Current Measurement Technology: Moorings, HF Radar, and Profilers

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Abstract: - **Water flow as current, wave, or turbulence, can be measured at a single point with a current sensor, over a region of the surface with HF Radar, or over a vertical or horizontal profile with an acoustic Doppler profiling instrument. Point sensors are generally mounted flexibly on a mooring or rigidly on the seafloor. In-line on a mooring or under a surface buoy, a point current meter measures instantaneous current, revealing wave motion and average current; separation of these two parameters requiring some processing in order to remove the motion of the mooring or buoy. If a measure of turbulence is sought, rigidity is valuable so that the motion of the support can be neglected. In fact, turbulence sensors have been mounted on AUVs so a fixed mount is not absolutely required as long as motion of the support can be known and subtracted. Extending a point measurement to a greater geographic range so that structure of current in a bay or estuary might be determined is possible by using an array of point sensors and the Expendable Benthic Lander or XBL has been proposed to make such an extension. However, HF Radar from shore-mounted antennas has shown itself well suited to making two-dimensional surface current maps over distances ranging from several kilometers to 30 km or more. These maps can even give information about the depth of the surface current if several HF frequencies are used. Vertical profiles of current have been measured routinely for two decades now with the Acoustic Doppler Current Profiler, ADCP. High frequency provides finely resolved depth bins over short ranges with rapidly repeated profiles. Currents at greater depths can be measured at low frequency with larger depth bins and less frequent profiles. Waves can be measured with acoustic Doppler profilers by two methods: fan beams to yield directional spectra of surface waves or by direct Doppler return from the surface reflection of a vertical acoustic beam. When an acoustic Doppler profiler is mounted horizontally, cross-channel flows in inlets or rivers can be revealed, a valuable assist to ships in harbors.**

I. INTRODUCTION

Current measurement technology has a history of thirty years within the IEEE/OES community. There have been nine Current Measurement Technology Committee (CMTC) workshops held in this period [1]. At these workshops, papers presenting ways to measure water flow have preceded papers describing intercomparison of these new methods or instruments with older methods, and these in turn have preceded papers describing uses of the new techniques or instruments in observing currents, waves, and/or turbulence. Of course, currents, waves, and turbulence have been measured far longer than that. Current measurements go back to antiquity when speed of vessels sailing against currents are considered and waves have been estimated and related to winds through sea-state reports for more than 200 years. Turbulence measurements have a more recent history and until the 1970s were restricted to laboratory studies in tanks and flumes. However, modern techniques and instruments have been well represented at the CMTC workshops. Oceans conferences held yearly in North America as well as in Europe in odd years and in Asia/Pacific in even years also have sessions on current measurement at nearly every conference. Taken together, there are reports of current measurement technology that well represent this subject.

II. FLOW

A. *Currents, Waves, and Turbulence*

Strictly speaking, currents, waves, and turbulence are all motion of water and their measurement is simply measurement of flow. However, we distinguish the three by characteristics that also reflect their significance and their means of measurement.

B. *Current*

Current is the mean transport of water. To obtain this mean, waves and turbulence must be removed by averaging. The averages must be longer than the greatest wave period by many times. Averaging will also reduce the contribution of turbulence since this, like waves, is a zero-mean phenomenon. There will remain some noise in the current estimate because moderate length averaging only reduces but does not totally cancel the contributions from waves and turbulence. Currents in the sea or large lakes are generally variable in direction though typically constrained to the horizontal plane and variable in strength and duration as well. Knowledge of current may have value for shipping (Ben Franklin advised colonial packets sailing from North American English colonies to Great Britain to use the Gulf Stream current to shorten the time of passage and those returning to avoid the current) [2]. It is now valued for predicting transport of damaging pollutants and drifting shipwrecked sailors and is of greatest concern for estimating transport in balancing the earth's budgets of heat and dissolved gases.

