J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

HYDROMETERS

Hydrometric measurements are fundamental to the development and application of hydrological science. Progress in hydrology largely depends on improved methods of hydrometric data collection obtained from networks at various spatial and temporal scales. A network of gauging stations is necessary for assessment, management, and control of water resources. The primary object of a gauging station is to provide the stage-discharge relation that is determined from field measurement of stages and the corresponding discharges.

Hydrometry is usually considered as the physical measurement of terrestrial waters, which may be flowing above or below ground or quasistatic in lakes, reservoirs, and underground formations. A hydrometer is then a hydrometric instrument of flow metering. To solve hydrometric problems such as the gauging of discharge during flood periods on flushy streams, a short-time and accurate measurement with a suitable hydrometer is necessary. There are different methods to measure river flow: the stage, velocity-area method with probe techniques, structural and dilution techniques, and moving boat methods. Each method has advantages and limitations in relation to the site conditions and to the available resources of the gauging authority. Important are the selection of the site, the selection of equipment, and design and installation.

The applicability of existing instruments has been improved considerably by refining the design and introducing more electronics using digital outputs and microprocessor technology. In particular, the following areas of advance may be claimed: ultrasonic flow metering, electromagnetic flow metering, optical velocity measurement, frictionless contacts and electronic counters in current meters, the moving boat technique, telemetering, use of satellites in hydrometry, remote sensing, and acquisition and processing of river flow data.

The World Meteorological Organization (*WMO*) is concerned with the establishment of hydrometric networks and the collection and application of hydrometric data. An international symposium, especially on hydrometry, was recommended by the WMO Commission for Hydrology and the proceedings were edited by Cole (1). An overview about hydrometry was given by Herschy (2).

Stage Measuring Instruments

The stage is generally known as the most important measurement of the water level with respect to the datum at a gauging station. Stage measuring instruments may be separated into two types: direct reading and indirect reading.

Direct-Reading Gauges.

Direct reading means the stage measurement in units of length without any intervening influences. The stage instruments can be grouped into a few important categories: staff gauges, crest-stage gauges, needle gauges, wire-weight gauges, and float gauges.

A staff gauge is a vertical or inclined staff with graduations and with a permanent installation at a stable point in the river unaffected by turbulence or waves. Staff gauges need an accurate and clear graduation and they should be constructed of durable material with a low coefficient of expansion by the influence of temperature and moisture. Figure 1 shows the meter graduation of a vertical staff. The stage is read to an accuracy of ±3 mm.

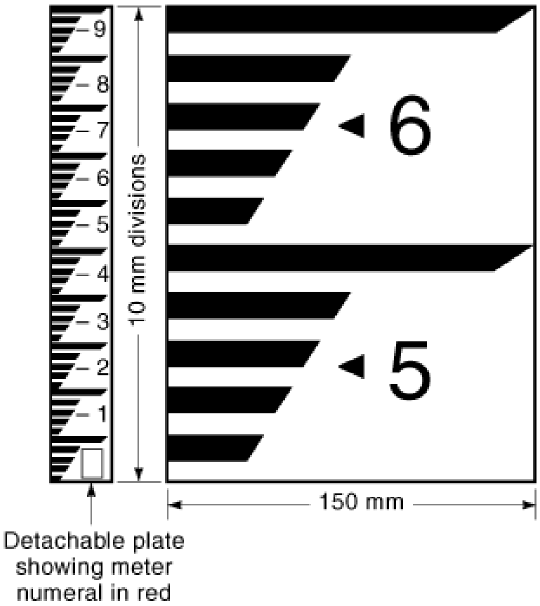

Fig. 1. Meter graduation of a vertical staff. A series of vertical staff gauges can be used for a large range.

A crest-stage gauge is used to obtain a record of the highest water peak level. The standard crest-stage gauge consists of a 50-mm-diameter steel tube perforated near the bottom for water entry. Inside the tube is a removable rod with a water mark from a floating granular cork or the rod is coated with a paint whose color is permanently affected by the water.

A needle gauge consists of a metal rod with a tip that is adjusted to the free-water surface from above (the point gauge) or from below (the hook gauge). The position is determined from an engraved scale graduated downwards from top to bottom.

