A responder is a device that receives an acoustic pulse and then re-transmits that signal after a predetermined time interval. Figure 17 shows the use of this device.



Upstream traveltime is computed as follows

$$t_{up} = t_{AB} + t_L + t_R + t_{CD} + t_{CP}$$

where

t_R = Time delay in responder electronics

t_{CP} = Time delay in central processor

t_L = Time delay in cables between transducer and electronics

Downstream traveltime is computed as follows

$$t_{dn} = t_{DC} + t_L + t_R + t_{BA} + t_{CP}$$

Then

$$V_P = \frac{B}{2}\left(\frac{1}{t_{dn}} - \frac{1}{t_{up}}\right)$$

where V_p is the water velocity component along the acoustic path, and B is the total length of the acoustic path from A to B and from C to D

Figure 17—Components necessary for responder system (Laenen and Smith, 1983).

A signal can be transmitted downstream from transducer *A* along a diagonal path to transducer *B*. The received signal is then routed to a responder where it triggers a transmit signal (after some minimal electronic delay, t_R). This signal again travels downstream along another diagonal acoustic path from transducer *C* to transducer *D* and is received back at the central processor (again after some minimal electronic delay, t_{CP}). For the upstream traveltime the above procedure is reversed. Reciprocity is ensured because all paths traveled in opposite directions are equal.

Accuracy

The sources of error in the measurement of line velocity are dependent on system resolution and on the deviation of the acoustic signal caused by refraction from the straight line path between transducers.

The accuracy of velocity measurement along the acoustic path is limited only by the resolvable difference in sound speed (traveltime) between upstream and downstream transducers. Fluctuations in the speed of sound caused by uniform changes in water density have no effect on the computation of velocity (refer to Laenen and Smith, 1983). Determination of traveltime in an AVM system is normally accomplished by voltage threshold detection of the received signal. The frequency of the received signal, the precision of the threshold detection scheme, and the path length determine system resolution.

If received signals are so attenuated that the first cycle of the signal is below the trigger level and if only a single level of detection is used, then an error equal to one cycle of the carrier frequency can result. If multiple-threshold levels (sometimes referred to as signal-quality checks) are employed, then errors are typically reduced to less than one-fourth of a cycle. Table 2 lists some possible resolution errors for selected operating frequencies and path lengths. The value of multiple-threshold detection schemes is apparent from comparison of the possible error columns.

The accuracy of the line velocity measurement can be predicted if signal bending is calculated (see section on "Refraction"). For many streamflow applications, the acoustic signal can be assumed to travel a straight line between transducers for each level measured in the stream cross section and the error assumed to be negligible. However, signal bending should be analyzed at sites where density gradients are known to exist; this helps in the prediction of system performance and velocity accuracy (see section on "Calibration").

Site Selection

In the selection of sites, consideration must be given to the limiting acoustic criteria, to equipment requirements, and to installation problems.

AVM's are normally located at sections that suit flow measurement by current meter for two reasons: (1) There is a need to make the best possible velocity measurement and (2) if the system is rated by current meter, measurements need to be made as close as possible. Therefore, a stream reach should be found where velocity distribution is somewhat regular and flow is confined. Sections where velocities are very slow can be included because AVM systems are accurate low-flow meters. Sections where velocities are very fast can also be included (provided installation is practical) because AVM systems have no upper limit of measurable velocity. Acoustic velocity meters are frequently used for measuring nonsteady-state flows. Check measurement by current meter should be made near the AVM site to avoid the effects of changes in channel storage.

Field Reconnaissance

Among the items necessary for evaluation of the performance and accuracy of an AVM system are the stream cross section, water temperature, and salinity profiles. Observations of any conditions that may affect acoustic trans-

Table 2 —Possible resolution errors for selected AVM operating frequencies and path lengths

Path length (m)	Transducer frequency (kHz)	Possible error using multiple-threshold detection (m/s)	Possible error using single-threshold detection (m/s)
1-5	1,000	0.280-0.056	1.12 -0.225
5-20	500	.112- .028	.450- .112
20-50	300	.047- .018	.187- .075
50-200	200	.028- .007	.112- .028
200-500	100	.014- .005	.056- .022
500-1,000	30	.018- .009	.075- .037

mission should be noted; for example, air entrainment, algae, moss, weed growth, barnacle or other encrustations, and suspended-sediment concentrations. It will be necessary to accumulate data over a period of time in order to estimate maximum temperature or salinity differentials, maximum sediment concentrations and particle-size distribution, and maximum and minimum stages.

Cross-section geometry is a controlling factor in locating an AVM system. It determines whether the acoustic path system should be single, multiple, or cross. To ensure proper performance, approximately one meter of depth is required for every 100 meters of acoustic path. To determine the exact clearance necessary for AVM operation, refer to the section on "Multipath interference." Channel stability is also an important consideration. Calculation of discharge requires knowledge of cross-sectional area as well as velocity. A changing cross section also means a changing relationship of path velocity to mean velocity. If the cross section is unstable, then some method of monitoring cross-section change is necessary.

In many streamflow situations, temperature or salinity gradients are minor and it will be unnecessary to collect profile information. Look for gradients in streams with slow-moving or ponded water, downstream from tributaries, downstream from thermal discharges, or in tide-affected reaches.

Special attention should be given to any air or gas entrainment in the water. Some bubble sources that could affect AVM performance are dam spillways, natural stream riffles, and decaying vegetation. For dam spillways, bubbles can persist for 25-40 minutes after spilling occurs. If air entrainment is a recognized problem, then a test system to define the attenuation is recommended. Other solutions include moving to a more downstream location or decreasing the acoustic path lengths, which can be accomplished in some situations by measuring the cross section by means of two separate paths at the same level.

Equipment Considerations

The specific equipment requirements for AVM measurements at a site are best assessed in the field. The convenience of locating an AVM system near available power, of using an existing structure to house the instrumentation, of using an existing structure to carry the cable link or to mount a transducer can be assessed.

Simple systems now require 20-30 watts of continuous AC power. Future systems may require approximately 2 watts of continuous 12v DC power. Available systems require some source of heat when air temperatures are below -5 °C (small heaters can be placed inside the equipment enclosure); and lightning and voltage surge protection are also required. Standard Survey shelters should be adequate for housing most systems; however, bulletproofing may be cost beneficial.

Versatile systems require continuous AC power as high as 400 watts, dependent on system configuration. Minicomputer systems require an environment in which temperature, humidity, and dust are controlled in order to operate without undue trouble. A substantial amount of space is required to house the computer console, a heater, and an air conditioner. Microprocessor systems are smaller and less demanding of power and environmental control but still require a minimum of 100 watts of continuous AC power, heating at temperatures below 0 °C, ventilation at temperatures above 30 °C, lightning and voltage surge protection, bulletproofing, and three times the space of the simple system.

Installation Considerations

Mounting transducers and laying the attached cables is likely to be expensive, perhaps more expensive than the cost of instrumentation. Transducer mounts need to be adjustable in the horizontal for direction alignment, and in the vertical for level adjustment. Because of complications involved with diving operations, these adjustments should be made visually above the water before the transducers are lowered into position. Where convenient, a track arrangement can be used to lower the transducers. Transducer adjustment can be performed underwater, but that is usually less desirable. Figures 18 and 19 show some transducer mounts and field alignment.