Large scale current structures in the open ocean are also subject to study with current measurements. Eddies shed by major ocean currents like the Warm Core eddies north of the Gulf Stream are observable by their currents even after the surface thermal signature has been filled in by cooler Slope water. Coastal and tidal currents are important for fisheries, navigation, safety of recreation, and scientific understanding of transport and mixing of nearly anything coming off the land into the sea. These are susceptible to measurement with near-shore current meters. More exotic structures of ocean currents include jets and squirts that are associated with fronts and intrusions of one water mass into another. Sometimes these are observed by satellite in color or by radar backscatter patterns indicating steepening of waves as they propagate into an adverse current and they can sometimes be detected by direct current measurements from a ship. Upwelling and downwelling are also observable by current measurements, often near the bottom rather than on the surface and such measures are important for weather, primary productivity, fisheries, and beach conditions for recreation.

C. *Waves*

Waves have a nearly zero mean transport of mass although they carry energy and momentum. The flow vectors in a wave are approximately circular over the period of the wave, returning a particle to its origin as the wave propagates past a point. With increasing distance from the surface, the wave orbits flatten and in shallow water become linear oscillations at the bottom. Bottom stress generated in the extremely thin wave boundary layer often dominates over the boundary layer stress from current and thus is generally responsible for sediment erosion and suspension [3]. Current then transports such suspended sediment so that flux of sediment responds to both waves and current.

Waves are also of concern to operations including small craft navigation and marine construction. Waves are substantially more difficult to characterize than current because they have direction of propagation that may vary for each frequency component and these in turn may vary with time. Descriptions of waves generally require a time series of directional wave spectra. The measurements of 3-D vector velocities, or two-axis velocities plus pressure are used for these observations.

Wave spectra without direction can be obtained with pressure measurements alone or surface elevation of the free surface, and when an array of either of these sensors is deployed, directional wave spectra can be obtained. Finally, a burst of such measurements must be made since characterizing a single wave is insufficient for a directional spectrum. (A burst is an interval of samples separated from another interval of samples by an interval without samples.) The criteria for observational burst length is that it be long compared to the longest period wave but short compared to the evolution time scale of the wave field. If the burst is too short, the frequency spread of the spectrum will be poorly resolved. If the burst is too long, the evolution of the wave field will appear poorly resolved in time [4].

Wave measurements by acoustic Doppler methods are some of the most recent additions to this subject. Fan beams from an acoustic Doppler profiler can track the Doppler shift of scattering from bubble clouds in surface undulations progressing towards or away from the instrument and when resolved along a range of directions, the directional wave spectrum can often be determined [5]. But, near-surface scatterers are not always present so the technique is still developmental.

D. *Turbulence*

Chaotic velocity fluctuations, especially at small scale, are characteristic of turbulence. The flow is zero-mean and not repeated and can only be represented statistically. Yet turbulence is the final stage of stirring on the way to mixing. Mixing is significant for establishing the properties of the ocean from a scale of several centimeters to many thousands of kilometers. The boundary processes where most mixing occurs also carry sediment into the interior of the fluid. It is principally through decay of larger scale motions such as boundary-layer shear that turbulence develops and there are well-developed theories for describing the turbulence cascade in stratified as well as unstratified flow. Dissipation of turbulence is the end result of a cascade of energy from shear generated by breaking waves and by boundary layer flow.

Measurements of these weak flows over small scales have been a difficult target for ocean fluid dynamists for decades. Whole classes of probes using heat dissipation or lateral strain on a forward moving body have been deployed in mixing regions to describe the dissipation rates and dissipation layers. These layers in turn are related to larger scale stratification and larger scale velocity shear.

Wind, differential heating, and differential evaporation of water from the surface of the global ocean drive large-scale flow. Between that and the ultimate dissipation of velocity on the molecular scale, pass all of the fluid processes of the ocean. Monitoring these processes from currents, waves, and turbulence provides us with the understanding of global distributions of water properties and mixing.

III. PLATFORMS

All flow sensors are mounted on some kind of platform. Even observations from satellite have that object as a platform. The sensor-platform entity defines most specific instrument systems for measuring flow. These can be divided into moorings, vehicles, and arrays.

