PROFILING CURRENT METERS

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Introduction

Surface moorings, which may be deployed in water depths from tens of meters to thousands of meters, provide a suitable platform for the deployment of single-point current meters. Placing multiple sensors along the mooring line gives a discretized velocity profile and thus single-point sensors can be used to resolve the vertical structure of ocean currents. However, in deep water the number of sensors necessary to obtain sufficient vertical resolution throughout the water column quickly becomes prohibitive. Thus, a variety of techniques have been developed to obtain velocity profiles from a single sensor. Ideally, such profiles resolve the oceanic velocity fine structure (vertical scales of 1–10 m) and are synoptic in the sense that they are obtained over a time short compared to the characteristic timescale of the phenomena of interest.

There are three basic approaches to velocity profiling: vertically cycling single-point sensors, free-fall probes, and acoustic profilers. A fourth category involves the combination of these approaches. Single-point sensors may be cycled between the surface and some depth by use of a winch or cycled within the water column along a mooring line. The simplest free-fall probes are streamlined objects that are dropped through the water column and tracked acoustically. Acoustic Doppler techniques rely on a measurement of Doppler shift from a range-gated transmission that ensonifies the water column.

Vertically Cycling Sensors

It is a relatively simple matter to vertically cycle a single-point sensor from a ship using a winch, but interpretation of the resulting velocity is complicated by motion of the ship relative to the Earth and motion of the sensor relative to the ship. Cycling along a mooring line mitigates these problems, but the energetic vertical motion and potentially large inclinations of a surface mooring line are undesirable (wave-driven profilers are an exception, see below). Thus, the most common implementation involves vertically cycling an instrument package along a subsurface mooring line or a taut section of surface mooring line that is dynamically decoupled from the surface buoy. A limitation introduced by these schemes is that the upper 20–30 m of the water column are inaccessible to the profiler. The benefit is that the relative stability of the mooring line allows the motion of the instrument relative to the Earth to be ignored, and the problem reduces to one of propelling the single-point velocity sensor or choice along the line. Solutions to this problem fall into four classes based on the nature of the propulsion: traction, buoyancy, waves, and currents.

Traction profilers use an electric motor to drive a traction wheel that propels the sensor package along the mooring line. The package is designed to be neutrally buoyant at mid-depth of the profile. Buoyancy-driven profilers achieve propulsion by varying the displacement of the package without changing its mass. This may be done by alternately filling and emptying a bladder external to the pressure housing with a fluid or gas. Alternatively, a piston may be driven in and out of a flooded chamber. Cycling is typically controlled by a microprocessor that turns a pump or motor on and off at preset times and/or pressures. Mechanical stops attached to the mooring line limit travel at the upper and lower extremes of the profiling range. Traction and buoyancy-driven systems are similar in that they carry their energy source with them in the form of batteries, and they require roughly the same amount of energy to propel a given instrument package. Traction systems are more easily configured to profile to great depths. Both techniques are capable of providing a total vertical travel distance of order 1 Mm per deployment. In a typical configuration a traction system may be configured for 100 round trips to 5000 m, while a buoyancy-driven system may be configured for a 1500 round trips to 300 m.

Wave-driven profilers make use of the vertical motion of a surface mooring to travel downward. During the down cycle the clamp attaching the sensor to the mooring also acts as a ratchet that allows the mooring line to pass through only when it is moving upward relative to the sensor. The sensor package is buoyant, but its inertia tends to keep it in place while the mooring line moves upward during the passage of a wave crest. With successive waves the sensor ‘crawls’ down the line until it reaches a mechanical stop. The ratchet is then released and the package rises to the starting point, where the ratchet is reset. In a typical configuration such a system may profile to 200 m depth every two hours. A current-driven profiler uses a similar technique, but the relative motion between the mooring line and the sensor is due to the generation of lift from the passage of ambient currents over a wing that is incorporated into the sensor package. Wave- and lift-driven devices are distinguished by the ability to draw on the surrounding environment for power, so that deployment durations are in principle limited only by the power and storage requirements of the sensors. However, these systems are likely to have a more limited vertical range than traction or buoyancy-driven systems and may be ineffective where waves and currents are small.