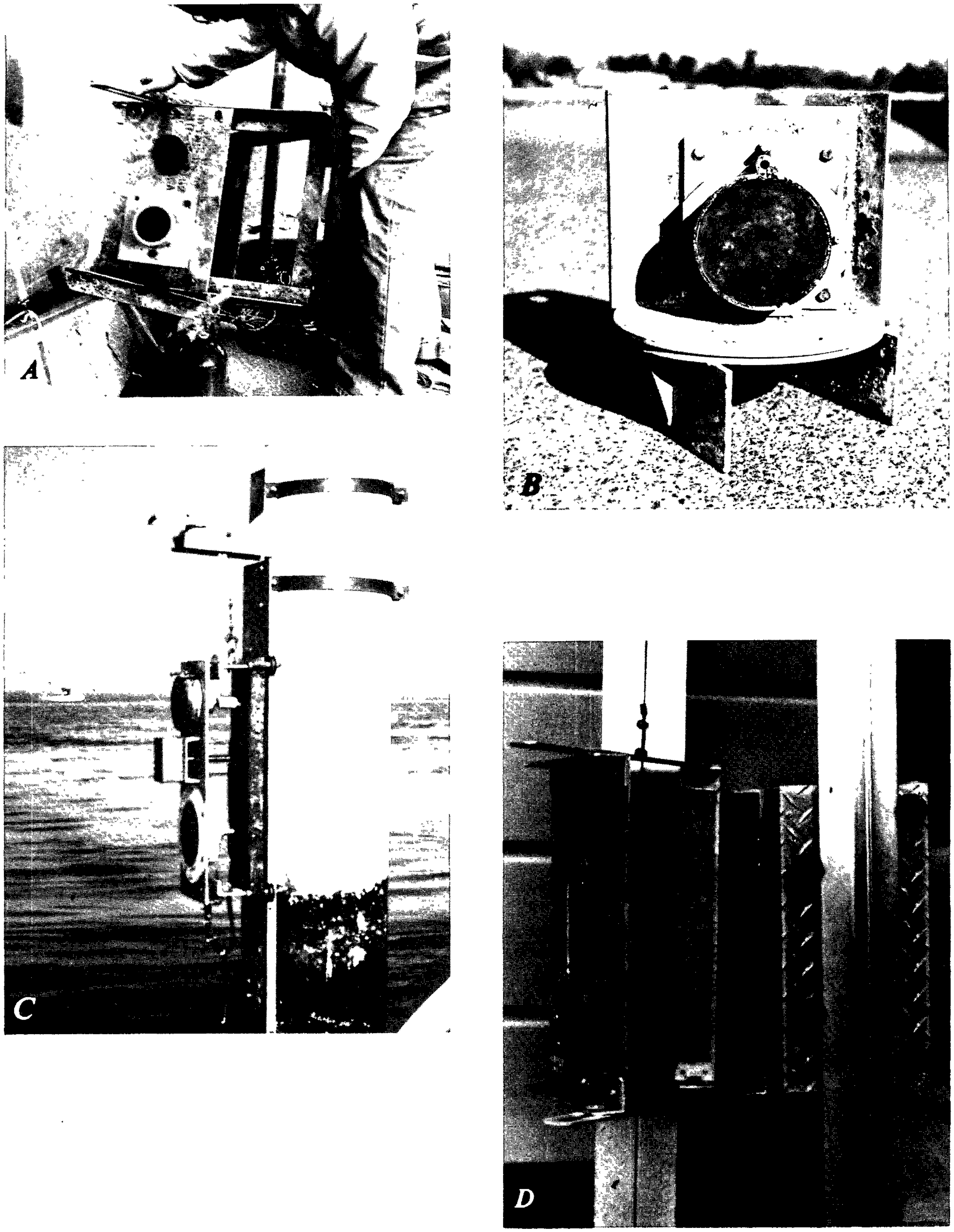


Figure 18.—Transducer mounts.

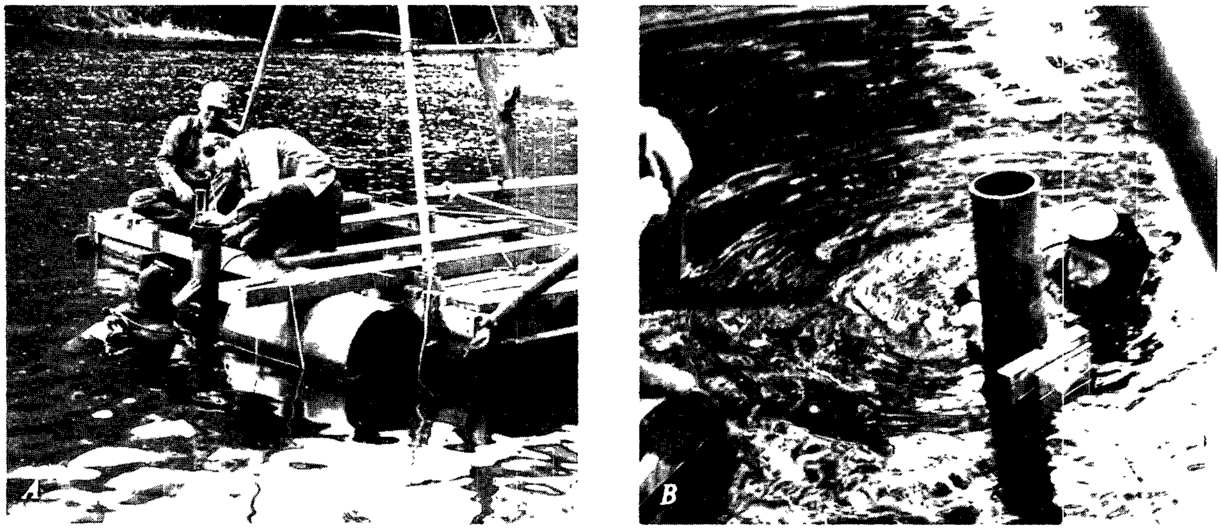
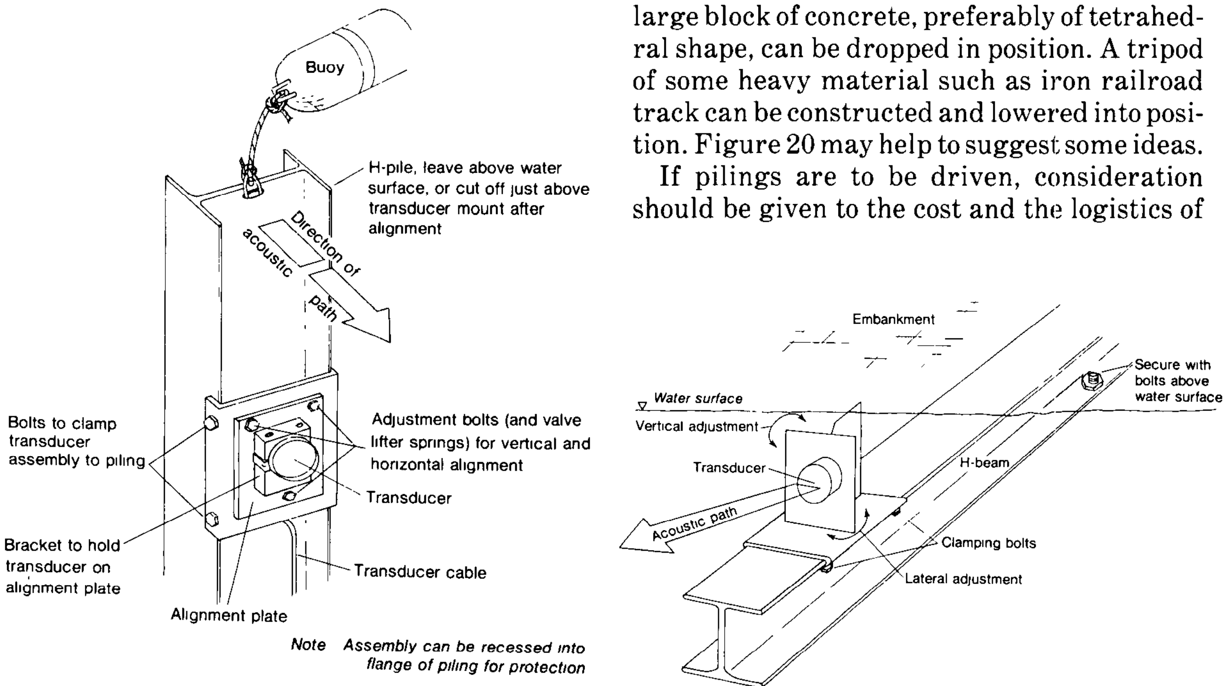


Figure 19.—Transducer alignment.

Transducers have been mounted satisfactorily on many kinds of objects. Time should be taken to consider existing structures on which transducers may be mounted, such as bridge piers, seawalls, and navigation pilings. Wood or iron piling can be driven especially to accommodate transducers. A steel H-pile anchored parallel to the slope of the bank is satisfactory for mounting, and the end of the pile is usually extended beyond the last anchor. A large block of concrete, preferably of tetrahedral shape, can be dropped in position. A tripod of some heavy material such as iron railroad track can be constructed and lowered into position. Figure 20 may help to suggest some ideas.