A. *Moorings*

Physical oceanographers generally have an interest in where the water goes. The flow of water carries heat, salt, dissolved minerals, and gases. Flow also carries sediment, larvae, and larger entities such as wreckage, flotsam, and under-powered vessels. Such flow measurements are often made from fixed moorings, cables buoyed at the top and anchored at the bottom by a heavy weight. If for no other reason than convenience, a mooring is relocatable at the site where it was deployed so it can be recovered expeditiously. Time-series observations from an array of such moorings also fit the theoretical description of fluid dynamics well. This is a field theory and a fixed grid of observations is easily dealt with.

B. Subsurface Moorings

The ocean surface with waves, high velocity currents due to wind, and ship traffic is a dangerous place for a mooring buoy so most current meter moorings since 1970 have used subsurface buoyancy. The top of a subsurface mooring is typically 10 to 50 m below the surface to keep it out of this dangerous region. It also makes it invisible to a surface ship. An acoustic command release (ACR) permits recovery at the end of the deployment. Such a subsurface mooring consists of an anchor of about a ton of iron, several meters of chain to an ACR, a short length of chain to several glass balls providing sufficient buoyancy to float the release, and from there to the subsurface buoyancy near the surface is plastic jacketed wire rope, alternated with current meters chained to clusters of glass balls that float each current meter and the wire rope beneath it to the next instrument. The subsurface float has a flashing light and VHF radio for night recovery and relocation in poor visibility. Fig. 1 shows such a mooring.

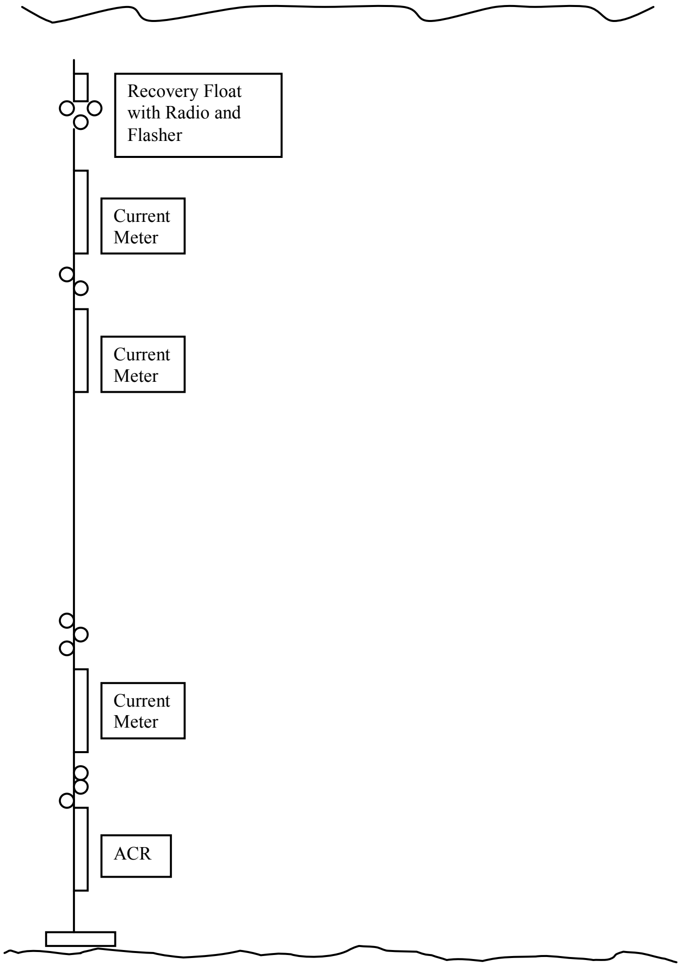


Fig. 1. Subsurface mooring with current meters.

