A Contribution to the Encyclopedia of Ocean Science

Sensors: Current Meters – Single Point

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Introduction

A current meter estimates the speed and direction of water moving relative to the instrument. The single point current meter is, therefore, only part of a measurement system that includes the mooring or mounting hardware or technique. This article begins with a discussion of the interaction between the current meter, the method of mounting and the characteristics of the currents within the environment being studied. This is followed by an introduction to the principles of current meter design, which are largely independent of the chosen implementation technology. Some examples of commonly used instruments follow, with an assessment of the strengths and weaknesses of the different types of sensor. The importance of direction measurement and calibration are discussed as prerequisites to making accurate observations. Typical current meter moorings are discussed by Weller (2001). This article concludes with a note on the future for current measurement systems.

Measurement of current in the open sea is usually achieved by mounting the instrument on a mooring. Movement of the mooring makes true fixed-point, or Eulerian, measurement impossible, although careful attention to mooring design can generally provide an acceptably good approximation to a fixed point. In some circumstances a fixed measurement platform can be used, for example in shallow seas, or at the deep ocean floor. Care then needs to be taken to avoid, as far as possible, disturbance to the flow by the sensor itself, and by any supporting structure. In the case of moored current meters the design of the mooring must minimize vibration, which can lead to the sensor sampling in its own turbulent wake, thereby generating significant errors. With proper attention to design of the mooring or platform, and selection of an appropriate current meter, it should be possible to make most deep sea measurements to within about 1 cm s^{-1} in speed and 2-5° in direction, and with rather better precision in the case of bottom mounted instruments. Howarth (1989) reviewed many of the issues of current meter data quality.

Particular problems arise in the case of near-surface measurements. Wave orbital motion decays exponentially with depth but may be considered significant – if somewhat arbitrarily - to a depth equivalent to half the wavelength of the dominant surface waves. In the open ocean the influence of surface waves can thus easily extend to a depth of several tens of metres. Within this region the difficulty presented by the lack of a fixed Eulerian frame of reference for current measurement is compounded by the presence of three-dimensional wave orbital velocities, which can be large compared with the horizontal mean flow, making it difficult to avoid flow obstruction by the sensor itself and necessitating a linear response over a large dynamic range. If instruments are suspended some way beneath a surface buoy large errors can result from vertical motion induced by the surface buoy relative to the local water mass.

However, a more fundamental problem arises in the surface wave zone. This may be illustrated by reference to a water particle undergoing progressive wave motion in a simple small amplitude wave. Neglecting any underlying current, a particle at depth z experiences a net Lagrangian displacement, or Stokes drift, in the direction of wave travel of O[$\mathbf{a}^2 \sigma k \exp(-2kz)$], where **a** is the wave amplitude, k is the wavenumber and σ is its angular frequency. In 10 s waves of amplitude 2 m this amounts to about 4.5 cm s^{-1} at a depth of 10 m. Measurements made in distinct Eulerian and Lagrangian reference frames are not directly comparable, and if it is fixed, even an instrument that is perfect in all respects will not be able to detect the Stokes drift. Nevertheless an instrument that is moving in a closed path in response to wave action will record some unknown value related in a complex fashion to the drift (Collar, Carson and Griffiths 1983). Close to the surface, where the current sensor path over a wave cycle can be more easily arranged to approximate the path of a water particle, the value recorded by the instrument should more closely resemble the surface value of the local Stokes drift. This has been verified in laboratory measurements involving simple waves, but is not easily tested in the open sea.

Current meter design

Fluid motion can be sensed in a number of ways: techniques most frequently employed nowadays include the rotation of a mechanical rotor, electromagnetic sensing, acoustic travel time measurement, and measurement of the Doppler frequency of backscattered acoustic energy. Figure 1 shows examples of practical current meters based on these techniques, and Table 1 shows the main characteristics of some commonly used instruments. The evolution in design of experimental and commercial instruments from 1970 to 2000 can be traced by comparing the descriptions of the current sensors and *in situ* processing in Myers *et al*. (1969) through Dobson *et al*. (1980) to Appel and Curtin (1991) to the 3-D current mapping discussed by Pinkel and Smith (1999). Acoustic Doppler and correlation backscatter techniques can also measure current profiles, as discussed elsewhere in this volume by Plueddemann (2001).