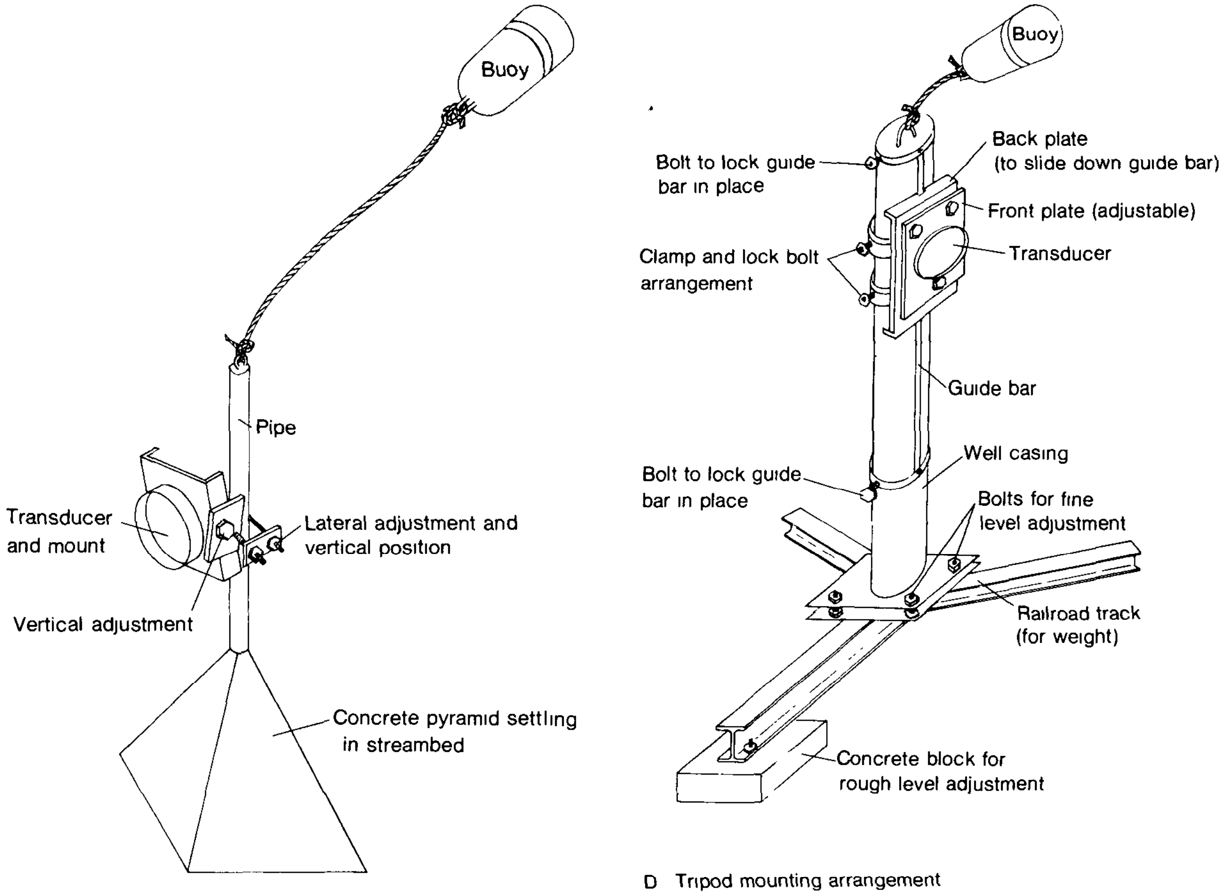
If pilings are to be driven, consideration should be given to the cost and the logistics of



A Mounting on H-pile facing approximately along the acoustic path

B Cantilever mounting from above the water

Figure 20.—Sketches of typical transducer mounts.



C Concrete pyramid for slow-moving streams

D Tripod mounting arrangement

Figure 20.—Sketches of typical transducer mounts—Continued.

moving pile-driving equipment. Navigation and safety requirements should be investigated no matter what type of structure or appurtenance will be used.

Attention should also be given to the problems of cable installation. If a submarine cable is to be used, how will it be secured? If an overhead cable is to be used, how will it be suspended? Will there be any objections from land owners? Would a responder link be more appropriate than either a submarine or overhead cable link?

Analysis

After long-term information has been accumulated, an analysis should be made to determine the most appropriate transducer locations and to estimate system performance.

Multipath Interference

For the section between the proposed transducer locations, plot the water depth versus distance at 1:1 or 10:1 scale. Include on the plot the minimum water-surface elevation to be expected. Using equation 8 to define the minimum clearance from either water surface or streambed, locate transducers in the cross section. To reduce the possibility of encountering significant temperature gradients, locate transducers at least 1/2 meter below the minimum water surface. Draw lines from the transducers to the center of the streambed as shown in figure 21A. If these lines intersect the streambed at any other point other than near the midpoint of the cross section, the point of intersection should be checked for the minimum clearance. Cross sections having a pan-

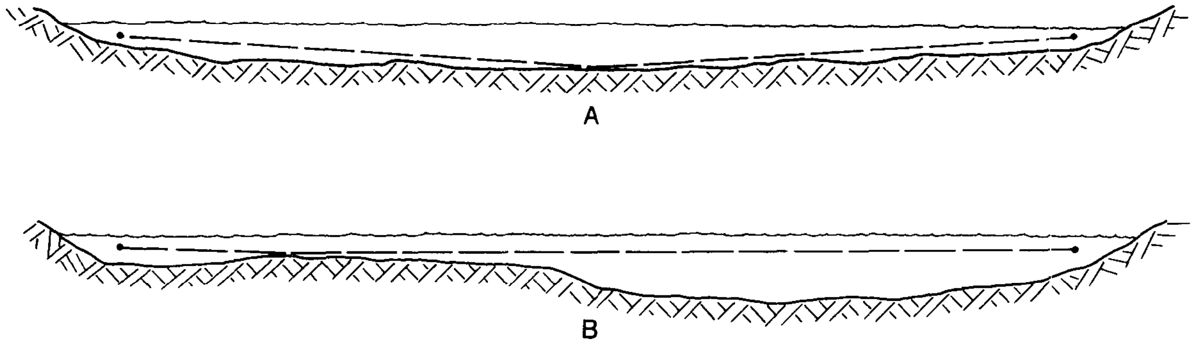


Figure 21.—Typical cross sections to define interference from bottom-reflected signals. A, Reflection from regular-shaped cross section. B, Reflection from panhandle-shaped cross section.

handle shape such as those shown in figure 21B or having obstructions near transducer locations may have interference problems. Either relocate transducers, remove obstructions, or use more than one acoustic path to measure the distance.

For AVM paths to be used at higher flows, in situations where transducers will be out of water at low flows, plot the median water surface for the flow of interest. As the water surface recedes past the critical clearance distance and approaches the transducer level, the received signal will be cancelled by multipath interference. As the water recedes below the transducers, they will continue to transmit in air but attenuation will be too great for reception.

Ray Bending

Ray bending in the cross section can be determined by equations 6 through 8 or by plotting programs available from the Survey. See Appendix I for Fortran listing. Where gradients vary across the stream, bending becomes complex, and so computer programs should be used for calculation. The object in defining the actual acoustic path (or at least the most probably divergent path from the straight line) is to (1) determine if acoustic transmissions will be reliable and (2) determine the accuracy of the line velocity versus mean velocity relation.

The moving sound pulse can be conceptualized as rays emitted from the sending transducer. Plot only those rays that intersect the receiving transducer. Of primary interest is the ray that will take the most direct route; however, secondary routes are important to define interference. If the most direct ray reflects either from water surface or streambed, an AVM system should probably not be used. Reflected signals can be both intermittent and weak. Normally the water surface is a good reflector, but if the surface becomes rough the reflection becomes scattered.

Example of Ray-Bending Analysis

The Chehalis River is one of the larger coastal streams in western Washington. The river reach selected for velocity and discharge measurements is tide affected and is just below the confluence of a major tributary. The cross-section depth and temperature and the mean low-flow information were obtained in a field survey. Field surveys showed that no vertical temperature gradients were greater than 0.1 °C/m and that the temperature differences in the horizontal plane was a maximum of 2 °C. Records for a period of several years indicated that maximum temperature differences between the main stem and the tributary were 4 °C. No salinity gradients were expected.

Figure 22 is the plot of direct and bounce rays for the maximum vertical temperature gradient expected. The direct ray does not bounce from either the surface or the bottom. Therefore, there should be no loss of signal due to ray bending. Reflected signals are nearly midway in the acoustic path so interference was no problem. Clearance height was determined to be 0.58 m from equation 8 and from figure 22, and transducer locations meet this requirement.