A wire-weight gauge consists of a drum wound with light cable, a weight at the end of the cable, and a metering counter to measure the cable length until the weight just touches the water surface. Wire-weight gauges are mounted directly over the water surface on a bridge or dock.

A float gauge consists of a moving float looped over a geared pulley with a counterweight and a pen marking on a chart or recording of water level on punch paper tapes. The float gauge must be installed in a stilling well to exclude waves and turbulence of the main water flow and also the effects of wind to the tape.

Indirect-Reading Gauges. *Indirect reading* means the stage measurement by a pressure or an acoustic measurement. A pressure gauge consists of a pressure transducer that converts the hydrostatic pressure at a submerged datum to the water level above. Battery-operated equipments are available. Another type of pressure gauge is the gas-purge (bubbler) technique that is widely used for transmitting pressure. The pressure sensor detects the pressure of compressed air or noncorrosive gas required to displace the water in a tube. Changes in the density of water dependent on the temperature, dissolved-solid content, and suspended-solid content have to be incorporated. An acoustic-level gauge consists of an ultrasonic pulse probe with transmitter and receiver. The pulse of ultrasound from the subsurface transducer is reflected normally from the water surface, and the distance from the transducer to the water surface is then

$$h = 0.5tc \tag{1}$$

where h is the distance above the water, c is the velocity of ultrasound in air, and t is the total duration of pulse travel time. The velocity c changes with changes in temperature and humidity so that most acoustic-level gauges incorporate one of several methods for automatically correcting.

Since 1974 the electromagnetic technique of flow gauging has been extended from full pipes to open channels and rivers. The basic principle is the measurement of a voltage induced by the conducting water flowing through a magnetic field. A coil is installed below the river bed or bridges across the channel to generate the vertical magnetic field across the full width up to 25 m wide. Electrodes, set into opposite banks of the river, sense the voltage induced by the water flow through the magnetic field. The electromagnetic gauge technique covers a very large dynamic range with high accuracy and reliability.

Discharge Measuring Instruments

The velocity-area method is the most direct method to obtain the discharge in relation to a stage measurement. The total cross section of the river is divided into verticals spaced at intervals no greater than one-fifteenth of the width across the flow. A good estimate of the average velocity v_{mean} in a vertical is obtained by taking the mean of velocity measurements at 0.2 and 0.8 depth. Then the discharge Q is the summation of the products of mean velocities in the verticals with the related segments a_i of the total cross section A:

$$A = \sum_i a_i \qquad (2)$$

$$Q = \sum_i v_{\mathrm{mean},i} a_i \qquad (3)$$

As shown by Shaw (3), the calculation of the discharge from the velocity and depth measurements can be made in several ways. In comparison with the determination of the fixed cross section it is much more difficult to get consistent measurements of the flow velocities $v_{\mathrm{mean},i}$. Most velocity measuring instruments are designed to provide only the magnitude of the velocity vector, because in many cases of river flow measurement, the direction of velocity is known.

The use of heated-element meters and of the salt-velocity technique is limited to special measurements and therefore are not discussed.

Floats. Using a float means the simple determination of the velocity v by timing the travel of a float over a known distance s:

$$v = s/t \qquad (4)$$

where t is the time of travel. Floats are designed as surface float, canister float, or rod float, as are shown in Fig. 2. Measurements with surface floats give only the surface velocity, and a correction factor of about 0.7–0.8 must be applied to give the mean velocity over the depth. Canister floats and rod floats have a velocity that is equal to the mean velocity in the vertical section parallel to the hydraulic axis of the river. Wind can effect velocity values, especially for surface and canister floats. Another practical float technique is based on the integrating float technique using air bubbles as rising integrating floats. The principle of the rising float is shown in

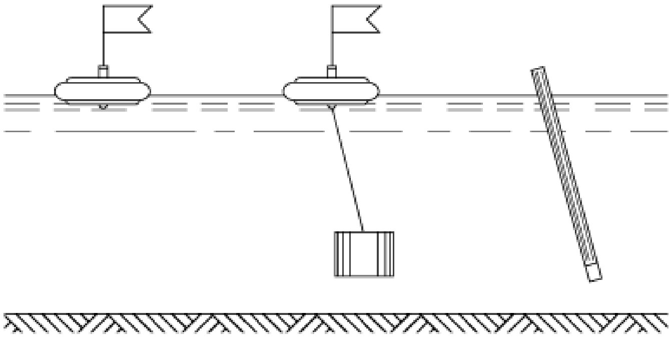

Fig. 2. Different types of floats: surface float, canister float, and rod float. Canister float and rod float can measure mean velocity.