In steady flow relatively unsophisticated instruments often produce acceptable results. However, in circumstances in which an instrument may need to cope with a broad frequency band of fluid motions, as in the wave zone or when subject to appreciable mooring motion, there are implications for the design of the sampling system.

If the sensor is to determine horizontal current it should be completely insensitive to any vertical component, while responding linearly to horizontal components across a frequency band which includes the wave spectrum.

Then if, as is usual, the sensor output is sampled in a discrete manner, the provisions of the Nyquist sampling theorem must be observed, i.e. the sampling rate must be at least twice the highest frequency component of interest, while negligible spectral content should exist at frequencies above the highest frequency of interest. The highest frequencies that need to be measured are encountered in velocity fluctuations in small-scale turbulence, for example in measurements of Reynolds stress from the time-averaged product of a horizontal velocity component with the vertical velocity. A frequency response to at least 50 Hz is required, perhaps even higher frequencies if the measurements are being made from a moving platform. In this case, specialist turbulence dissipation probes that employ miniature sensors measuring velocity shear are used, as discussed elsewhere in this volume by Oakey (2001).

Experiments involving the use of laser backscatter instruments have been carried out at sea, for example to measure fine scale turbulence near the ocean floor, but their characteristics are generally better matched to high resolution studies in fluid dynamics in the laboratory.

Apart from the study of turbulence, the existence of significant wave energy and instrument motion down to periods of 1 second means that a sampling rate (f_s) of ≥2 Hz is often used. At this frequency substantial amounts of data are generated and, unless the high frequency content is specifically of interest, it is usual to average before storing data. If done correctly this involves the summation of orthogonal Cartesian components individually prior to computation of the magnitude. Any other form of averaging can produce erroneous results.

If the instrument makes a polar measurement, for example if it measures flow by determining instantaneous rotor speed V_i and the instrument is aligned with the current using a vane whose measured angle relative to north is θ_i the averages are formed:

$$\overline{E} = \frac{1}{n}\sum_{i=1}^{n} V_i \sin\theta_i$$

$$\overline{N} = \frac{1}{n}\sum_{i=1}^{n} V_i \cos\theta_i$$

If on the other hand the instrument measures orthogonal velocity components X_i, Y_i directly, as for example in electromagnetic or acoustic sensors, it forms:

$$\overline{E} = \frac{1}{n}\sum_{i=1}^{n} (X_i \cos\theta_i + Y_i \sin\theta_i)$$

$$\overline{N} = \frac{1}{n}\sum_{i=1}^{n} (-X_i \sin\theta_i + Y_i \cos\theta_i)$$

where θ_i is the instantaneous angle between the Y axis and North: n is chosen so as to reduce noisy contributions from, for example, the wave spectrum: a value of $nf_s^{-1} > 50$ seconds is usual.

The averaged magnitude and direction are then given by:

$$\overline{U} = ((\overline{E})^2 + (\overline{N})^2)^{0.5}$$

$$\overline{\theta} = \tan^{-1}\frac{\overline{E}}{\overline{N}}$$

Mechanical current meters

The first self-recording current meters were ingenious mechanical devices such as the Pillsbury instrument (first used in 1884) and the Ekman current meter, available in 1904, McConnell (1982). However, the slowness of progress during the first half of the twentieth century is reflected in the view of the German hydrographer Bohnecke in 1954 - quoted by McConnell (1982) - that "The subject of current measurements has kept the oceanographers busy for more than a hundred years without having found - this must honestly be admitted - an entirely satisfactory solution". In the 1960s and 70s the growing need for current measurements in the deep ocean provided a stimulus for the development of robust, self-contained recording instruments capable of deployment over periods of months – together with the equally essential mooring technology. At first sampling arrangements were relatively simple. For example, the early, mechanically encoded form of Aanderaa current meter combined a scalar average of speed with a spot measurement of the direction. Speed was measured by a rotor consisting of six impellers of cylindrical shape mounted between circular end plates. The rotor shaft ran in ball-race bearings at each end, and at the lower end two magnets communicated the rotation to an internal recording device. The large plastic vane, with a counterweight at the rear end, aligned the instrument with the current. As experience in a range of deployment conditions and types of mooring widened, such sampling schemes were found to be unsuitable when the sensor experienced accelerating flow as a result of wave motion or mooring movement. The introduction of vector averaging schemes followed, initially in the Vector Averaging Current Meter (VACM), figure 1, and provided a substantial improvement in accuracy in such conditions. Improved sampling regimes were facilitated in later instruments by low power microprocessor technology. It was realised also that it is necessary to understand fully the behaviour of speed/velocity and direction sensors in unsteady flow conditions. By the time the dual orthogonal propeller Vector Measuring Current Meter (VMCM) was developed in the late 1970s sufficient was understood about the pitfalls of near-surface current measurement to realise that rotor design required a combination of modelling and experimental testing in order to ensure a linear response. For example, the propellor in the VMCM was designed to avoid non-linearity due to the different response times to accelerating and decelerating flows that had been found in the 'S' shaped Savonius rotor of the VACM. Today, mechanical current meter development might be regarded as mature.

Electromagnetic current meters

In electromagnetic current meters an alternating current (ac) or switched direct current (dc) magnetic field is imposed on the surrounding seawater using a coil buried in the sensing head, and measurements of the potential gradients arising from the Faraday effect are made using orthogonally mounted pairs of electrodes (Shercliff, 1962), as illustrated in Figure 2. Some electromagnetic techniques make use of the Earth's field, but in self-contained instruments simple dc excitation is avoided. This is because unwanted potential differences arising for example from electro-chemical effects can exceed flow-induced potential differences, which are typically between 20 and 100 μVolts per m s^{-1}, by two orders of magnitude. Flow field characteristics around the sensor head - including hydrodynamic boundary layer thickness and flow separation - are of critical importance in determining the degree of sensor linearity as well as the directional response. Modelling techniques can help to evaluate specific cases.

Forms of sensor head that have been considered or used include various solids of revolution, such as spheres, cylinders and ellipsoids. Although hydrodynamic performance weighs heavily in choice of shape, this may be balanced by consideration of ease of fabrication and robustness. One neat solution incorporates the entire instrument within a spherical housing that can be inserted directly into a mooring line (Figure 1). For a smooth sphere, the resulting instrument dimensions would normally give rise to a transition from a laminar to a turbulent boundary layer over the instrument at some point within its working velocity range, at a Reynolds number of $\sim 10^5$, but this is forestalled by use of a ribbed surface so as to introduce a fully turbulent boundary layer at all current speeds. Good linearity is thereby achieved.

Minimum flow disturbance can be achieved using an open form of head construction (Figure 1) which has been shown to provide excellent linearity and off-axis response, the only disadvantage relative to solid heads being greater complexity in construction and perhaps some reduction in robustness.

Unlike mechanical current meters electromagnetic instruments have no zero velocity threshold. In the past zero stability has presented a problem, but with modern electronics, and care in head design and fabrication, stability to within a few mm s^{-1} over many months of immersion should be achieved.