The hardware in such a mooring typically is secure for two years although it is hard to find a current meter that can outlast the mooring. A recent development project with Carl Wunch of MIT and Nelson Hogg of WHOI sought a five-year mooring with current meter to lower the deployment and recovery costs for obtaining the data [6].

C. Surface Moorings

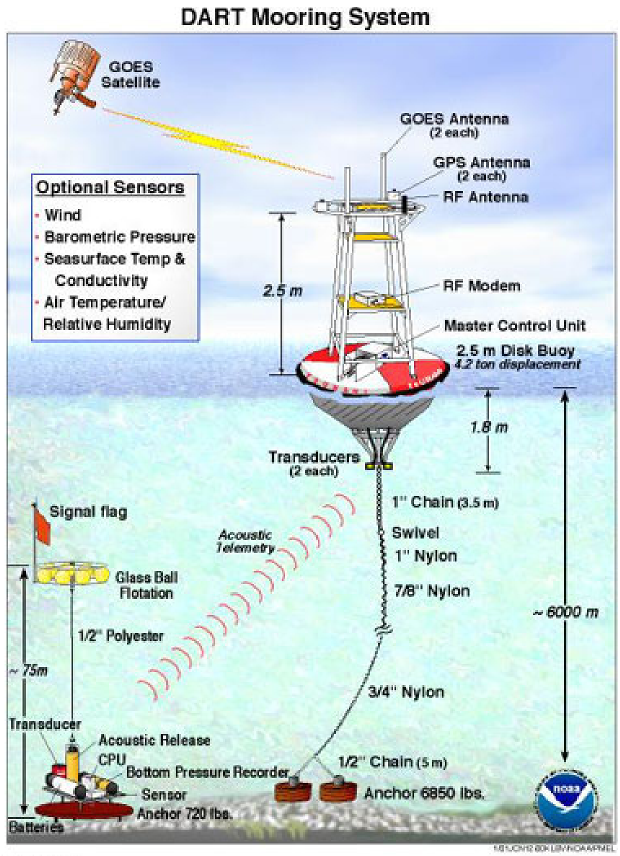
While addition of a surface float at the top of a mooring seems an obvious thing to do, it brings with it much risk and only since about 1990 have surface moorings worked well in the deep sea. The motivation for such a system is to obtain meteorological data and to send back data by satellite. The drag on a substantial surface float is sufficient to drag the mooring off station unless the anchor is several tons and has additional drag elements on it such as a Danforth anchor or sharp edges that can better resist horizontal pull. The surface float may be dragged under and must be able to retain buoyancy even when submerged 30 meters.

Slack in a mooring line is undesirable since the line may kink and then break when tension again is felt so the mooring is generally designed to be stretched slightly when vertical and a section of nylon rope is inserted near the release and below the fish-bite depth to provide elasticity whereby this stretch can be accommodated. The surface buoy tends to follow the surface slope of the waves and the bearing between the float and the top length of mooring cable becomes worn and corroded for an early failure unless the connection is carefully bushed with nylon and a stainless steel pin in a universal joint.

If the surface buoy does not need to support a meteorological array of sensors but only a satellite transmitting link, it can be connected to a subsurface float with a slack tether. The slack tether should neither reach the surface where it might be cut nor hang down below the subsurface buoy where it might wrap around the taut cable and be cut. This design is a so called S-Tether and consists of a section of buoyant line above the subsurface float but not long enough to reach the surface and then a section of non-buoyant line that is shorter than the buoyant line so that it will not hang down as far as the subsurface float.

This compliant link to the surface buoy is wanted to convey data from instruments below the subsurface buoy to the float and there are three choices for doing this. The most traditional way is through a conductive cable with a swivel connection but this has been notoriously unreliable. The next level of complexity is data telemetry by inductive modem. In this case, signals are inductively coupled to the mooring cable, which is plastic jacketed and thus insulated from seawater. The return circuit is through the seawater and this electrical connection can be carried through the swivel to the surface buoy. The most sophisticated telemetry system uses acoustic transmitters on each instrument and an acoustic telemetry receiver on the surface buoy. All of these have been used. The real time data return is in some cases sufficiently valuable that this complexity is warranted.