Free-fall Probes

A probe that follows the horizontal motion of the surrounding water during a descent to the ocean bottom and return to the surface can be used to determine the vertically averaged current. In a typical implementation the probe itself is buoyant, but carries a weight that is dropped upon encountering the bottom. The depth-average (vector) current $\bar{U}$ is computed from the horizontal distance between the drop and recovery points divided by the travel time. In principle, velocity precision is limited only by the precision of the position fixes, but in practice the fact that the probe may not faithfully follow the water must be considered. Vertically averaged currents over variable depth ranges can be obtained by programming weights to drop before the bottom is reached.

A velocity profile is obtainable if the motion of the probe can be tracked during its descent. Tracking is done acoustically, often using inexpensive, expendable beacons. Two or more beacons are configured to 'ping' synchronously relative to a known timing reference, deployed from a ship, and then surveyed to accurately determine their relative positions. A transponder in the probe is used to detect the arrival times of signals from the beacons relative to the same time base, allowing the probe's horizontal position relative to the beacons to be determined. Vertical position is determined by a pressure sensor. The result is a profile of the total (vector) velocity (eqn [1], where $u(z)$ is the baroclinic component).

$$U(z) = \bar{U} + u(z) \qquad [1]$$

Velocity precision depends on the accuracy of the beacon positions and the precision of the timing; errors are typically near $1\,\mathrm{cm\,s^{-1}}$. Vertical resolution is limited by the product of the fall rate and the time between pings, which is typically several meters. Temperature and salinity sensors can easily be added to the probe, providing a complete hydrographic profile. Since return to the surface is not essential when tracking is used, an alternative to the recoverable probe is to use inexpensive, expendable probes, and reverse the roles of the beacons and the transponder.

A conventional velocity sensor attached to a free-fall probe measures the relative velocity between the probe and the water (eqn [2]).

$$U_{\mathrm{rel}} = \bar{U} + u(z) - U_{\mathrm{probe}} \qquad [2]$$

Acoustic tracking can be used to determine U_{probe} and recover the total velocity profile. The advantages over tracking alone are higher precision and higher vertical resolution. Alternatively, the measured velocity can be used as a basis for a total velocity estimate. In this approach, U_{rel} is used as the input to a predetermined transfer function, which accounts for the probe's response to lateral forces and produces an estimate of the acceleration of the probe's center of mass. This information is used to estimate U_{probe}, which is then added to U_{rel} to produce a total velocity profile. The complication of tracking is eliminated, but uncertainties in the transfer function may result in larger errors.

Without a means of determining U_{probe}, only the velocity shear (or the baroclinic velocity relative to an unknown constant) can be determined. However, this approach has significant utility because the probe motion acts as a high-pass filter in vertical wavenumber space, i.e., for vertical wavelengths larger than the probe length (typically 2–3 m) the sensor follows the water, while for smaller wavelengths it does not. Thus, an appropriate (fast response) single-point sensor can be used to measure the velocity profile at high vertical wavenumber. This technique is routinely used to detect velocity microstructure.

The necessity of tracking a free-fall probe or using a transfer function for the probe's large-wavelength response could be eliminated if the sensor was capable of directly detecting the total water velocity during its descent. This can be accomplished by exploiting electromagnetic induction. The motion of sea water (a conductor) in the presence of the Earth's vertical magnetic field B_z induces horizontal electric currents E_{h} in the water column that can be measured. For a probe that perfectly follows horizontal water motion the relationship is given by eqn [3].