As a variation of the above example, if the

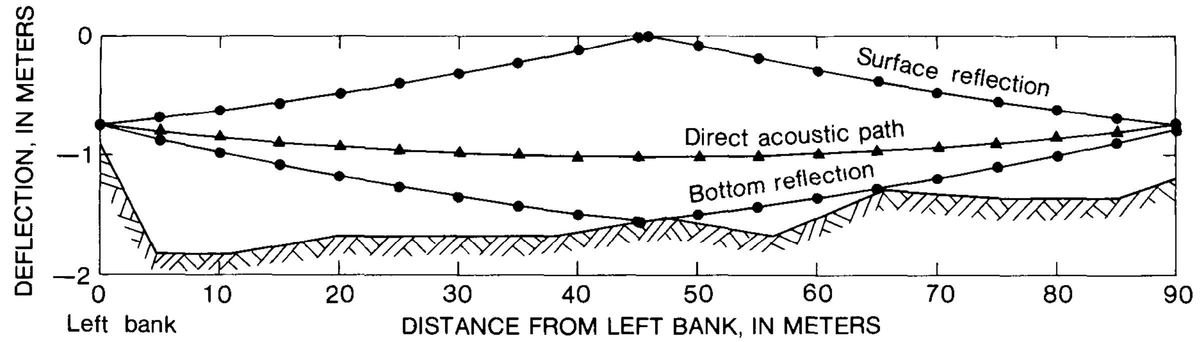


Figure 22.—Cross section at the Chehalis River, Wash., showing paths of direct and reflected signals for the maximum expected gradient.

maximum vertical temperature gradient is assumed to be greater than 0.3 °C/m (fig. 23), then no ray would be able to reach the receiving transducer without reflecting from a surface. The closest nonreflecting ray would miss the transducer by about 0.15 m. The most direct signal would be reflected from the surface and thus would be unreliable. The importance of the example is to show that the acoustic path should be shortened (transducers installed closer together). The rays shown in figure 23 are the closest nonreflected signal, two surface reflected signals, and a bottom-to-surface reflected signal. This extreme bending would cause unacceptable accuracy in the calculation of velocity.

A good approximation of the accuracy associated with line velocity measurements affected by ray bending can be established for various stages. From figure 22, the velocity measured near the midpoint in the stream will be at a depth of 1.05 m instead of 0.75 m. The velocity measured at 1.05 m depth will be approximately 9.5 percent lower than that measured at the 0.75 m depth (see fig. 26). Assuming uniform flow and a nearly rectangular cross section, the estimated velocity is about 5 percent less than actual velocity. If the AVM velocity is rated by current-meter measurements under varying conditions of vertical temperature gradients, the velocity error becomes approximately ±2.5 percent. For more irregular channels and flow conditions, the cross section can be segmented and weighted (refer to calibration section).

Figure 24 is a plot of maximum ray bending caused by the horizontal temperature gradient. The direct ray and those rays associated with the transducer's beam width are plotted. To define a maximum effect, a temperature difference of 2 °C was applied over an estimated 2 m at 5 m from the transmitting transducer. Applying these conditions to figure 24 shows that deflection is not great enough to affect signal loss. Had a gradient of 5 °C/m been used, then the transmissions received by the opposing transducer would have been outside the beam width (they would probably be too weak to receive) and the use of an AVM at this location should be questioned. Increased path length and bending in the horizontal plane should not affect accuracy significantly because the acoustic path traveled is approximately the same in both directions.

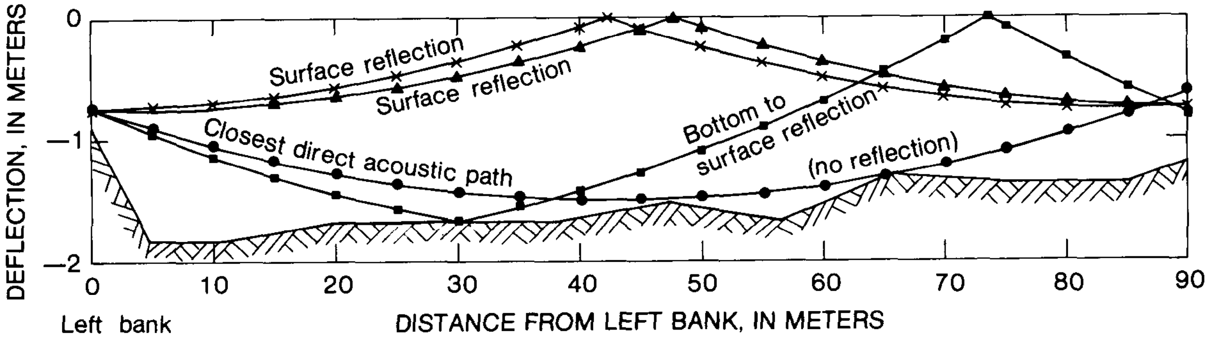


Figure 23.—Cross section at the Chehalis River, Wash., showing paths of direct and reflected signals for a hypothetical density gradient greater than expected maximum. Hypothetical temperature gradient (0.3 °C)

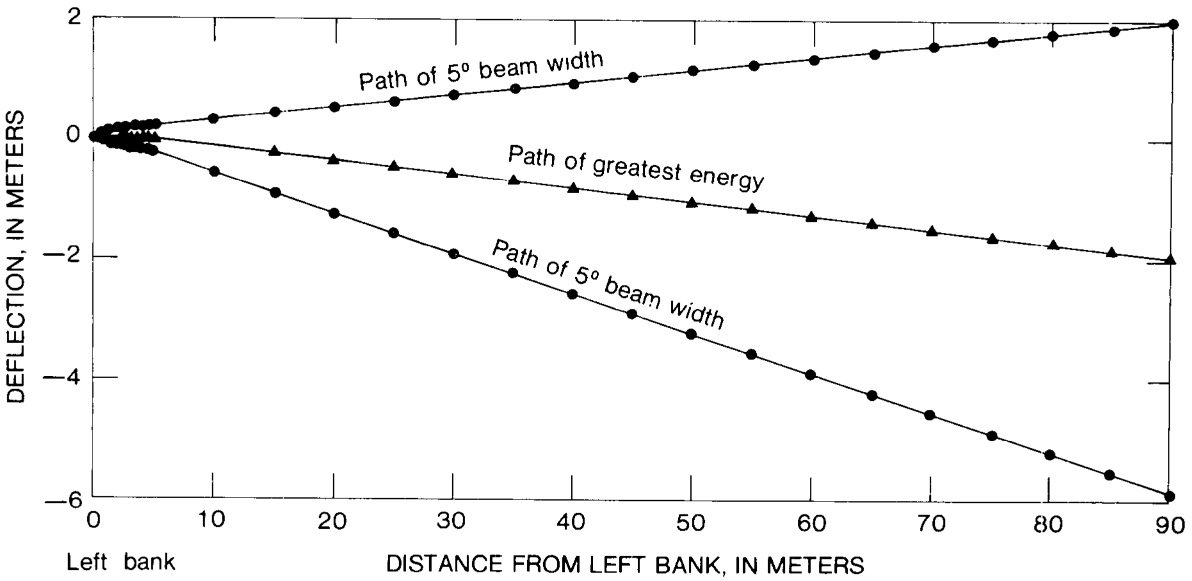


Figure 24 —Plan view of signal-beam deflection caused by the worst expected temperature gradient (4 °C differential).

Signal Attenuation

To determine if the path distance to be measured will be too great for an AVM system to operate with respect to attenuation, the sources of attenuation need to be accumulated and compared to the maximum allowable. As noted previously, the allowable attenuation for 100-kHz systems is about 14 nepers, for 200-kHz systems about 12 nepers, and for 500-kHz systems about 10 nepers.

Example of Attenuation Analysis

The Cowlitz River drains some of the area devastated by the 1980 eruption of Mt. St. Helens volcano in Washington. The heavily sediment-laden stream cannot be rated by conventional methods and needs to be constantly measured. Transducers can conveniently be mounted on bridge piers, which are 40 m apart. Although sediment concentrations more than 800,000 mg/L were measured during the major eruption, 90 percent of the time concentrations are less than 10,000 mg/L.

For most streamflow situations attenuation from absorption will be negligible. From figure 12, using a 200-kHz frequency, the attenuation will be about 0.032 nepers. Attenuation from spreading is calculated by equation 12 and is equal to 3.8 nepers. Attenuation from scattering can be calculated as follows: Suspended sediment in the Cowlitz River has an approximately equal ratio of sand to silt-clay. The sand has an average grain diameter of 125 micrometers, and the silt-clay about 16 micrometers. For a 200-kHz frequency, the average attenuation from figure 13 will be about 8×10^{-8} n/cm. This attenution rate is multiplied by path length and sediment concentration. For the 40-m path and a concentration of 10,000 mg/L, attenuation caused by scattering would be about 3.0 n. Total attenuation is the sum of attenuation from spreading plus scattering (3.8 + 3.0 = 6.8 n). Therefore, an AVM system should work with sediment concentrations of 10,000 mg/L for a path length of 40 m. The maximum sediment concentration that could be tolerated for the same 40-m path and 200-kHz system would be about 25,000 mg/L.

To demonstrate the critical effects of distance between transducers on performance when sediment concentrations are high, the preceding calculations were made for one-half and for double the 40-m distance. Using the 20-m distance, the maximum sediment concentration that could be tolerated would be about 55,000 mg/L. With the path doubled (80 m), the maximum tolerable concentration would be about 11,000 mg/L. If a 100-kHz AVM system were used, the maximum tolerable concentration for an 80-m path would be about 24,000 mg/L (lower frequency systems will penetrate more sediment).