The DART (Deep-ocean Assessment and Reporting of Tsunamis) system for tsunami warnings uses a surface buoy with acoustic telemetry receiving data acoustically from a bottom mounted pressure sensor and relaying it by satellite to the International Tsunami Information Center in Honolulu [6]. Fig. 2 shows this system.



Courtesy of PMEL

Fig. 2. Surface buoy for telemetry of tsunami generated pressure signals using acoustic telemetry from the sensor on the bottom to the retransmitting buoy on the surface.

D. *Bottom Tripod or Jetted Pipe*

When a rigid mount for a current meter such as a turbulence probe is wanted, a tripod may be weighted to sit on the bottom. Fig. 3 shows such a tripod used extensively in the HEBBLE (High Energy Benthic Boundary Layer Experiment), CODE (Coastal Ocean Dynamics Experiment), and similar experiments [7, 8]. The BASS (Benthic Acoustic Stress Sensor) tripod in the figure is 6 m tall with six sensors of velocity from 35 cm to 5 m above bottom. The tripod was deployed by dropping from the surface and recovered by release of the weighted base. While this jettisoning of the base in the deep sea was unavoidable, on the shelf this would be hazard to fishing so a release line was floated to the surface for recovery on the shelf and the entire tripod including the base was recovered. In shallow water, just outside the surf zone, pipe jetted into the bottom served as a mount for a MAVS current meter with a cable to shore. Fig. 4 shows this installation off Nantucket, Massachusetts [9]. The MAVS (Modular Acoustic Velocity Sensor) current meter like the BASS current meter is an acoustic differential travel-time current meter with no moving parts but not dependent on scatterers in the water for its signal [10].

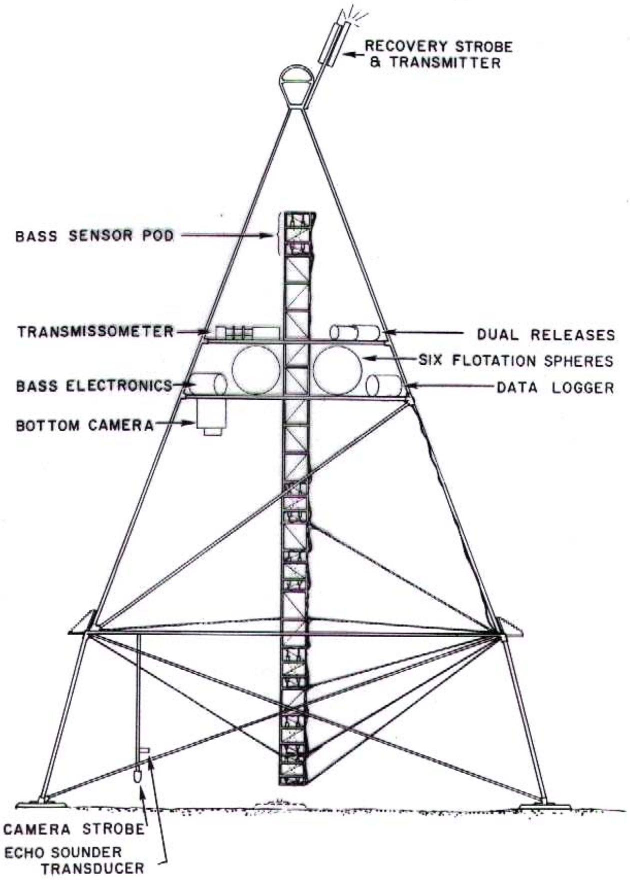


Fig. 2. BASS tripod for rigid support of near bottom current sensors.