Acoustic Travel Time (ATT) current meters

ATT systems are based on the valid assumption that the resultant velocity of an acoustic pressure wave propagating at any point in a moving fluid is the vector sum of the fluid velocity at that point and the sound velocity in the fluid at rest. The method involves the measurement of the difference in propagation time of an acoustic pulse along reciprocal paths of known length in the moving fluid, although the principle can be realised equally in terms of measurement of phase or of frequency difference. Using reciprocal paths removes the need to know the precise speed of sound. The three techniques present differing design constraints. Typically an acoustic path length l may be of order 10 cm. For resolution of currents $\Delta v$to 1cm s^{-1}, the required time discrimination of acoustic pulse arrivals can be calculated from:

$\Delta t = \Delta v \,.\, l / c^2$

or about 4×10^{-10} seconds, requiring stable, wideband detection in the electronic circuitry. In contrast, phase measurement, made on continuous wave signals, is effected within a narrow bandwidth, thereby relaxing the front-end design in the receiver. Phase measurement provides good zero stability and low power consumption, but the path length may be constrained by the need to avoid phase ambiguity.

Whichever method is chosen hydrodynamic considerations are important in achieving accuracy: rigid mounting arrangements which do not disturb the flow significantly are required for the transducers at each end of the acoustic path. Techniques for minimizing flow obstruction have included the use of mirrors to route sound paths away from wakes and, with the development of substantial *in situ* processing, the use of redundant acoustic paths. For a given instrument orientation, the least disturbed paths can be selected for processing.

ATT techniques have been implemented in various forms for a range of applications, including miniature probes for laboratory tanks, profiling instruments and self-recording current meters. Of the three basic methods, the measurement of frequency difference seems to have been the least exploited, although it has been successfully used in such diverse applications as a miniature profiling sensor for turbulence measurement, and a buoy-mounted instrument with 3 metre path length providing surface current measurements.

ATT current meters offer well defined spatial averaging, high resolution of currents (>1mm s^{-1}), potentially good linearity and high frequency response. The main disadvantage, tackled with varying degrees of success in individual types of instrument, is associated with disturbance of flow in the acoustic path by transducers, support struts, and the instrument housing.

Remote sensing single point current meters

One current measurement technique that avoids flow obstruction altogether is that of acoustic backscatter, using either Doppler shift or spatial or temporal cross correlation. In the past, these computationally intensive techniques were restricted to being used for current profilers, where the relatively expensive instrument could nevertheless substitute for an array of less expensive single point current meters. Nowadays, the availability of low cost, low power yet high performance digital signal processing circuits has made it possible and economic to produce single point acoustic backscatter current meters. Such instruments provide a combination of several desirable specifications, including: rapid data output rate, with 25 Hz being common; a dynamic range extending from 1 mm s^{-1} to several m s^{-1}; an accuracy of $\pm$ 1% or $\pm < 5$ mm s^{-1}; a typical sampling volume of a few cm^3 and the capability of operating within a few mm of a boundary. These characteristics make this class of instrument almost ideal for current measurement within boundary layers, in the surf zone, while also enabling the collection of concurrent velocity and directional wave spectrum information through sensing the wave orbital velocity components.

Directional Measurement

The directional reference for measurement of current is invariably supplied by a magnetic compass, two main types of which are in common use (Hine 1968). The first type is the traditional bar magnet, often mounted on an optically read encoded disc. The entire assembly is mounted on jewelled bearings, with arrangements for damping and gimballing. In the fluxgate compass, the second type of sensor, a soft magnetic core is driven into saturation by an ac signal. Orthogonal secondary windings detect the out-of-balance harmonic signals caused by the polarising effect of the Earth's field and, from an appropriately summed output, the orientation of the sensor relative to the Earth's field can be determined. In current meters a gimballed two-component system may be used, but as in the case of the magnet compass, this does require that the system will respond correctly to any rotational and translational motions arising from mooring or platform motion.