System Considerations

Considering the use of an AVM system, the following questions need to be answered:

1. Given the site location and knowing system limitations, will the system work?
2. What type of data and what kind of accuracy are needed?
3. What system configuration is needed to fulfill the necessary requirments?
4. Is there a compromise between data needs and equipment requirements (cost benefit for different configurations)?
5. What are the installation constraints?

Hypothetical Consideration

Consider the site mentioned in a previous example from the Cowlitz River in Washington: The river at this location is 120 m wide. The acoustic path previously discussed is between the two center piers of the bridge. Two additional acoustic paths would have to be monitored between the center piers and each streambank. Transducer mounting near streambanks would require that pilings be driven. A major tributary, the Toutle River, carries almost all the sediment load and enters the main stem about 1,000 m upstream on the left bank. Flow distribution across the channel at the site is constantly changing. The cross-sectional area changes continuously because of sediment fill and scour.

1. Given the site location and knowing system limitations, will the system work? Yes, an AVM could measure a line velocity between bridge piers (see example attenuation analysis); however, because of the changing cross section, discharge would be difficult to compute accurately unless adequate sounding information were readily available.
2. What type of data and what kind of accuracy are needed? The necessary data requirements for the proposed location would be to compute discharge within 10 percent with fewer man-hours involved. It would require having a recording system that would operate 90 percent of the time.
3. What system configuration is needed to fulfill the necessary requirements? There are basically two system configurations to consider: (1) A simple 3-path system with 200- or 100-kHz transducers to measure line velocity only. Cross-section changes could be recorded periodically by field measurement. (2) A versatile 3-path system with 200- or 100-kHz transducers using additional transducers looking downward to record bottom changes, and a transducer looking upward to record the stage.
4. Is there a compromise between data needs and equipment requirements (cost benefit for different configurations)? Before installing an expensive versatile system, a less complex, less expensive simple 3-path system would be tried. Because flow information is important, it would be cost effective to operate the system with 100-kHz transducers at a maximum tolerable sediment concentration of 41,000 mg/L. The use of lower frequency transducers would increase the equipment costs by 50 percent. Will the proposed equipment (and technique) be accurate enough and require less manpower? How soon will installation cost be recovered by its use?
5. What are the installation constraints? Constraints imposed by physical hazards encountered in the stream channel are probably the single most important consideration for this hypothetical example. Can the transducers be mounted to withstand scour and heavy debris conditions in the stream?

Calibration

Computation of Discharge

In general, single-path AVM systems will be calibrated by current-meter measurements in order to compute discharge. Hydrologic data recorded are stage (h) and the average velocity along the acoustic path (V_p). These parameters are correlated to the geometric and hydraulic conditions at the gaged site in order to define the basic-flow equation:

$$Q = A\bar{V}, \qquad (13)$$

where

Q = discharge,
A = area of the cross section, and
$\bar{V}$ = mean velocity of the cross section.

The relation between area and stage can be adequately defined by a second-order polynomial equation:

$$A = C_1 + C_2h + C_3h^2, \qquad (14)$$

where

C_1, C_2, and C_3 are constants that can be evaluated from data obtained during conventional current-meter measurements.

The relation between the AVM path velocity and the mean velocity in the cross section can also be determined by a second-order equation:

$$K = \frac{\bar{V}}{V_L COS\Theta} = \frac{\bar{V}}{V_p} = C_4 + C_5h + C_6h^2, \qquad (15)$$

where

K = a ratio that may or may not include the path angle (Θ), and

C_4, C_5, and C_6 = constants evaluated from current-meter measurements and corresponding AVM path velocities.

Constants can be defined with polynomial curve-fitting computer programs. Figure 25 shows K curves as defined by current meter and as theoretically computed for the Sacramento River at Freeport, Calif.

Relation of Line Velocity to Mean Velocity

The equation generally used for the computation of vertical velocity distribution in turbulent flow is the Prandtl-von Karman universal-velocity-distribution law (Chow, 1964),

$$v_y = 2.5 \sqrt{\frac{\tau_0}{\rho}} \ \ln\left(\frac{y}{y_0}\right), \qquad (16)$$

where

v_y = velocity at a distance above the stream boundary,

$\sqrt{\frac{\tau_0}{\rho}}$ = shear velocity of the boundary,

y = distance above the boundary, and

y_0 = distance of zero velocity above the boundary.

When empirical relationships of the mean velocity (as defined by the Survey from observations of mean velocity at 0.6 depth, and 0.2,

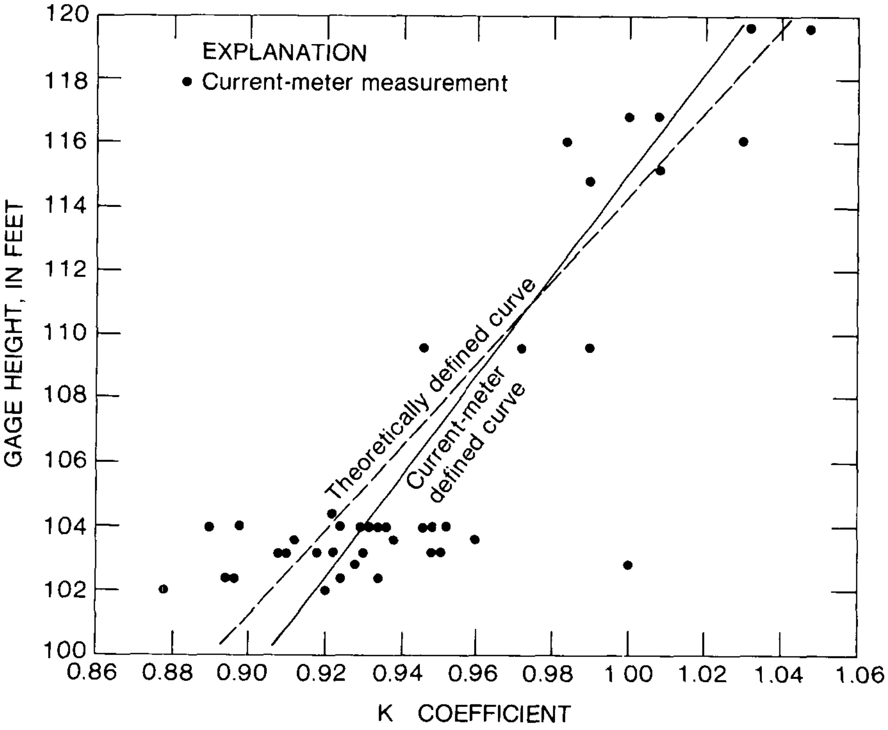


Figure 25.—Mean velocity to line velocity relation (*K*) for various stages on the Sacramento River at Freeport, California.

and 0.8 average depth) are substituted in equation 16, it becomes:

$$v_y = 0.1948\ \bar{V} \ln \left(423.7 \frac{y}{D}\right), \qquad (17)$$

where

$\bar{V}$ = mean velocity and
D = total depth.

Figure 26 shows a unit velocity profile from Buchanan and Somers (1969).

A mean velocity relation can be established now at each point along the acoustic path. The ratio (K_n) of mean velocity to the point velocity is a variable dependent on depth (stage). Therefore, the ratio (K) of mean velocity to line velocity would be a depth-weighted average of K_n along the horizontal line:

$$K = \frac{\displaystyle\sum_{1}^{n} \frac{D_n}{0.1948 \ln\ 423.7 \frac{y_n}{D_n}}}{n}. \qquad (18)$$

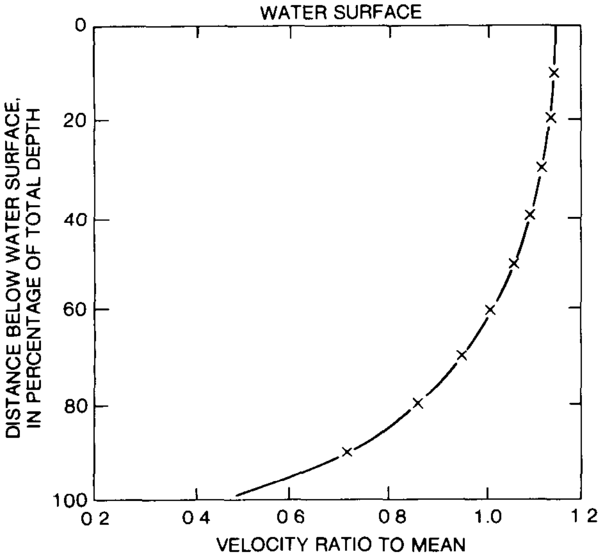


Figure 26.—Theoretical vertical velocity distribution (Buchanan and Somers, 1969).