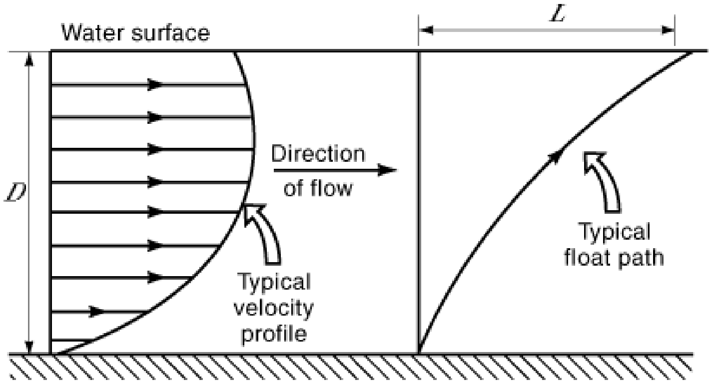

Fig. 3. Principle of the rising float using air bubbles rising from the bed to the surface. Rise velocities dependent on bubble size can be calculated for known bubble sizes.

Fig. 3. The discharge q per unit width is given by

$$q = v_{\mathrm{r}} L \tag{5}$$

where v_{r} is the terminal velocity of rise, and L is the horizontal displacement of the float. The total discharge Q is then evaluated by using a number of floats across the stream. Air bubbles as rising floats can be conveniently produced using compressed air. On the other hand, air bubbles as rising floats restrict the range of rise velocity available in dependence on the given bubble diameter.

Drag-Body Current Meters. All such velocity measuring devices use different shapes and configurations of drag elements that are governed by the drag equation:

$$F = 0.5 C_{\mathrm{D}} \rho A v^2 \tag{6}$$

where F is the drag, C_{D} the drag coefficient, A the projected area, v the flow velocity, and ρ the fluid density. The drag coefficient depends on the Reynolds number Re and is changed if the surface of the drag elements

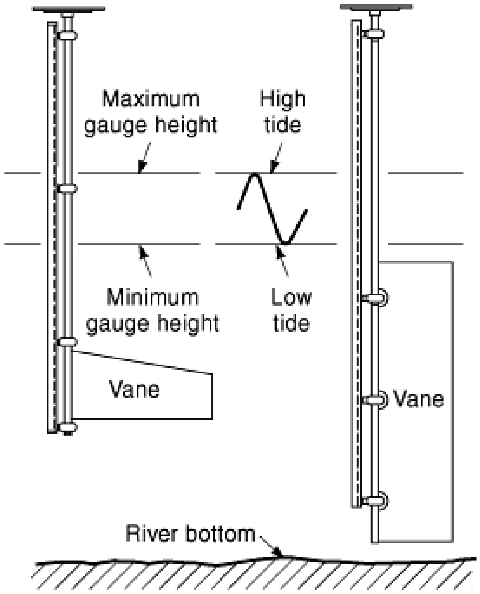

Fig. 4. Two examples of a drag-body current meter using a vane. The deflection of vanes is indicated by a scale and pointer at the top.

becomes fouled with aquatic growth or debris. All drag-body current meters are insensitive to extremely low velocities.

As an example, the drag coefficient of a sphere is given by

$$C_D = \frac{24}{\text{Re}} \quad \text{for} \quad \text{Re} \le 0.1 \tag{7}$$

$$C_D = \frac{K_1}{\text{Re}} + \frac{K_2}{\text{Re}^2} + K_3 \quad \text{for} \quad \text{Re} > 0.1 \tag{8}$$

K_1, K_2, and K_3 are constant with different values for different ranges of Reynolds numbers. An example of a wide assortment of this type of velocity measuring devices is shown in Fig. 4. The vane on the left is designed for the measurement of the local velocity, whereas the vane on the right can integrate the velocities over the vertical length.