Calibration, evaluation and intercomparison

The calibration, evaluation and intercomparison of current measuring instruments are closely related and are central to the issue of data quality assurance. Basic velocity calibration can be carried out in a tank of nominally still water by moving the instrument, usually suspended from a moving carriage, at a constant, independently measured velocity. Compass calibration is done, typically to a precision of ~1° in an area free from stray magnetic fields either using a precisely orientated compass table equipped with a vernier scale or by invoking a self-calibration program built in to the instrument that obviates the need for an accurate heading reference. Modern instruments can correct for heading-dependent errors in real time as well as correcting for a user-supplied magnetic variation. However, older instruments usually require the corrections to be applied at the post-processing stage.

A variety of practices exists relating to routine calibration, ranging from checks before and after every deployment to almost complete lack of checks. It has been argued that sensitivities of acoustic and electromagnetic sensors are determined by invariant physical dimensions and stable electronic gains, while mechanical instruments require only a simple in-air test to ensure free revolution of the rotor. However, good practice is represented by regular calibration checks in water.

Current meters generally behave well in steady flows but, as remarked above, in the near surface zone - or in the presence of appreciable mooring or platform motion - substantial differences can occur in data recorded by different instruments at the same nominal place and time. The fact is that no amount of simple rectilinear calibration in steady flow conditions can reveal the instrument response to the complex broadband fluid motions experienced in the sea and as yet there are no standard instruments or procedures for more comprehensive calibration. Some efforts have been made, however, to model the errors incurred in some specific instruments, with a view to the prediction of performance at sea from dynamic simulation data acquired in the laboratory test tank.

Laboratory tests in controlled conditions thus provide a necessary, though insufficient basis for judging performance, and when a new instrument, or technique, is first used at sea considerable effort is put into intercomparisons with other, longer established instruments or techniques. Not surprisingly, most of the impetus for testing and intercomparison has come from the scientific community: the costs of providing anything other than basic performance data in controlled flow conditions is, with some justification, considered prohibitive by manufacturers. Extensive information on the performance at sea of instruments of many types is therefore to be found in the scientific literature, although cheaper instruments are generally less well represented.

Evolutionary Trends

As a result of the advances in electronics and battery technology in recent years, and the painstaking evaluation work accompanying the introduction of new instrument types, sufficient is now known about current measurement that it can in this sense at least be regarded as a relatively mature technology. Yet clear evolutionary trends are in evidence, driven by an increasing operational need for data in support of large scale monitoring programmes. A further factor is the growing commercial involvement in data gathering. The tendency is towards cheaper, lighter instruments which are more easily handled at sea, and which can be deployed in larger numbers. An example of changes in size, recording capacity and weight that have taken place over the past 25 years is shown by comparing the Vector Averaging Current Meter from the 1970's with a modern acoustic or electromagnetic current meter of similar performance (Figure 1 and Table 1).

Another trend brought about by the growth of processing capability *in situ* is towards the incorporation of current measurement within a complete measurement system embracing a range of physical, chemical and biological parameters (Figure 3). Operational requirements for current data may also in time result in the routine deployment of telemetering systems. At present satellite telemetry of surface and near-surface measurements is well established, but telemetry of midwater measurements is not yet common practice.

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Table 1 Main characteristics of some contemporary current meters and a VACM from the 1970's

