

ACOUSTIC DOPPLER METHODS FOR REMOTE MEASUREMENTS OF OCEAN FLOWS—A REVIEW

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The evolution of acoustic Doppler methods for remote measurements of ocean flows has been briefly reviewed in historical perspective. Both Eulerian and profiling methods have been discussed. Although the first acoustic Doppler current meter has been developed in the early sixties, the progress in this area has been hampered for some time for lack of miniature computing devices and compatible signal processing techniques. Development in these areas led to great advances in remote profiling of ocean currents using moored and ship-borne profilers incorporating three-, four-, and five- system.

INTRODUCTION

One of the limitations of the conventional Eulerian type of oceanic flow measuring instruments is the obstruction of the flow field by the instruments themselves, as well as dependence of measurement accuracy on the instruments' azimuth and tilt responses which are normally far from the ideal cosine responses. A second major limitation is introduction of large errors in measurements as a result of the motion of the flow meters in the flow field. A third limitation is the necessity of a large number of instruments for measurements from various depths. The acoustic Doppler methods permit remote measurements of ocean flows from locations far away from the measuring instrument. This superb capability of acoustic Doppler method circumvents most of the above mentioned limitations of conventional methods of measurements of vertical profiles of horizontal flows. The use of acoustic Doppler methods were initially limited to Eulerian types of current meters. With the advances in microprocessor technology and signal processing methods, the use of acoustic Doppler techniques have recently been extended to the domain of profile measurements as well. In this paper, the evolution of acoustic Doppler methods for ocean flow measurements is briefly reviewed.

Principle of flow measurements using acoustic Doppler methods

The acoustic Doppler methods of current measurement relies on the mechanism of acoustic volume scattering from a cloud of scatterers in the flow field. The term "scatterer" encompasses any kind of inhomogeneity in water including suspended particulate matter, biological organisms, minute bubbles etc. These scatterers serve as passive tracers of the mean water mass velocity field. In operation, an acoustic sonar transmits a narrow beam into the flow field in a given direction, and the Doppler shift of the volumetric echo from the scatterers in the flow field is used to determine the relative radial velocity between the scatterers and the sonar. If the transmitter, receiver and the flow velocity vector v are in the same plane, the

frequency f_r of the received acoustic wave differs from the transmitted frequency f_t according to the relation (Clay *et al.* 1977),

$$f_r = f_t (c + v \cos \theta_t) / (c - v \cos \theta_r) \quad (1)$$

where c is the velocity of sound in water, θ_t and θ_r are the angles made by the horizontal flow velocity vector v with the transmitter and the receiver beams respectively. For a given geometry, the Doppler shift is +ve or -ve depending on the direction of the flow. For ocean flows, the received frequency differs only slightly from the transmitted frequency.

An important factor that influences the development of a Doppler sonar is the transmission frequency f_t . For a given flow velocity, higher transmission frequencies are desired to produce larger Doppler shifts. The transmission frequency also influences transducer design, its weight, and size. However, the acoustic attenuation increases as the transmission frequency increases, and the choice of frequency will be, therefore, a compromise.

The backscattered signal, normally of microvolts in amplitude, is composed of the random sum of the individual scattering amplitudes, each having a Doppler frequency shift associated with the radial velocity of the scatterer. Since the microinhomogeneities that cause the scattering are of random sizes, the received signal is subjected to amplitude modulation. Phase incoherencies also arise as a result of different ranges of the individual scatterers as well as their random motion due to turbulence within the defined scattering volume. The signal is also corrupted by an additive white Gaussian noise. Thus the received signal is a highly distorted version of the transmitted signal wherein its deterministic properties are no longer valid, rather the signal is statistical in nature with Gaussian distributions. No wonder, extraction of Doppler shift information using analytical methods such as counting of zero-crossings, phase tracking etc. proved unreliable.

Since the returned signal is statistical in nature, a realistic approach for estimation of Doppler shift information is some form of statistical methods. Most of the Doppler shift information is contained in the 1st and 2nd moments of the Doppler spectrum. One method of obtaining these moments is to Fourier transform the received echoes. These can also be obtained from estimates which do not involve the Fourier transform operation. Two types of scattering processes are involved namely; coherent and incoherent, and the general schemes used for computing the Doppler shift information are known as coherent and incoherent processing.