Assuming that the angle of the acoustic path can be accurately measured and will not vary and that the vertical velocity profile in the stream will remain normal, then a mean velocity ratio *(K)* may be calculated theoretically using equation 18. Theoretical calibration of a single-path system can yield accuracies to within ±3 percent. Figure 25 shows theoretical K values as compared with values from current-meter measurements; the standard deviation is only ±2.6 percent. Accurate measurement of the path angle may be difficult. If current-meter measurements cannot or will not be made, then the addition of a crossed acoustical path along the same horizontal plane will be necessary to define streamflow orientation.

To define theoretically the coefficients in equation 15, it is necessary to define the relation between the ratio (K) and stage (h) at the acoustic path depth across the diagonal section measured. In order to accomplish this, these steps are suggested:

1. Plot the cross section, locate the acoustic path, and locate the water surface.
2. Divide the cross section into about 20 subareas. For each subarea, define the ratio of mean velocity to path velocity (K) and weight the ratio by multiplying by the subarea. Use equation 18 to define K.
3. Sum the weighted ratios and divide by the total cross-sectional area.
4. Repeat steps 1 through 3 for selected water levels throughout the range in stage.
5. Regress the K ratio against stage to determine coefficients in equation 15. Use any statistical package available for the regression analysis or refer to Riggs (1968). If it is necessary to analyze the accuracy of the system because of significant ray bending caused by density gradients, an extra step (after step 2) can be inserted to calculate the deviation at each subarea. This value can be summed and repeated in steps 3 and 4. To simplify the procedure, a computer program has been written and is available from the Survey. See appendix II for Fortran listing.

Operation and Maintenance Requirements

Increased use of AVM systems and other sophisticated electronic equipment in the field requires that personnel be trained in equipment operation and maintenance. It requires the need for in-house expertise in setting up and working with electronic probes, servo systems, minicomputer and microcomputer systems, and data loggers. New procedures need to be outlined. Test equipment and spare parts need to be made available.

Personnel

Although AVM systems can be installed by most competent hydrologic technicians, experienced personnel should be on hand to achieve peak performance. A competent technician is able to maintain and diagnose problems in an AVM system, but special training and experience in electronics is invaluable. New microprocessor systems are self-diagnosing to an extent; however, knowledge in diagnosing problems and in the use of an oscilloscope and other electronic test equipment is more effective. Maintenance and installation of equipment can be accomplished by contractual agreement with the manufacturer, but this can be expensive and generally leads to extended periods of downtime.

Test Equipment

In order to properly install and maintain an AVM system, a delayed sweep oscilloscope is required, as are a good digital multi-meter and an insulation tester. Although oscilloscopes are not difficult to operate, an experienced operator is normally required.

Spare Parts

Microprocessor-based AVM systems being used currently are sold from inventory, and spare parts are readily available. The most common failures have been associated with internal power supplies and data logging equipment. As equipment becomes older, it is important to have spare parts on hand. Establishing a common spare parts inventory supported by several districts with similar equipment should be considered.

Maintenance and Troubleshooting Procedures

AVM systems probably require no more maintenance than any other electronic equipment being used by the Survey. AVM systems are not entirely fail-safe, but error (fault) indications are normally displayed by most systems. When operation is relatively fault free, then yearly examination will be adequate to insure proper system performance. Procedures provided by the manufacturer in the operation and maintenance manual should be followed.

Troubleshooting will not be a problem if adequate training is provided to service personnel. Newer microprocessor systems have diagnostic messages to help identify system failures, including power supply malfunctions, signal losses, and microprocessor errors. Even so, an oscilloscope is sometimes necessary to view received pulses in order to determine signal degeneration and observe trigger level operation. Again, the manufacturer will provide troubleshooting procedures.

Careful attention by maintenance personnel to factors that affect the acoustic propagation of sound in water is necessary in the continued performance of an AVM system. Changes in the acoustic environment need to be documented and the signal response noted (by oscilloscope observation).

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APPENDICES I, II

Appendix I.--Acoustic ray bending program.

```
Source File: <SURVEY>ALAENEN>RAY.F77
Compiled on: 840911  at: 08:24  by: FORTRAN-77 Rev 19.1
Options: OPTIMIZE-2 BIG INTL LOGL SAVE 64V UPCASE ERRTTY
```

```
C
C     INTERACTIVE PROGRAM TO COMPUTE THE SONIC PATH
C     USING LINEAR TEMPERATURE AND SALINITY GRADIENTS
C
      DIMENSION SD(2),W(2),NAME(20)
      INTEGER*2 LPINF(29),LPBUE(500),LPCD
      CHARACTER Y,N,IRPLY,IANS,IPRI
      DATA Y,N/'Y','N'/
      OPEN(5, FILE= 'RAY1.DAT',STATUS='NEW')
      OPEN(6, FILE= 'RAY2.DAT',STATUS='NEW')
      OPEN(7, FILE= 'RAY3.DAT',STATUS='NEW')
      OPEN(8, FILE= 'RAY4.DAT',STATUS='NEW')
      OPEN(9, FILE= 'SETUPV.DAT',STATUS='NEW')
      OPEN(10,FILE= 'SETUPH.DAT',STATUS='NEW')
      LPINF(3)=00
      LPINF(4)='  '
      LPINF(5)='  '
      LPINF(6)='  '
      WRITE(1,100)
  100 FORMAT(1X,//,' GOOD DAY! THIS IS THE RAY BENDING PROGRAM')
      WRITE(1,90)
   90 FORMAT(1X,//,' STREAM NAME ?  ')
      READ(1,95)NAME
   95 FORMAT(20A2)
C     ENTER IN THE PATH DEPTH, PATH ANGLE, BEAM WIDTH
      WRITE(1,103)
  103 FORMAT(1X,//,' WHAT IS THE TRANSDUCER DEPTH [IN METERS]  ')
      READ(1,*)DEPTH
      WRITE(1,101)
  101 FORMAT(1X,//,' WHAT IS THE HORIZONTAL PATH ANGLE [IN DEGREES]  ')
      READ(1,*)ANGLE
      WRITE (1,102)
  102 FORMAT(1X,//,' WHAT IS THE INITIAL STARTING ANGLE OR',/,
     &'  BEAM DIVERGENCE [IN DEGREES + OR -]?  ')
      READ (1,*)BEAM
      WRITE(8,104)NAME,BEAM
  104 FORMAT(15X,' PROGRAM TO COMPUTE SONIC RAY BENDING IN A ',
     1 'GIVEN CROSS-SECTION ',//,10X,20A2,/,20X,'INITIAL STARTING ',
     2 'ANGLE = ',F6.2,' DEGREES',///,20X,'INPUT DATA',35X,
     3 'VERTICAL OUTPUT', 21X,'HORIZONTAL OUTPUT', //,
     4 4X,'STATION',5X,'DEPTH',5X,'TEMP.',5X,'COND.',4X,
     5 'BOTTOM',4X,'STATION',4X,'RADIUS',4X,'THETA DEFLECTION',
     6 7X,'STATION    HANGLE  DEFLECTION', /,6X,'(M)',8X,
     7 '(M)',4X,'(DEG C)',3X,'(UMHOS)',5X,'(M)',8X,'(M)',7X,'(M)'
     8 ,6X,'(RAD)',4X,'(M)',13X,'(M)',6X,'(RAD)',5X,'(M)',/)
```

Appendix I.--Acoustic ray bending program--Continued

```
      PI=3.141592654
      PHI=BEAM*(PI/180.0)
      XSUM=0.0
      SUMH=0.0
      OFSET=0.0
      DIHSUM=0.0
      SDEFH=0.0
      ZERO=0.0
      HANG=0.0
      DEFO=0.0
      TH1=0.0
      REFR=0.0
      WRITE(5,20)XSUM,DEPTH
      WRITE(8,30)XSUM,DEPTH
      WRITE(7,20)SUMH,DIHSUM
      WRITE(8,40)SUMH,DIHSUM
   20 FORMAT(5X,2F15.5)
   30 FORMAT(52X,F10.4,20X,F10.4)
   40 FORMAT(97X,F10.4,10X,F10.4)
C
C     COMPUTE THE VELOCITIES AND RADIUS FOR EACH STATION
C
  108 NO=0
  106 I=0
      K=1
      E=0
      F=0.0
      P=0
      Q=0.0
      RO=0.0
      WSUM=0.0
  107 WRITE(1,105)NO
  105 FORMAT(1X,//,' ENTER IN THE 1ST SET OF DATA FOR STATION #',I3)
      WRITE(1,110)
  110 FORMAT(1X,' DISTANCE FROM THE SURFACE [METERS]:  ')
      READ(1,*)D1
      WRITE(1,115)
```