$$E_{\mathrm{h}}(z) = B_z \mathbf{k} \times (U(z) - \bar{U}^*) \qquad [3]$$

Here $\mathbf{k}$ is the vertical unit vector and $\bar{U}^*$ is a weighted vertical integral of the horizontal velocity. In general, the depth-average contribution $\bar{U}^*$ is not known, and only the baroclinic component $u(z)$ can be determined. The electromagnetic induction technique yields baroclinic velocity profiles with vertical resolution of 5–10 m and precision of about $1\,\mathrm{cm\,s^{-1}}$. The technique has been implemented both on small, expendable probes (similar in operation to XBT, expendable bathythermographs) and on larger, more complex recoverable probes. By adding a self-contained acoustic velocity profiler to the latter, it is possible to estimate $\bar{U}^*$ and determine the total velocity profile (see Combined Approaches below).

Acoustic Doppler Sensors

An acoustic Doppler sensor estimates fluid velocity by detecting the Doppler frequency shift of the acoustic reverberation (or 'backscatter') from objects in the water column. For an acoustic Doppler current profiler (ADCP) operating in the 50–500 kHz frequency range, the primary scatterers are biological (zooplankton and micronekton). The scatterers are assumed to be drifting passively with the surrounding water, although this may not always be the case. During operation, an acoustic transducer emits a pulse of acoustic energy along a narrow beam (3–4° half-power beam width) ensonifying a volume of fluid determined by the beam width, the pulse duration, and the distance from the transducers. As the time after transmission increases, the returned signal comes from successively more distant sample volumes known as range bins. Backscattered energy from each range bin arrives at the transducer with a Doppler shift proportional to the average speed of the scatterers within the volume. For a transmission at frequency f_t through a medium with sound speed c, the velocity in the direction of the beam is related to the mean Doppler shift Δf eqn [4].

$$U_{\mathrm{beam}} = -c\Delta f/2f_t \qquad [4]$$

Estimation of U_{beam} for successive range bins results in a profile of water velocity as a function of distance along the beam.

The typical ADCP configuration consists of four downward-slanting beams separated by 90° in azimuth and inclined at 20° or 30° from vertical. The four beams form two coplanar pairs that can be combined to estimate horizontal and vertical velocity components as long as the horizontal scale of the motion is greater than the beam separation. The along-beam extent of a range bin is related to the transmitted pulse duration T_p by $\Delta r_p = cT_p/2$. The nominal vertical resolution is set by the vertical extent of the range bin, $\Delta z_p = \Delta r_p \cos\theta$, where θ is the angle of the beam from vertical. The backscattered return is generally processed during intervals (range gates) of the same duration as the pulse. In this situation, the velocity for each depth bin is a weighted average resulting from a triangular weighting function with a 50% overlap between bins. Instrument tilt and heading are used to compensate for vertical misalignment of range bins between coplanar beam pairs and convert the measured velocities into geographic components.

The standard deviation of horizontal velocity estimates from an ADCP with transmitter frequency f_t has the general form of eqn [5].

$$\sigma_v \sim c[f_t T_p \sin\theta]^{-1} \qquad [5]$$

The precision [5], based on a single transmission, is often too large for practical applications and is reduced by averaging over many transmissions. In the field, precision may be adversely affected by motion of the scatterers and motion of the measurement platform (the most significant difficulty in computing geographic velocity components is compass error). It is evident from [5] that velocity precision can be increased for a given vertical resolution by using a higher transmission frequency. However, profiling range R decreases with increasing frequency. It is also possible to increase precision for fixed f_t and T_p by using wideband transmission or coded pulses, and this technique is now routinely implemented. Commonly used configurations include high-precision ADCPs ($\sigma \approx 2\,\mathrm{cm\,s^{-1}}$; $\mathrm{R} \approx 20\,\mathrm{m}$) operating near 1 MHz and long-range ADCPs ($\sigma \approx 10\,\mathrm{cm\,s^{-1}}$; $\mathrm{R} \approx 500\,\mathrm{m}$) operating near 75 kHz. Very high-resolution systems ($\sigma \approx 0.1\,\mathrm{cm\,s^{-1}}$; $R < 10\,\mathrm{m}$), which utilize a different approach to data processing, are also available.