Evolution of acoustic Doppler methods of flow measurements

(i) Eulerian type measurements

In the initial designs of acoustic Doppler current measuring devices a bistatic configuration (i.e., the transmitter and the receiver located at different points) has been employed. These transducers were inclined to each other so that the volume of intersection of the transmitted and the received beams defined the scattering volume. This is shown in Fig. 1. Depending on the spatial separation and the angle between the transducers, the Doppler shifted echoes were received from a

reverberation volume located at a known distance from the transceivers (Koczy et al. 1962). An advantage of the acoustic Doppler measurement technique, over conventional current measuring devices, was that the geometry could be set to receive the backscattered signals from a region sufficiently away from the body of the meter so that the velocity of flow could be non-intrusively detected from the undisturbed flow field. The basic accuracy of measurements is determined by the stability of transmission frequency, precision of mechanical alignment of the transducers, and a knowledge of the velocity of sound in water. The frequency used for transmission was in the range of 1 to 10 MHz.

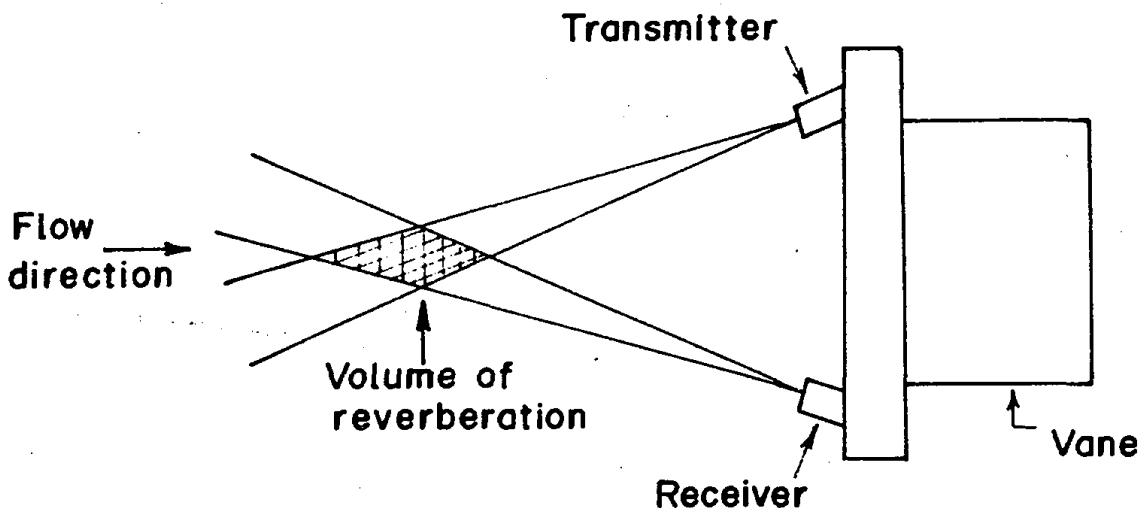


Fig. 1. Acoustic current meter geometry with a bistatic configuration.

In situations where a vane oriented the instrument into the direction of the flow, only a single transceiver set has been used (Kronengold et al. 1965). In order to avoid a vane, either two sets of mutually orthogonal transceiver systems (Katz et al. 1979), or a single transmitter and three receivers pointing to a single location sufficiently above the instrument (Wiseman Jr. et al. 1972) have been used.

(ii) Profile measurements

In the design of acoustic Doppler profilers a monostatic configuration is usually employed, where a single transceiver detects radial flow velocities in a given direction. Since the same transducer is used for transmission as well as reception, both θ_r and θ_t in equation 1 are equal (say θ). In this case the Doppler shift f_D can be reduced to a form.

$$f_D = (2f_t v \cos \theta)/c \quad (2)$$

$$\text{where } f_D = f_r - f_t$$

While considering the radial flow velocity component v , the value of θ in equation 2 reduces to zero so that

$$v = (f_D c)/(2f_t) \quad (3)$$

In commercially available acoustic Doppler profilers, three or more transceivers, inclined to each other, are often employed so that the acoustic beams are generally divergent from each other. The mean horizontal flow vector at a given water layer, away from the sensor, is estimated from measurements of these radial flow components in this layer.