Type	**Speed accuracy**	**Resolution ($cm\ s^{-1}$)**	**Range ($cm\ s^{-1}$)**	**Direction accuracy**	**Depth Rating (m)**	**Weight (kg)**	**Data capacity (records)**
Aanderaa RCM9 MkII Single point Doppler	±0.5 $cm\ s^{-1}$	0.3	0 - 300	±5° for 0 - 15° tilt	2000	Air: 17 Water: 12	up to 36 100
Aanderaa RCM8 Vector averaging rotor-vane	±1.0 $cm\ s^{-1}$ or ±2% of speed, whichever greater	Not specified	2 - 295	±5° for speeds 5 - 100 cm s-1 ±7.5° for 2.5 - 5 $cm\ s^{-1}$ and 100 - 200 $cm\ s^{-1}$	6000	Air: 29.3 Water: 22.7	up to 43 600
InterOcean S4 Electromagnetic sensor	±1.0 $cm\ s^{-1}$ or ±2% of speed, whichever greater	0.03 to 0.43 depending on range	0 - 350	±2° for 0 - 5° tilt ±4° for 15 - 25° tilt	S4 1000 m S4Deep 6000 m	S4 Air: 11 S4 Water: 1.5 S4Deep Air: 34.5 S4Deep Water: 10.5	S4 348,000 S4A 7 000 000
Sontek Argonaut-ADV Acoustic travel time	±0.5 $cm\ s^{-1}$	0.01	0 - 600	optional extra, at ±2°	60 m	Air: 3.2 Water: 0.45	> 100 000
FSI 3D ACM Acoustic travel time	±1.0 $cm\ s^{-1}$ or ±2% of speed, whichever greater	0.01	0 - 300	±2.5° at unspecified tilt	1000 m	Not specified	200 000
EG&G VACM (1970s design)	2.6 $cm\ s^{-1}$ threshold accuracy not stated	Not stated	2.6 - 309 $cm\ s^{-1}$	+/- 2.8°	6096 m	Air: 72.5 kg Water: 34.9 kg	50 925 - 76 388

Source: Company specification sheets

Illustrations

Figure 1 Current meters based on different sensors. Clockwise from top left: Aanderaa RCM4 deep ocean rotor-vane instrument, Aanderaa RCM9 single cell Doppler current meter, Vector averaging electromagnetic current meter based on an annular sensor, Nortek Aquadopp high precision single cell Doppler instrument, Interocean S4 electromagnetic current meter, EG&G Vctor Averaging current meter with dual Savonius rotor (at the base) and small vane (immediately above).

Figure 2 Sketch showing the Faraday effect, which forms the basis of the electromagnetic current meter. The effect results in a potential difference $E= B V L$ induced between two electrodes (*X* and *XX*) with a separation *L* when a conductor (seawater) moves at a resolved velocity *V* perpendicular to the line *A-B* and perpendicular to a magnetic field with a flux density of *B* induced by coil *C*.

Figure 3 Acoustic travel time current meter as one instrument among many on a package capable of crawling up and down a wire mooring to obtain profiles of properties in water depths of up to 5000 m.

Key Words

Acoustic current meters; electromagnetic current meters; moorings; current measurement; heading measurement; calibration.