Rotating-Element Current Meters. In 1663 Robert Hooke introduced the current meter with rotating elements in flow measurement of open canals, rivers, and in pressure pipes. Reinhard Woltman introduced it in 1790. Since that time the design of the mechanical current meter has been changed by means of modern electronics, and the measurement of the discharge by the current meter is now a standard method. The principle of operation of a rotating-element current meter is the proportionality between the local flow velocity and the resulting angular velocity of the meter rotor. The calibration of the angular velocity is established experimentally by towing the meter at different known velocities in a straight open channel with still water. Each individual instrument has its own calibration relationship, and with regular use it must to be checked

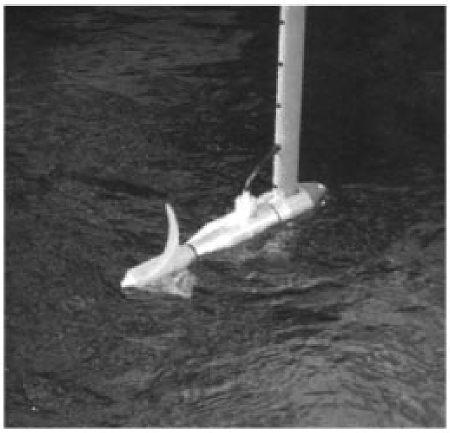

Fig. 5. Rotating-element current meter with horizontal axis nearly parallel to the direction of flow. The local flow velocity is proportional to the angular velocity of meter rotor.

each year. It was shown by Herschy (2) that group rating need not reduce the accuracy of current meter gaugings, but the cost saving is significant. A group rating is based on the average of a number at least 10 individual ratings of meters of the same type and maker. During the local flow measurement, the angular velocity can be determined by counting the number of revolutions of the rotor over an interval of time that is signalled by a battery-operated buzzer or digital counter. The range of velocities is limited to 0.015–10 m/s with various current meters.

There are two main types of meter: vertical-axis meters with their rotating axis perpendicular to the flow direction and horizontal-axis meters with their rotating axis coinciding with the direction of flow. The vertical-axis meters can be divided into cup or bucket wheel, and vane rotor, the horizontal-axis type into vane with two or more vanes comprising the rotor, and helical screw with two or more blades (Fig. 5). The cup type is more robust and registers the local velocity whatever its direction with 5% accuracy. The more sensitive propeller type records the required velocity component normal to the cross section with 2% accuracy.

The Ott current meter has an intelligent electronics inside and can determine the direction of velocity, the contact with the ground, the temperature, and the pressure.

There are different types of current meters for all applications. A main advantage is the low price; a main disadvantage is the frequent recalibration.

Electromagnetic Current Meters. The law of electromagnetic induction was discovered by Michael Faraday in 1831. About 143 years later, the electromagnetic current meter is based upon Faraday's law. As a conductive liquid like water cuts lines of magnetic flux, an electromotive force is induced in water and can detected by a pair of electrodes on the surface of the meter. The magnitude is proportional to the strength of the magnetic field and the average velocity of water. In order to avoid different detection problems, an alternating-polarity magnetic field is generated. The sensor is shaped to minimize any disturbances in the flow field. The measuring principle of an electromagnetic current meter is illustrated in Fig. 6. An electromagnetic current meter needs liquids with an electrical conductivity of at least 5 μS/cm. The electrical conductivity of water is caused by the content of dissolved salts. Rivers, drinking water, or cooling water usually have a conductivity in the range of 100 μS/cm to 1000 μS/cm.