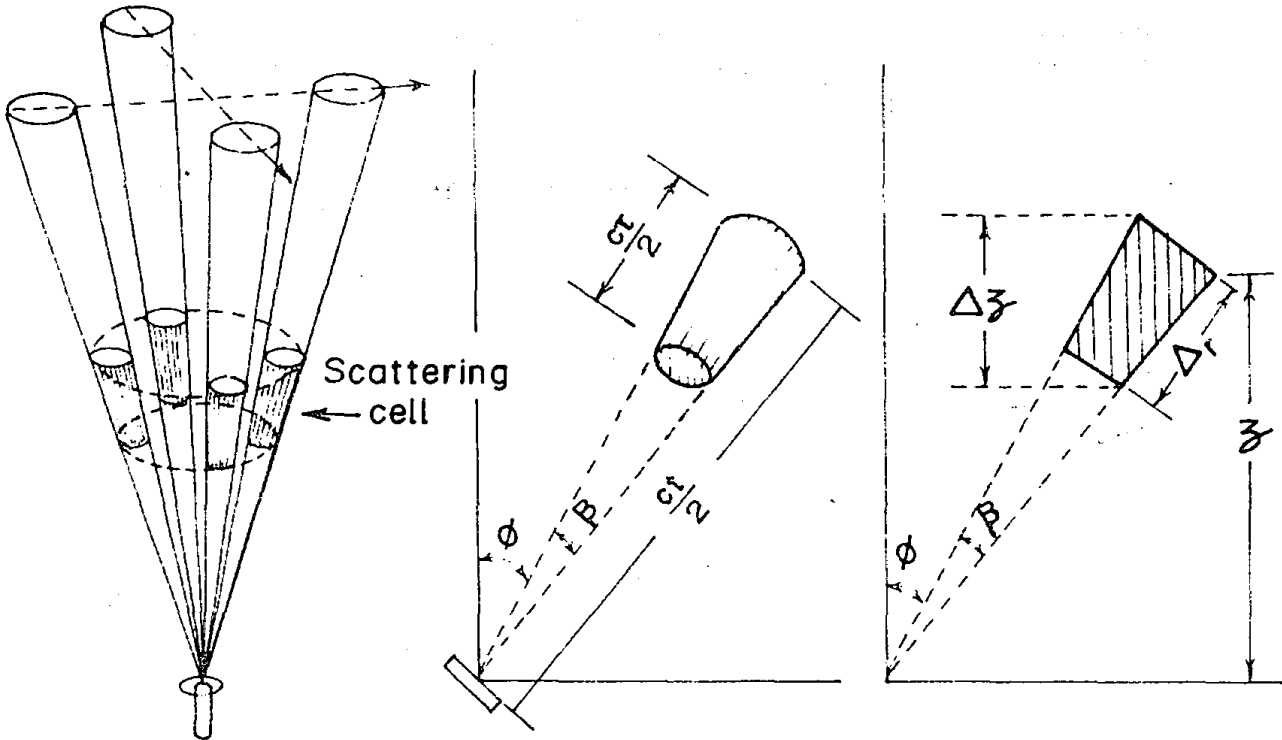


Fig. 2 (a), 4-beam configuration, (b) Expanded view of a scattering cell, (c) Geometry illustrating vertical extent (Δz) of the wavefront.

A basic assumption made in the estimation of the horizontal flow in any given layer is that the flow is uniform throughout this layer (Fig. 2a). The mean horizontal flow in any given layer is computed by averaging the flow "samples" from these, often widely separated,insonified volumes along the acoustic beams.