Appendix I.--Acoustic ray bending program--Continued

```
  115 FORMAT(1X,' TEMPERATURE [DEG. CELCIUS]:  ')
      READ(1,*)T1
      WRITE(1,125)
  125 FORMAT(1X,' CONDUCTIVITY [UMHOS]:  ')
      READ(1,*)CON1
      Z1=1.0+(0.04*T1)
      S1=((CON1/Z1)**1.08)/1000.0
      C1=1449.2+4.6*T1-0.055*(T1)**2+0.00029*(T1)**3+
     &(1.34-(0.01*T1))*(S1-35.0)+0.016*D1
      WRITE(1,135)NO
  135 FORMAT(1X,//,' ENTER IN THE 2ND SET OF DATA FOR STATION #',I3)
      WRITE(1,140)
  140 FORMAT(1X,' DISTANCE FROM THE SURFACE [METERS]:  ')
      READ(1,*)D2
      WRITE(1,145)
  145 FORMAT(1X,' TEMPERATURE [DEG. CELCIUS]:  ')
      READ(1,*)T2
      WRITE(1,150)
  150 FORMAT(1X,' CONDUCTIVITY [UMHOS]:  ')
      READ(1,*)CON2
      Z2=1.0+(0.04*T2)
      S2=(CON2/Z2)**1.08/1000.0
      C2=1449.2+4.6*T2-0.055*(T2)**2+0.00029*(T2)**3+
     &(1.34-(0.01*T2))*(S2-35.0)+0.016*D2
      WRITE(1,126)
  126 FORMAT(1X,' SOUNDING DEPTH [METERS]:  ')
      READ(1,*)SD(K)
      IF (K.NE.1) GO TO 152
      WRITE(8,151)XSUM,D1,T1,CON1,D2,T2,CON2,SD(1)
  151 FORMAT(1X,4F10.4,/,11X,4F10.4)
      WRITE(6,20)XSUM,SD(1)
C
C     COMPUTE THE RADIUS FOR EACH STATION
C
  152 R1=(C1/(C1-C2))*(D2-D1)
      W(K)=(C1+C2)/2.0
      I=I+1
      IF(I.EQ.2) GO TO 200
```

Appendix I.--Acoustic ray bending program--Continued

```
      WRITE(1,165)
  165 FORMAT(1X,///,' IS THE LINEAR GRADIENT CONSTANT? [Y,N]:  ')
      READ(1,170)IRPLY
  170 FORMAT(A1)
      IF(IRPLY.EQ.Y) GO TO 199
      RO=R1
      NO=NO+1
      K=K+1
      GO TO 107
  199 NO=NO+1
      K=K+1
      WRITE(1,180)
  180 FORMAT(1X,///,' AVE. SOUNDING DEPTH ALONG LINEAR PATH [METERS]: ')
      READ(1,*)SD(K)
C
C     COMPUTE THE VERTICLE DEFLECTIONS BETWEEN EACH STATION
C
  200 WRITE(1,201)RO,R1
  201 FORMAT(1X,//,' RO=',F15.5,/,'  R1=',F15.5)
      M=NO-1
      WRITE(1,205)M,NO
  205 FORMAT(1X,///,' WHAT IS THE PATH DISTANCE BETWEEN STA. #',
     + I3,' AND STA. #',I3,'  :  ')
      READ(1,*)X
      WRITE(1,215)
  215 FORMAT(1X,' HOW MANY POINTS DO YOU WANT PLOTTED IN THIS ',
     + 'INTERVAL?  ')
      READ(1,*)J
C
C     COMPUTE FOR RAY BENDING IN THE VERTICAL
C
      SDA=SD(1)
      SDB=SD(2)
      SDMAX=AMAX1(SDA,SDB)
      SOND=(SDA+SDB)/2.0
      IF (ABS(RO).LT.0.01) GO TO 216
      II=1
      JJ=J/2
      R=RO
      GO TO 220
```

Appendix I.--Acoustic ray bending program--Continued

```
  216 R=R1
      II=1
      JJ=J
  220 DO 235 K=II,JJ
      ICNT=0
      K1=K
      KK=K-II+1
      XX=(X/J)*KK
      XY=(X/J)*K
      DIST=XY+XSUM
  225 THO=TH1+PHI
      TH2=ASIN(XX/(2.0*R))
      THETA=THO+TH2
      DEF=XX*TAN(THETA)
      DEFL=DEFO+DEF
      DEF1=DEPTH-DEFL
      ICNT=ICNT+1
      XX=SQRT(XX**2+DEF**2)
      IF(ICNT.EQ.1) GO TO 225
      IF(DEF1.LE.0.0) GO TO 300
      IF(DEF1.GE.SOND) GO TO 305
      GO TO 230
C
C     COMPUTE REFLECTION FROM SURFACE
C
  300 ZIP=0.0
      A1=DEF2
      A2=-DEF1
      SIGN=-1.0
      DEPTH=0.0
      GO TO 310
  305 ZIP=SOND
      A1=SOND-DEF2
      A2=DEF1-SOND
      SIGN=1.0
      DEPTH=SOND
  310 IF(DEF1.NE.ZIP) GO TO 320
      PHI=-2.0*THETA
      TH1=0.0
```

Appendix I.--Acoustic ray bending program--Continued

```
      GO TO 230
  320 XREFL=(X/J)/(1.0+A2/A1)
      RANG=ATAN(A1/XREFL)
      REFR=REFR+(X/J)-XREFL
      PHI=RANG*SIGN
      II=K
      THETA=PHI
      DEFO=(DEF1-ZIP)*SIGN
      DEF1=ZIP-DEFO*SIGN
      TH1=0.0
      DISTR=(X/J)*(K-1)+XREFL+XSUM
      WRITE(5,241)DISTR,ZIP
      WRITE(8,234)DISTR,R,RANG,ZIP
  230 DEF2=DEF1
      WRITE(5,241)DIST,DEF1
  241 FORMAT(5X,2F15.5)
      WRITE(8,234)DIST,R,THETA,DEF1
  234 FORMAT(52X,F7.1,F13.2,2F10.4)
  235 CONTINUE
      TH1=TH1+TH2*2.0
      DEFO=DEFL
      IF (K1.GE.J) GO TO 250
      II=JJ+1
      JJ=J
      R=R1
      GO TO 220
  250 XSUM=XSUM+X
      GO TO 700
C
C     COMPUTE RAY BENDING IN THE HORIZONTAL
C
  700 IF(IRPLY.EQ.Y)THEN
      T=0.0
      ELSE
      T=(W(1)-W(2))/(W(1)*SIN(ANGLE*(PI/180.0)))
      ENDIF
      IF(T.EQ.0.0) THEN
      HORANG=0.0
      ELSE
      RADIUS=TAN(ANGLE*(PI/180.0))*X/T
```

Appendix I.--Acoustic ray bending program--Continued

```
      HORANG=ASIN((X/J)/(2.0*RADIUS))
      ENDIF
      DO 720 K=1,J
      DISH=(X/J)*K
      ANGLH=HORANG*K+PHI+HANG
      DEFH=DISH*TAN(ANGLH)+OFSET
      STAT=DISH+SUMH
      ABSDEF=ABS(DEFH)
      YMAX=AMAX1(ABSDEF,ZERO)
      YMAX=YMAX*1.5
      YMIN=YMAX*(-1)
      WRITE(8,730)STAT,ANGLH,DEFH
      WRITE(7,710)STAT,DEFH
  730 FORMAT(97X,F7.1,F13.4,F10.4)
  710 FORMAT(5X,2F15.5)
  720 CONTINUE
      IF(IRPLY.EQ.Y) GO TO 999
      SUMH=SUMH+X
      OFSET=DEFH
      HANG=2.0*HORANG*K
  900 WRITE(1,905)
  905 FORMAT(1X,///,' DO YOU WANT TO CONTINUE?  [Y,N]:  ')
      READ(1,170)IANS
      IF(IANS.EQ.Y) GO TO 106
  999 WRITE(8,151)XSUM,D1,T1,CON1,D2,T2,CON2,SD(2)
      WRITE(6,20)XSUM,SD(2)
      WRITE(9,805)XSUM,SDMAX
      WRITE(9,805)ZERO,ZERO
  805 FORMAT(5X,2F15.5)
      WRITE(10,805)XSUM,YMAX
      WRITE(10,805)ZERO,YMIN
C
C        EXPLANATION OF PLOT ROUTINES
C
      WRITE(1,950)
      WRITE(8,950)
  950 FORMAT(1X,///,10X,'INSTRUCTIONS FOR USING LOCAL PLOTTER',//,
     1' File RAY1.DAT contains cross-sectional information for the ',
     2 'vertical ray.',/,' File RAY2.DAT contains cross-sectional ',
     3 'information on streambed soundings.',/,' File RAY3.DAT ',
```