A main advantage of the electromagnetic current meter is the meter design without rotating parts like the rotor of the rotating-element current meters. Only each model type of electromagnetic current meter has to

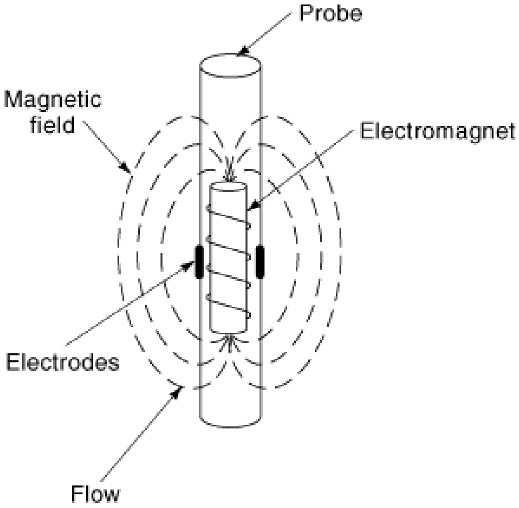

Fig. 6. Measuring principle of an electromagnetic current meter. The magnitude of the induced voltage is proportional to the strength of the magnetic field and the average velocity of water.

be calibrated by towing the meter at various well-known velocities in straight-open channels with still water. Then every meter of the same model type has the same long-time accuracy.

A variety of instrument specifications and built-in options are provided: portable current meter or use in permanent application, microprocessor-based current meter with recording of velocity and flow level, monitoring of temperature, outdoor installation, remote communication, battery-operated system, portable processor for data analysis of stored data.

A main disadvantage is the measuring error by contamination of the measuring electrodes and therefore the need to calibrate the meter periodically. The sensors of Marsh-McBirney's 500 series electromagnetic water current meters are spherically shaped to reduce the effects of clogging or fouling. Both the direction and the magnitude of the water velocity in a horizontal plane can be measured with a solid-state electromagnetic flow sensor in these water current meters.

Figure 7 shows an example for channel flow measurement with an electromagnetic current meter combined with a level measurement and the determination of the cross section A.

Marsh-McBirney now presents an insertable electromagnetic flowmeter. The streamlined sensor can be installed for different pipe size in minutes without system shutdown. See Table 1 for a list of manufacturers.

Ultrasonic Velocity Meters. The ultrasonic (acoustic) velocimeters can be divided into velocity meters based upon a pulse travel time and upon the Doppler effect.

Acoustic Travel-Time Velocimeters. The acoustic travel-time velocimeters use the principle that the velocity of an ultrasound pulse in flowing water is the algebraic sum of the acoustic propagation rate $c \approx 1500$ m/s and the component of water velocity parallel to the acoustic path. Several acoustic travel-time velocimeters have been developed: the total travel-time circuit, the total sing-around circuit, and the differential time circuit. From Fig. 8 the operating principles of the total travel-time system can be derived and the result is

$$v_{\mathrm{L}} = \frac{L}{2\cos\theta}\left(\frac{1}{T_{\mathrm{BA}}} - \frac{1}{T_{\mathrm{AB}}}\right) \tag{9}$$

Table 1. List of Manufacturers

Dantec Dynamics A/S
Tonsbakken 16–18
P. O. Box 121
DK-2740 Skovlunde
Denmark
Tel: +45 44 57 80 00
Fax : +45 44 57 80 01
www.dantecmt.com

Marsh-McBirney, Inc.
4539 Metropolitan Ct.
Frederick, MD 21704-9452
Tel: 301-874-5599
Fax: 301-874-2172
www.marsh-mcbirney.com

Ott Messtechnik GmbH&Co.KG
P. O. Box 2140
Ludwigstrasse 16
D-87411 Kempten
Germany
Tel: +49-831-5617-0
Fax: +49-831-5617-209
Info@ott-hydrometry.de
www.ott-hydrometry.de

Parsum GmbH
Annaberger Strasse 240
D-09125 Chemnitz
Germany
Tel: +49 371-5347-328
Fax: +49 371-5347-327
info@parsum.tcc-chemnitz.de
www.tcc-chemnitz.de/firmen

SonTek, Inc
6837 Nancy Ridge Dr, Ste A
San Diego, CA 92121
Tel: +1 858-546-8327
Fax: +1 858-546-8150
Inquiry@sontek.com
www.sontek.com

TSI, Inc
P. O. Box 64 394
St. Paul, MN 55164
Tel: 651-483-0900
Fax: 651-490-2748
tsiinfo@tsi.com
www.tsi.com