Since radial flow components are to be measured from various layers in the water column the transceiver system is to be operated in a multiplexed mode, i.e. configuring it for transmission at one time followed by reconfiguring it as a receiver before the backscattered signals reach the transducer. In operation, each transceiver emits a stream of narrow band acoustic pulses, insonifying the scatterers along its path, and receive the Doppler-shifted backscattered return echoes as these pulses propagate through the water column. The duration of the pulse equals the gating time τ . The Doppler shift, as a function of time after transmission, yields the relative radial velocity as a function of the slant range in sequential layers at each of the "range sliced" insonified volumes of the overlaying water column. Each measurement is an averaged value over a distance into the medium along the beam, expressed in terms of the two-way travel time. If a pulse of duration τ seconds,

representing a time-burst, is transmitted the observation (integration) time must be equal to this duration. By adjusting the transmitted pulse length, the portion of the water column insonified at any given instant can be controlled and the desired range resolution can be achieved. In the case of stationary transducers, the Doppler-shift directly yields the absolute water velocity profiles. If the transducers are non-stationary (for example, mounted on a buoy or at the bottom of a ship), the absolute water velocity profile may be obtained from a knowledge of the motion of the transducers.

The dimensions of the scattering cell (Fig. 2b) is related to τ , the transmission beam width β , and time t after transmission. The radial length of the scattering cell, i.e., its length along the beam direction, at any instant in time is given by $c \tau / 2$ where c is the velocity of sound in water. The far-end of the scattering volume will be at a distance of $ct/2$ away from the transceiver along the beam direction. It can be seen that the cross-sectional area of a given scattering volume increases with time along the beam direction. The radial distance between the transceiver and the mid-point of the scattering cell is given by $((ct/2) - (c \tau / 4))$. Since the radial length of the scattering cell along the beam direction is $(c \tau / 2)$, its length projected on the axis of symmetry of the profiler equals $(c \tau / 2) \cos \phi$, where ϕ is the beam-pointing angle with respect to the axis of symmetry of the profiler. For a narrow-beam acoustic transmission, the cell thickness $(c \tau / 2)$ times $\cos \phi$ determines the spatial resolution of the profiler. The spatial resolution deteriorates, therefore, with increase in τ . Increasing τ improves accuracy in the estimation of flow speed but reduces spatial resolution. It has been observed (Theriault, 1986) that the vertical resolution is only approximately controlled by τ ; rather it is also a function of the system geometry and the depth of observation, z (Fig. 2c). Since the acoustic beam is slanted away from the axis of symmetry of the profiler, and is spreading as it propagates away from the transceiver, the total vertical extent, Δz of the insonified cell is given by (Theriault, 1986),

$$\Delta z = z\beta \tan \phi + \Delta_r \cos \phi \quad (4)$$

where Δ_r is the along-beam extent of the pulse.

The above relation suggests that the spatial resolution degrades with distance from the profiler, and that the severity of this degradation increases with increasing β and ϕ . While no control is possible on distance, spatial resolution can be improved by the use of narrow beam acoustic signal. This emphasises the importance of narrow beam acoustic signal in pulse-Doppler acoustic current profilers. It may, however, be noted that as the beam width decreases the size of the transducer correspondingly increases.

Profiler geometries

The ADCPs are of various geometries. These typically include three-, four-, and five-beam systems. The three-beam configuration is generally used only with hull-mounted systems. In a typical three-beam system, the beams are spaced 120° apart in the azimuth, and each beam points down at an angle of ϕ degrees from the vertical. One beam (say beam 1) is generally oriented forward along the ship's

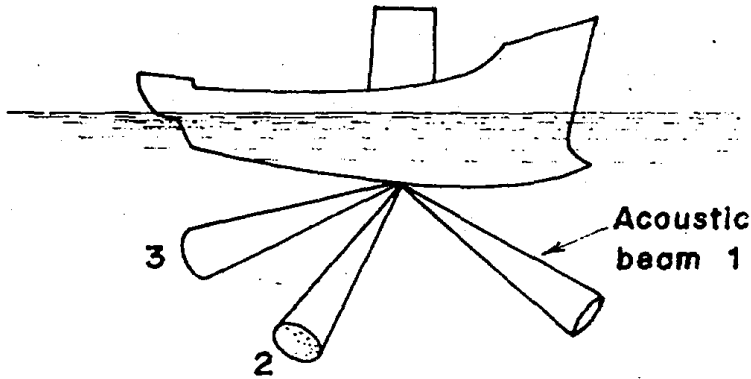


Fig. 3. Geometry for a three-beam Doppler current profiling system.