By selecting an operating frequency matched to the desired profiling range, it would appear that ADCPs could provide full water column velocity profiles in depths up to 500 m. However, difficulties arise in using ADCPs near surface and bottom boundaries. The first one or two range bins (nearest the transducer) may be corrupted by transient signals from the pulse transmission that saturate the system electronics. Range bins near the surface (or the bottom if the instrument is down-looking) are corrupted by reflections from the side-lobes of the acoustic beam. As a result, many applications use single-point sensors near the surface and bottom boundaries combined with ADCPs that profile the central water column.

ADCPs mounted in a frame or housing that sits directly on the seafloor generally provide the highest-quality current profiles, because platform motion is eliminated and compass error is reduced to a constant (rather than a function of direction). On subsurface moorings, ADCPs are often deployed as the uppermost element, facing upward into undisturbed water. This is an attractive option when bottom mounting is impractical owing to deep water and surface conditions prohibit use of a surface element. Platform motion is increased relative to a bottom mount, but remains significantly less than on a surface mooring. On surface moorings, ADCPs may be mounted within the buoy bridle facing downward, or attached to the mooring line facing either upward or downward. Deployment in a buoy bridle is attractive because near-surface currents can be detected, but performance may be degraded as a result of wave motion. It has been shown that small sensors mounted in-line along a mooring do not affect ADCP performance, and thus the deployment of relatively inexpensive point sensors measuring temperature (or temperature and conductivity) along with one or more ADCPs has become standard practice on both surface and subsurface moorings.

Practical issues important to shipboard ADCP operation include installation method, transducer alignment, platform motion, and navigation. The installation must account for the presence of bubbles, which are generated under the hull in rough seas and swept past the transducers, interfering with acoustic transmissions. This problem may be alleviated by extending the transducers below the bubble layer, or by using a faired housing, or both. Separating the ADCP from the ship and deploying it in a towed body eliminates interference from bubbles and reduces platform motion, but the complexity of operation is increased. After installation, the transducers must be 'calibrated' to account for imperfect mechanical alignment, which may result in both magnitude and direction errors in the observed current. The accuracy of the calibration depends principally on the quality of the shipboard navigation and compass. Of course, the accuracy of navigation also determines the accuracy of the absolute velocity obtained from a shipboard ADCP. When operating in water shallow enough that the ADCP receives a reliable acoustic return from the bottom, the speed of the ship over the earth can be estimated directly from the ADCP in 'bottom track' mode, alleviating the need for independent navigation. However, the availability of more accurate navigation (via the Differential Global Positioning System) has allowed absolute velocity profiling from ships in the absence of bottom tracking to be done routinely.

Combined Approaches

A combined approach that has become relatively common on deep-ocean hydrographic cruises is the use of an ADCP in conjunction with a vertical cycling CTD (conductivity–temperature–depth profiler), often called a lowered ADCP or LADCP. In the most common application, a relatively long-range ADCP (e.g., $f_t = 150\,\mathrm{kHz}$) is mounted on a CTD/rosette frame with the transducers facing downward. As the frame is lowered during occupation of a hydrographic station, the ADCP transmits rapidly ($\approx 1\,\mathrm{Hz}$), collecting a series of overlapping profiles. Each profile is relative to an unknown (but assumed constant) velocity resulting from horizontal motion of the frame during the cast. By separating the instrument motion into a portion U_{ship} due to ship drift and a portion U_{frame} due to the motion of the frame relative to the ship, the relative velocity observed by the LADCP can be written as eqn [6].

$$U_{\mathrm{rel}}(z) = \bar{U} + u(z) - (U_{\mathrm{ship}} + U_{\mathrm{frame}}) \qquad [6]$$