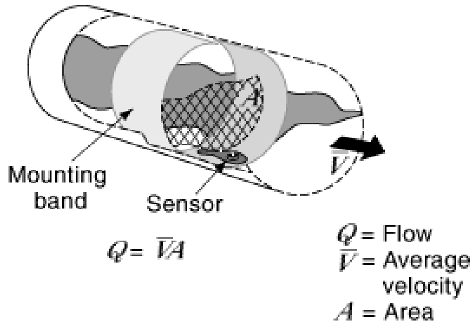

Fig. 7. Application of an electromagnetic area/velocity flow meter to flow measurement in filled or partially filled conduits or open channels. The level measurement is realized by a submerged differential pressure transducer.

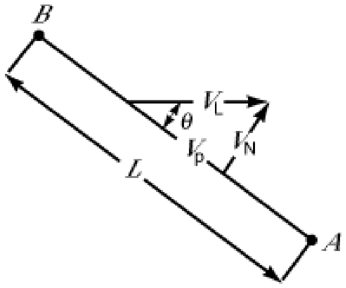

Fig. 8. Operating principle of the acoustic travel-time velocimeter. An acoustic pulse travels from A to B and in reverse from B to A. Then the travel time depends on the component of average water velocity V_{L} parallel or antiparallel to the acoustic path.

$$T_{AB} = \frac{L}{c - v_p}, \quad T_{\mathrm{BA}} = \frac{L}{c + v_p} \tag{10}$$

where v_{L} is the average water velocity along the streamline of flow, v_p is the average water velocity parallel to the acoustic path, L is the length of the acoustic path from A to B, T_{AB} is the travel time of an acoustic pulse from A to B, T_{BA} is the travel time of an acoustic pulse from B to A, and θ is the angle of departure between the streamline of flow and the acoustic path. Travel times are measured sequentially for pulses generating at A and then at B.

The sing-around circuit, sometimes referred to as the pulse-repetition frequency system, is allowed to continue operation. The differential time-circuit system uses two transducers that transmit signals simultaneously toward each other. The signal transmitted in the downstream flow direction arrives first and starts a time clock. The signal transmitted in the opposite flow direction is used to stop the clock. Acoustic travel-time velocimeters have been manufactured with path lengths of about 1 m to path lengths of several hundred meters.

Acoustic-Doppler Velocimeters. The acoustic-Doppler velocimeters are based upon the Doppler-shift effect. A single transducer emits an ultrasonic pulse into the water. The acoustic energy is scattered by suspended small particles such as sediments or small organisms. Some of this scattered energy is reflected to the receiver and the received signal is found to shift in frequency where the shift is proportional to the

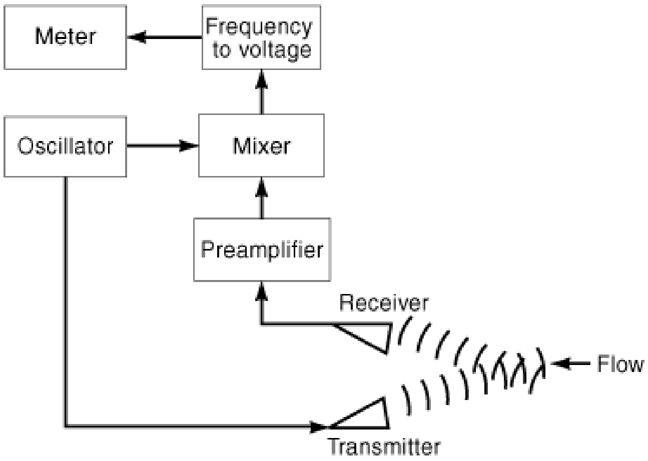

Fig. 9. Measuring principle of an one-dimensional acoustic-Doppler velocimeter. An ultrasonic pulse is emitted by the transmitter and suspended small particles in the water scatter the pulse. The signal of the receiver contains a Doppler shift that can be filtered out by a mixer technique. The Doppler shift is proportional to the local water velocity.

velocity of the suspended particles (scatterers). By frequency analyzing the Doppler shift can be found and the velocity of scatterers can be calculated. The measured particle velocity is equal to the water velocity because the slip velocity between the water velocity and the particle velocity is very small. The operating principle of a one-dimensional acoustic-Doppler velocimeter is illustrated in Fig. 9. The water velocity v is then

$$v = \frac{c\,(f_\mathrm{R} - f_\mathrm{T})}{f_\mathrm{T}\cos\alpha + f_\mathrm{R}\cos\beta} \tag{11}$$

where c is the velocity of sound in water, α the angle between the flow and the transmitter, β the angle between the flow and the receiver, f_T the transmitted frequency, and f_R the received frequency.