longitudinal axis and other two beams (say beams 2 and 3) lie along the port and starboard quarters. This is shown in Fig.3. Based on this geometry the along-track and the cross-track relative velocity components at various depth layers may be estimated in terms of the in-beam (radial) Doppler-shifts for the three beams from the corresponding depth layers. The mean relative horizontal flow velocity vector may be considered to consist of a horizontal flow component (say V_y) along the longitudinal axis of the ship (i.e., along its direction of motion) and an orthogonal horizontal flow component, say V_x . These components are given by the relation (Theriault, 1986),

$$V_y = (c/6W \sin \phi) (WD(2) + WD(3) - 2WD(1)) \quad (5)$$

$$V_x = (c/2 \sqrt{3} W \sin \phi) (WD(3) - WD(2)) \quad (6)$$

where c is the velocity of sound in water, W is the transmission frequency in angular notation, ϕ is the angle (in degrees) made by each beam from the vertical, and $WD(1)$, $WD(2)$, $WD(3)$ are the Doppler shifts (in angular notation) measured by the beams 1, 2, and 3 respectively. The value of ϕ ranges from 30 to 75 degrees. Depending on whether the shift is up-Doppler or down-Doppler the sign of WD will be +ve or -ve respectively.

The four-beam Doppler profiler employs two "Janus Configuration" consisting of a total of four beams oriented 90° apart in the azimuth, each beam making an angle of ϕ degrees to the axis of symmetry of the two modes namely; stationary mode for measurements of absolute flow profiles, and in hull-mounted mode for measurements of relative flow profiles from moving vessels. When mounted beneath a vessel, the system is generally operated with one pair of mutually diverging beams (say beams 1 and 2) oriented along the longitudinal axis of the ship, and other pair of beams (say beams 3 and 4) oriented along an orthogonal plane so that the profiler resolves the relative velocity field at any given depth layer into along-track and cross-track components. If $WD(1)$, $WD(2)$, $WD(3)$ and $WD(4)$ are the Doppler shifts measured along the beams 1, 2, 3 and 4 respectively, the relative horizontal flow component V_y along the longitudinal axis of the ship is given by the relation (Theriault, 1986),

$$V_y = (c/ 4W \sin \phi) (WD(1) - WD(2)) \quad (7)$$

and the relative horizontal flow component V_x perpendicular to the longitudinal axis of the ship is given by

$$V_x = (C / 4W \sin \phi) (W_{D(3)} - W_{D(4)}) \quad (8)$$

Depending on the relative direction of flow the sign of W_D will change.

While the ADCPs are mounted on moving vessels to map the vertical profiles of upper ocean horizontal currents, the measured relative velocity profiles can be transformed into an absolute velocity profile using the ship's speed and heading information for each data cycle. In locations where good LORAN-C coverage is available, the vessel's lateral motions can be determined by measurements of changes in LORAN-C position, within an uncertainty of 5 to 10 cm/sec. This data can, in turn, be used to correct the inherent errors which tend to creep into the velocity field map as a result of the ship's lateral motion during measurements of velocity profiles (Joyce et al. 1982). When both the LORAN-C and the Doppler profiler data are suitably filtered the resultant absolute velocity profiles are estimated to be accurate to within 2 cm/sec (Trump et al. 1985). Although this procedure cannot remove the wave-induced noise, these errors can be reduced to a certain extent by vector-averaging the measurements over many wave cycles. Despite the limit on the maximum allowable ship speed (Theriault, 1986), the ship-mounted acoustic profilers possess the remarkable feature of large spatial coverage.