In post-processing these profiles are differentiated with depth to eliminate the unknowns $\bar{U}$, U_{ship}, and U_{frame} (all assumed to be constant for a given profile) and the depth bins are indexed to pressure using the pressure record from the CTD. The overlapping shear profiles are then averaged together in common pressure bins and integrated to obtain the baroclinic velocity profile $u(z)$. If the profiles are continuous during the cast (i.e., not affected by drop-outs due to low scattering strength or acoustic interference near the bottom boundary) the vertical integral of U_{frame} will be zero. The depth-average component can then be estimated from eqn [7], where $\langle U_{\mathrm{rel}}(z) \rangle$ indicates a vertical average (taken to be equivalent to a time average over the cast) and $\langle U_{\mathrm{ship}} \rangle$ is estimated from position fixes at the start and end of the cast.

$$\bar{U} = \langle U_{\mathrm{rel}}(z) \rangle + \langle U_{\mathrm{ship}} \rangle \qquad [7]$$

In practice a small correction due to $\langle u(z) \rangle \neq 0$ may be included.

Another combined approach merges a free-fall probe fitted with an electromagnetic velocity sensor with an ADCP. In this application, a relatively long-range ADCP is mounted at the bottom of the probe with transducers facing downward. Rather than producing a profile of the water column velocity, the ADCP is configured to detect the motion of the instrument relative to the bottom. Of course, this is only effective when the probe is within acoustic range of the bottom (typically a few hundred meters). Within this depth interval, the ADCP provides an independent measure of $U(z)$, the motion of the instrument relative to the Earth, and the vertically averaged flow $\bar{U}^*$ can be determined. The velocity profile $U(z)$ can then be estimated over the entire water column from eqn [3].

See also

Bottom Landers. Ocean Circulation. Sonar Systems.

Further Reading

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PROPAGATING RIFTS AND MICROPLATES

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Introduction

Propagating rifts appear to be the primary mechanism by which Earth's accretional plate boundary geometry is reorganized. Many propagation episodes are caused by or accompany changes in direction of seafloor spreading. Propagating rifts, oriented at a more favorable angle to the new plate motion, gradually break through lithospheric plates. A propagator generally replaces a pre-existing spreading center, causing a sequence of spreading center jumps and leaving a failed rift system in its wake. This results in changes to the classic plate tectonic geometry. There is pervasive shear deformation in the overlap zone between the propagating and failing rifts, much of it accommodated by bookshelf faulting. Rigid plate tectonics breaks down in this zone. When the scale or strength of the overlap zone becomes large enough, it can stop deforming, and instead begin to rotate as a separate microplate between dual active spreading centers. This microplate tectonic behavior generally continues for several million years, until one of the spreading boundaries fails and the microplate is welded to one of the bounding major plates. Active microplates are thus modern analogs for how large-scale (hundreds of kilometers) spreading center jumps occur.

Propagating Rifts

Propagating rifts are extensional plate boundaries that progressively break through mostly rigid lithosphere, transferring lithosphere from one plate to another. If the rifting advances to the seafloor spreading stage, propagating seafloor spreading centers follow, gradually extending through the rifted lithosphere. The orthogonal combination of seafloor spreading and propagation produces a characteristic V-shaped wedge of lithosphere formed at the propagating spreading center, with progressively younger and longer isochrons abutting the 'pseudofaults' that bound this wedge. Although propagation rates as high as 1000 km per million years have been discovered, propagation rates often have similar magnitudes to local spreading rates. **Figure 1** shows several variations of typical mid-ocean ridge propagation geometry, in which a pre-existing 'doomed rift' is replaced by the propagator.

Geometry

Figure 1A shows the discontinuous propagation model, in which periods of seafloor spreading alternate with periods of instantaneous propagation, producing *en echelon* failed rift segments, fossil transform faults and fracture zones, and blocks of progressively younger transferred lithosphere. **Figure 1B** shows the pattern produced if propagation, rift failure, and lithospheric transferral are all continuous. In this idealized model a transform fault migrates continuously with the propagator tip, never existing in one place long enough to form a fracture zone, and thus V-shaped pseudofaults are formed instead of fracture zones. **Figure 1C** shows a