Appendix I.--Acoustic ray bending program--Continued

```
     4 'contains plan information for the horizontal ray.',/,
     5 ' File SETUPV.DAT contains max-min information for vertical ',
     6 'plot.',/,' File SETUPH.DAT contains max-min information for ',
     7 'horizontal plot.',//)
      WRITE(1,955)
      WRITE(8,955)
  955 FORMAT(1X,' To obtain additional plotting rays (e.g. to see ',
     1 'spread of the xducer beam ):', /,'    The initial starting ',
     2 'angle must be changed for vertical plots.',/,'    The path ',
     3 'angle must be changed for horizontal plots.',/,
     4 '    For overlay plots, run program repetitively and save ',
     5 'necessary files.',/,'    To plot, use SEG PLOTSRC>XY ',
     6 ' Format = (5X,2F15.5)')
      WRITE(1,960)
  960 FORMAT(1X,/,' DO YOU WANT A PRINTOUT ? [Y,N] ')
      READ(1,170)IPRI
      IF(IPRI.EQ.N) GO TO 1000
      CALL SPOOL$(INTS(1),'RAY4.DAT',INTS(8),LPINF,LPBUE,INTS(500),
     1 LPCD)
 1000 STOP
      END
```

Appendix II.--Listing K-curve calculation program.

```
Source File: <SURVEY>ALAENEN>KCOEF.F77
Compiled on: 840911  at: 08:25  by: FORTRAN-77 Rev 19.1
Options: OPTIMIZE-2 BIG INTL LOGL SAVE 64V UPCASE ERRTTY

C   PROGRAM TO CALCULATE THEORETICAL K CURVE
C   AND TO DEFINE INACCURACY CAUSED BY RAY BENDING
C
C
      DIMENSION STREAM(20),COMMENT(20),STA(90),DEPTH(90),BEAM(90)
      DIMENSION WIDTH(90)
      CHARACTER INFILE*32,STREAM*4,COMMENT*4,Y,N,IANS
      DATA Y,N/'Y','N'/
      OPEN (UNIT=6,FILE='KCOEF.PRT',STATUS='NEW')
      OPEN (UNIT=7,FILE='KCOEF.LST',STATUS='NEW')
      WRITE (1,100)
100   FORMAT(3X,'PROGRAM TO CALCULATE A THEORETICAL K CURVE',///,
     1       3X,'NAME OF STREAM OR LOCATION?')
      READ (1,110) STREAM
110   FORMAT(20A4)
      WRITE (1,120)
120   FORMAT(3X,'PRINTOUT COMMENTARY? (1 LINE)')
      READ (1,110) COMMENT
      WRITE (1,130)
130   FORMAT(3X,'ENTER CROSS-SECTION DATA:',//,
     1       3X,'ENTER STAGE:')
      READ (1,140) WS
140   FORMAT(F15.0)
      WRITE (1,150)
150   FORMAT(3X,'TRANSDUCER ELEVATION:')
      READ (1,140) TE
      DEL=WS-TE
      WRITE (1,160)
160   FORMAT(3X,'DO YOU HAVE A DATA FILE OF CROSS-SECTION DEPTHS? Y-N')
      READ (1,170) IANS
170   FORMAT(A1)
      IF (IANS.EQ.Y) THEN
      WRITE (1,180)
180   FORMAT(3X,'WHAT IS THE NAME OF THE DATA FILE?')
      READ (1,190) INFILE
190   FORMAT(A32)
```

Appendix II.--Listing K-curve calculation program--Continued

```
      OPEN (UNIT=5,FILE=INFILE,STATUS='OLD')
      READ (5,200) NXSEC
  200 FORMAT (I4)
      READ (5,210) GHMAX,GHMIN
  210 FORMAT (2F10.2)
      READ (5,220) (STA(I),DEPTH(I),BEAM(I),I=1,NXSEC)
  220 FORMAT (3F10.2)
      ELSE
      WRITE (1,230)
  230 FORMAT(3X,'DEFINE THE NUMBER OF POINTS IN THE CROSS-SECTION:')
      READ (1,200) NXSEC
      WRITE (1,240)
  240 FORMAT(3X,'WHAT IS THE MAXIMUM AND MINIMUM GAGE HEIGHT TO BE ',/,
     1       3X,'COMPUTED DEFINING THE THEORETICAL K CURVE?')
      READ (1,210) GHMAX,GHMIN
      WRITE (1,250)
  250 FORMAT(3X,'ENTER CROSS-SECTION DATA BY:',/,
     1       1X,'STATION  DEPTH      BEAM DEFLECTION (IF AVAIL.)')
      READ (1,220) (STA(I),DEPTH(I),BEAM(I),I=1,NXSEC)
      OPEN (UNIT=8,FILE='KCOEF.INFILE',STATUS='NEW')
      WRITE (8,200) NXSEC
      WRITE (8,210) GHMAX,GHMIN
      WRITE (8,220) (STA(I),DEPTH(I),BEAM(I),I=1,NXSEC)
      ENDIF
C
C   COMPUTE K COEFFICIENT FOR EACH GAGE HEIGHT SEGMENT
C
      WRITE (1,260)
  260 FORMAT(3X,'WHAT IS THE DESIRED GAGE HEIGHT INCREMENT?')
      READ (1,270) STINC
  270 FORMAT (F10.2)
      DO 280 I=1,NXSEC
      IF (I.EQ.1.OR.I.EQ.NXSEC) THEN
      WIDTH(1)=(STA(2)-STA(1))/2.0
      WIDTH(NXSEC)=(STA(NXSEC)-STA(NXSEC-1))/2.0
      ELSE
      WIDTH(I)=(STA(I+1)-STA(I-1))/2.0
      ENDIF
```

Appendix II.--Listing K-curve calculation program--Continued

```
 280  CONTINUE
      WRITE (6,300)
 300  FORMAT(10X,'PROGRAM TO CALCULATE A THEORETICAL K COEFFICIENT'
     1       ' FOR SPECIFIED GAGE HEIGHT INCREMENTS',///)
      WRITE (6,310) STREAM
 310  FORMAT(5X,20A4)
      WRITE (6,310) COMMENT
      WRITE (6,320)
 320  FORMAT(//,10X,'STAGE     KCOEF     BEAM DEFLECTION ERROR',/,
     1       12X,'FT      RATIO        PERCENT',//)
      STG=GHMIN-STINC
 325  STG=STG+STINC
      IF (STG.GT.GHMAX) GO TO 500
      SUMD=0.0
      SUMDER=0.0
      SUMK=0.0
      SUMAR=0.0
      DIF=STG-WS
      DO 330 I=1,NXSEC
      DPT=DEPTH(I)-DEL
      DPB=DEPTH(I)+DIF
      DP=DPT/DPB
      IF (DP.LE.0.0) THEN
      WRITE (1,322) STA(I)
 322  FORMAT(3X,'HEIGHT ABOVE TRANSDUCER IS GREATER THAN TOTAL DEPTH',/
     1      ,3X,'IN SECTION ',F7.2,'***ABNORMAL END***')
      GO TO 520
      ELSE
      AREA=DEPTH(I)*WIDTH(I)
      COEF=0.1948*ALOG(423.7*DP)*AREA
      ENDIF
      DBD=DPT+BEAM(I)/DPB
      IF (DBD.LE.0.0) THEN
      COEBD=COEF
      ELSE
```

Appendix II.--Listing K-curve calculation program--Continued

```
      COEBD=0.1948*ALOG(423.7*DBD)*AREA
      ENDIF
      SUMAR=SUMAR+AREA
      SUMK=SUMK+COEF
      SUMD=SUMD+DEPTH(I)
      DEFER=(COEF-COEBD)/COEF
      SUMDER=SUMDER+DEFER
330   CONTINUE
      COEFK=SUMK/SUMAR
      ERROR=(SUMDER/SUMAR)*100.0
      WRITE (6,340) STG, COEFK, ERROR
340   FORMAT (8X,F7.2,5X,F5.3,7X,F7.2)
      WRITE (7,350) STG, COEFK, ERROR
350   FORMAT (3F10.3)
      GO TO 325
500   WRITE (1,510)
510   FORMAT(3X,'*******NORMAL EXECUTION COMPLETE********',//,
     1       3X,'TO PRINT FILE: SPOOL KCOEF.PRT',
     2     /,3X,'A DATA LIST FOR PLOTTING IS IN FILE: KCOEF.LST')
520   STOP
      END
```