An example of a single point, high-resolution, three-dimensional (3-D) Doppler current meter is the SonTek MicroADV, which is shown in Figs. 10, and 11 and described by Lohrmann *et al.* (4). This current meter operates as a bistatic system with separate acoustic transducers for transmitter and receiver. The transmitter generates a short pulse of sound concentrated in a narrow cone, and the receiver is sensitive to sound coming from a narrow angular range. The 3-D MicroADV meter uses one transmitter and three acoustic receivers. MicroADV Doppler processing techniques provide several advantages: direct calculation of turbulent parameters such as Reynolds stress shown by Lohrmann and Cabrera (5), a compass/tilt sensor allows velocity data in an Earth coordinate system to be reported independent of probe orientation, the MicroADV meter can be used for detailed boundary layer studies with a low velocity to about 0.1 cm/s, and the sampling rate can be decreased to a 20 ms period. In general, the MicroADV meter requires a typical amount of scattering material (10 mg/l) for operation.

Another example is the monostatic acoustic Doppler SonTek profiler for 3-D vertical or 2-D horizontal current profiling. Monostatic profilers use the same transducer as transmitter and receiver. The profiling range is limited to a maximum of about 100 m with a resolution of 1 m. Sidelobe interference can effect the last 10% of the velocity profile. Different acoustic Doppler profilers are shown in Fig. 12.

Optical Current Meters. The main optical current meters can be divided into velocity meters based upon the Doppler effect and upon the spatial filtering technique. The 3-D laser Doppler velocimetry (*LDV*)

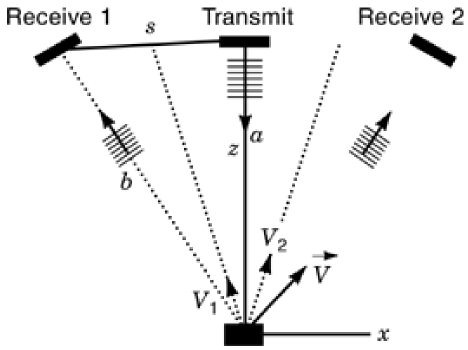

Fig. 10. 2-D simplification of a bistatic acoustic Doppler velocimeter made by SonTek. The result is the local measurement of the water velocity in two dimensions.

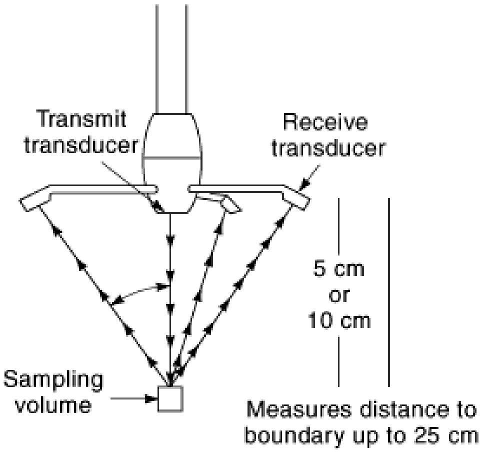

Fig. 11. Design of the 3-D microacoustic Doppler velocimeter made by SonTek. The result is the local measurement of the water velocity in three dimensions.

is now a well-known measuring technique for laboratory use and has the advantage of being drift-free and does not require calibration. The flow is not disturbed by the LDV. The probes are connected by optical fibers with the transmitters and receivers. Manufacturers are TSI and Dantec. Laser Doppler velocimeter need light scattering particles in the water, which are naturally given as suspended small particles.

Optical fiber flowmeters have involved only the use of optical fibers with turbine or vane meters, vortex shedding, and cross correlation techniques.