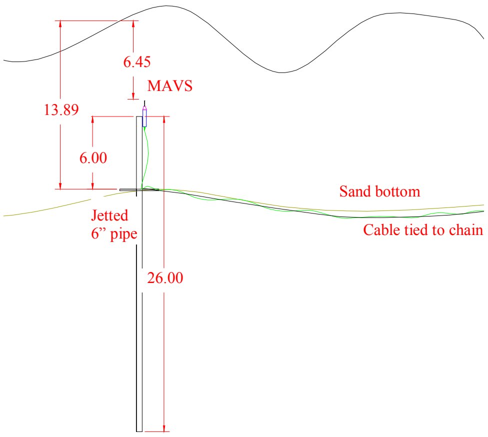


Fig. 4. Jetted pipe supporting MAVS current meter.

E. Vehicles

Moorings are fixed in space, but historically, current was measured from ship-lowered sensors. This provided snapshots of current at a set of distributed points but only for an hour or so before the ship moved to a new location. Anchor stations were an exception to this practice to determine tidal current ellipses. Tidal variations in current had been an issue with snapshot samples but variability at other frequencies –seiches, internal waves, and inertial oscillations – was not fully recognized until moorings provided long time series starting in the 1960s.

F. Autonomous Underwater Vehicles

AUVs are both a difficult and attractive platform for current measurements. They are difficult because they are moving and sometimes their movement is not well known except from surface fixes. They are attractive because they can occupy spaces often inaccessible by moorings or surface ships. The ADCP or Acoustic Doppler Current Profiler is an enabler of current measurements from AUVs. The ADCP makes a profile of velocity from the vehicle or close to it to a distance of from 100 to as much as 3000 m away depending on its frequency. In addition, the ADCP can bottom track to determine the velocity of the vehicle if the depth of water is within the range of the current meter. The Doppler signal from the strong scattering bottom gives the speed and direction of the AUV and the velocity profiles can be related to that. But, because of motion of the vehicle, waves are not well resolved by this process, and there is a potential for aliasing if the current varies on a time scale comparable to the survey time for the AUV mission.

Gliders, long term deployment vehicles that vary their depth and glide forward as they yo-yo in depth, may also be good platforms for velocity measurements [11]. The attraction is that they can cover vast areas over months of deployment, telemetering their data back by satellite when they are at the surface. The proposed current measurement technique is electromagnetic wherein the electric field is sensed from the skin of the vehicle [12]. When water flows in the earth's magnetic field, electric current is induced in the water with the electric current returning through the seafloor. The voltage drop in the water can be measured and related to the vertically averaged water current.

G. Ship

Oceanographic research vessels routinely make current profiles from hull mounted ADCPs. The sections obtained with these profiles plot eddies, meanders of strong ocean currents, and fronts between different water masses when the density difference between the water masses is balanced by shear, the thermal-wind effect. Although research vessels cover many regions of the world oceans, they don't go everywhere nor do they have the freedom to run parallel tracks to resolve the three dimensional shape of an eddy or even to distinguish an eddy from a meander. Yet the information from ship supported current profilers is valuable scientifically. Fig. 5 shows a section across the Drake Passage between Chile and the Antarctic Peninsula. The apparent reversal of eastward flow in the Antarctic Circumpolar Current at 57°S is suggestive of an anticyclonic eddy centered at 58°S.

Operations need current information for safety which can be provided from ships-of-opportunity or volunteer ships in the area of the operations. Gulf of Mexico oil drill rigs depend on installed ADCPs and other current meters to map out the Loop Current that threatens them on occasion. But ship mounted ADCPs supplement the rig supported sensors. Practical matters for improving the data from these measurements include determining the alignment of the acoustic beams, correcting for ship heading, and entering ship tilt. There have been schemes involving GPS sensors for ship attitude –pitch, roll, yaw, heave, sway, and surge – that were employed and these strategies and their successes have been reported in CMTC talks.