Cross-references

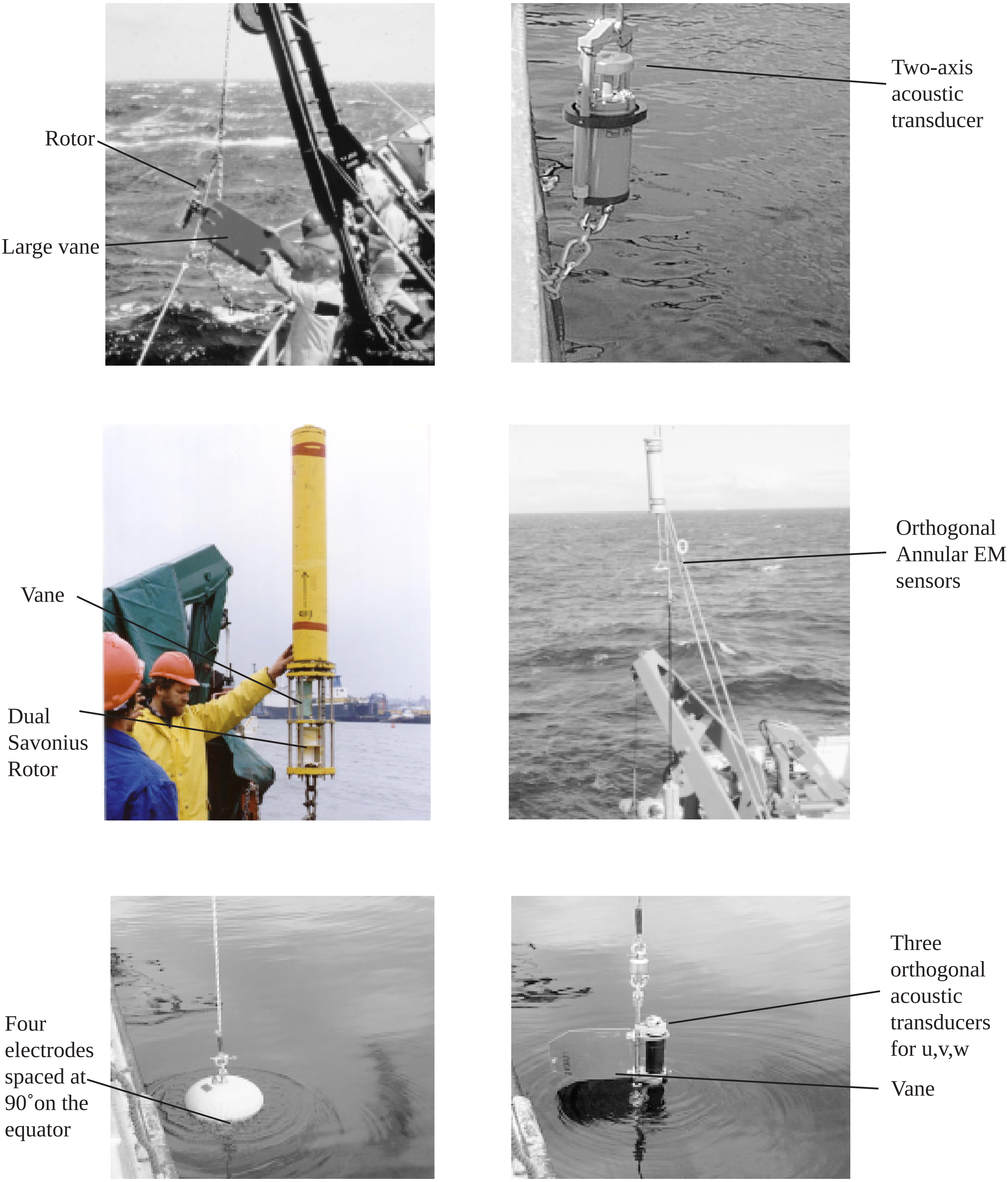
Sensors: Current Measurement: Profiling

Sensors: Turbulence dissipation sensors

Turbulence and diffusion: 3D turbulence

Acoustics: Sonar Systems

Ocean Circulation: General Processes



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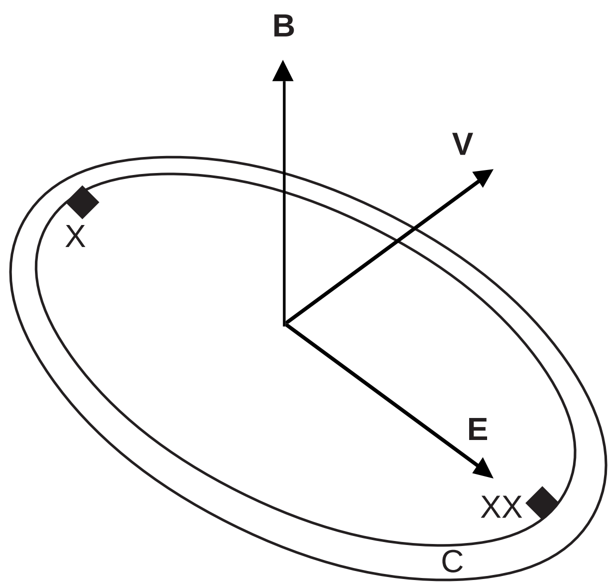

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Figure 3 Acoustic travel time current meter as one instrument among many on a package capable of crawling up and down a wire mooring to obtain profiles of properties in water depths of up to 5000 m. Illustration courtesy of McLane Research Laboratories.