Spatial Filter Velocity Meter. In comparison with the laser Doppler velocimeter, the spatial filter velocimeter is a low-cost hydrometer for use in the field. Theory and configurations have been described by Petrak *et al.* (6) Like a laser Doppler velocimeter, the spatial filter velocity meter determines the local velocity of tracer particles as the natural content of water flows. Rivers have suspended sediment load with particle sizes smaller than 2 μm and with slip velocities of about 2×10^{-6} m/s.

Figure 13 shows the operating principle of the spatial filter velocity meter that contains a microchannel for the velocity measurement. A spatial filter made by optical waveguides and a light source with a parallel beam are arranged at the top of the microchannel. The output signal is generated by projection of the particle

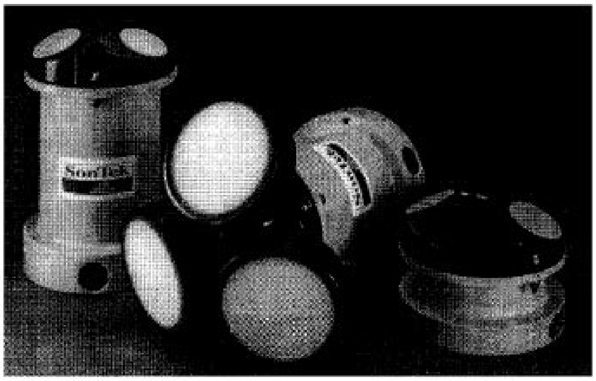

Fig. 12. Acoustic Doppler profilers made by SonTek.

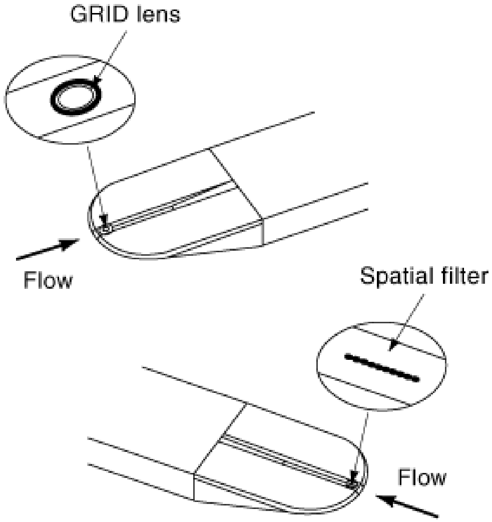

Fig. 13. Arrangement of the spatial filter sensor at the top of the spatial filter velocimeter made by Parsum GmbH. The sensor uses a spatial filter made by optical fibers to generate a velocity signal. The light source is a light emission diode combined with a GRID lens to produce a parallel beam. Measuring objects are small suspended particles.

shadow onto the spatial filter. Analyzing the output signal by a frequency analysis, the frequency distribution has a maximum at f_0 that is proportional to the water velocity v:

$$v = f_0 g \tag{12}$$

where g is the spatial filter interval. Signal processing is realized by a microprocessor system from Siemens. Figure 14 shows the spatial filter velocity meter for local field measurements, which is fabricated as a HMS probe by Parsum for the velocity range 0.01 m/s to 5 m/s. The spatial filter velocity meter has a simple and robust mechanical construction and needs no recalibration.

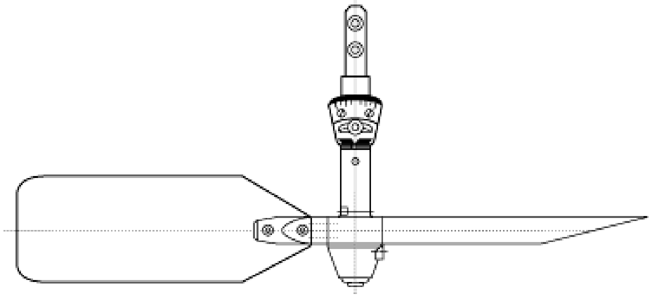

Fig. 14. Mechanical design of the spatial filter velocimeter made by Parsum GmbH.

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DIETER PETRAK
Chemnitz University of Technology