A 5-beam configuration is also sometimes employed for measurements of current profiles (Lhermitte, 1984). In the design of this profiler, four beams are configured

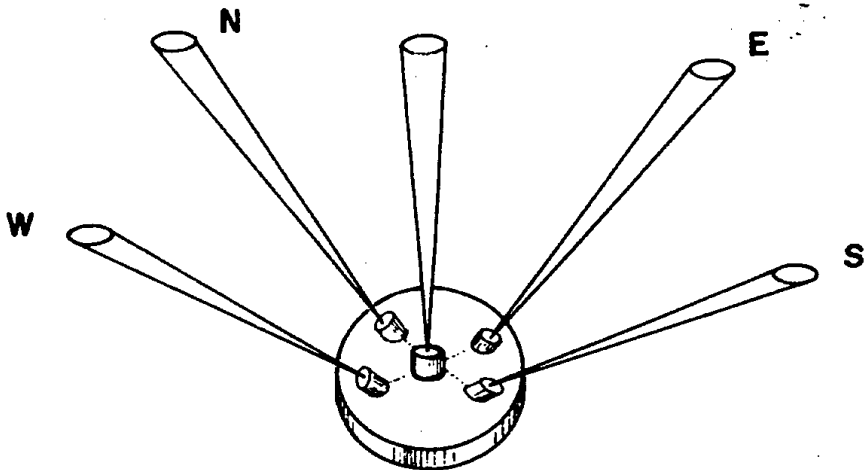


Fig.4. Geometry for a five-beam Doppler current profiling system.

in a fashion similar to the four-beam system described earlier, and the fifth beam points along the axis of symmetry of the transceiver assembly. When mounted in a bottom-mounted, upward-looking configuration (Fig. 4), the central beam measures the vertical flow component only, since the horizontal flow component cannot generate Doppler shifts in a vertically oriented transceiver. The remaining four beams measure the horizontal flow components.

Since only three components of velocity are present, i.e., two horizontal and one vertical component, only three beams are sufficient in order to fully describe the flow field. However, if the number of beams are more than three, the performance of the profiler correspondingly increases. For example, in a three-beam system mounted underneath a vessel, the along-track horizontal flow component V_y is coupled to the Doppler shifts from all the three beams (see equation 5). Further, since there is only one beam in a given plane, the three-beam system is sensitive to pitch and roll of the vessel. In the four-beam geometry consisting of two Janus configurations, each horizontal flow component is estimated as a mean of the Doppler shifts from the two symmetrically oriented beams in each of the Janus configurations in the two mutually orthogonal vertical planes. It is thus evident that, in the four-beam geometry, the Janus configuration tends to minimise sensitivity to pitch and roll of the vessel. In addition to these obvious differences in performances, statistical analysis performed by Theriault (1986) suggests that, for similar operating conditions, the inherent geometry of the three-beam system degrades its performance compared to that of the four-beam system. Since the 5-beam system provides an independent estimate of the vertical velocity, this system is superior to the other two systems. Thus, it is observed that, although only three beams are theoretically sufficient to fully describe the oceanic flow field, increase in the number of beams improves performance.

CONCLUSIONS

Since an acoustic Doppler current profiler operates like a radar, rapidly scanning the flow field and sampling it at large distances from it, currents from various layers of a water column can be remotely measured. Probably, the most important characteristics of the acoustic Doppler profiler is the fact that it enables a substantial increase in the vertical density of current data obtainable from a single instrument. Furthermore, since the majority of measurements are made remotely, only a small part of the current field - immediately surrounding the instrument - is perturbed. Current measurements are, therefore, made in a theoretically ideal way. Its remote sensing feature and the ability to "look" sideways in any direction permits monitoring of current fields in logistically difficult environments such as ports where high flow regimes, ship traffic, or fishing activity make the deployment and maintenance of conventional moorings impractical. In addition, use of acoustic Doppler current profilers mounted on subsurface floats can considerably reduce the number of Eulerian current meters that would have been required otherwise, and provides a better spatial resolution than normally achievable by conventional 'single-point' Eulerian current meter arrays. The capability of the ADCPs to be mounted on moving vessels permit them to map the vertical profiles of upper ocean currents. Although there is a limit on the maximum allowable ship speed, the ship-mounted acoustic profilers possess the remarkable feature of large spatial coverage.

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