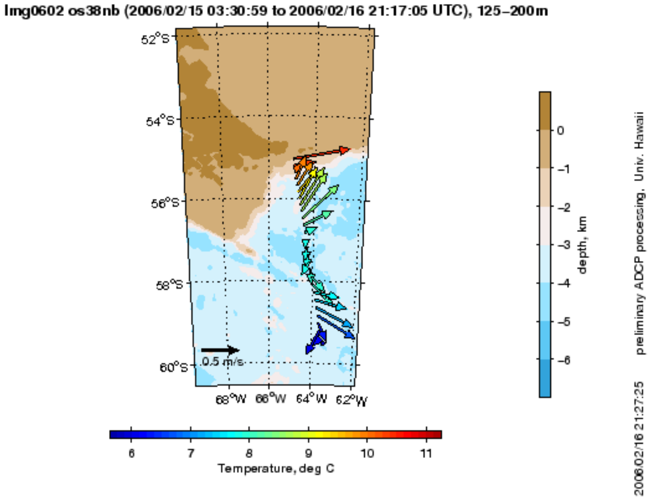


Fig. 3. ADCP current profile across the Drake Passage.

H. XBL Array

Marine observatories with cable connection to shore are being installed at several places in North America and elsewhere to provide continuous data from various sensors including current sensors and to be supplied with shore power. While these observatories permit arrays covering the edge of a tectonic plate including spreading centers for example, they are only able to observe where they have been installed and installation requires massive effort and expense.

Expendable Benthic Landers (XBL) offer another technology to capture currents and other oceanic properties over a horizontally extended area [13]. The XBL is a low cost current meter with ancillary sensors of temperature, pressure, conductivity, and optical turbidity, which can be dropped from a moving ship-of-opportunity. Although this instrument and system has not yet been produced, it will enable rapid response and rapid deployment of sensors to cover an area on the seafloor of up to 10,000 square km in less than a week.

The XBL units will return to the surface with recorded data after a preset time of several months to one year and be relocated and recovered by GPS coordinates transmitted via VHF radio. Condensed data will be transmitted simultaneously to satellite in case the instrument can't be recovered. In some cases, this might be the choice due to inaccessibility while in other cases it might be due to weather or accident. In either case, the essence of the observations can be recovered through the averaged summations and correlations of measurements that have been stored and relayed by satellite. Fig. 6 shows the XBL in a deep-sea configuration in which the sensor is down and anchored about a meter above the bottom.

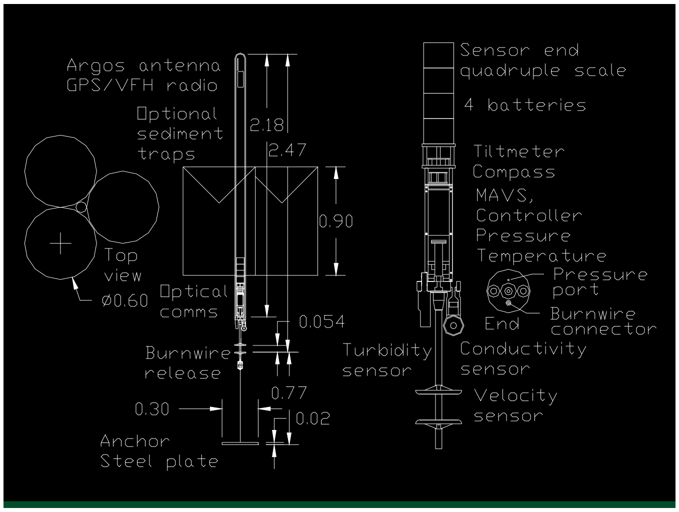


Fig. 4. XBL in the sensor-down configuration. The housing of glass is capable of 4000 m depth and the upper end, containing VHF radio and satellite transmitter and GPS receiver, is transparent to radio waves.

IV. HF RADAR

Surface currents advect wind waves. HF radio waves are Bragg scattered from those components of these wind waves that have a wavelength half that of the radio wave. The scattered radio waves have a Doppler shift due to the phase velocity of the spectral component of the wave field. This wave velocity is determined by the deep-water wave equation. Any deviation from this expected Doppler shift is due to the advective velocity from current. So a transmitter and receiver on shore beaming a radio signal to sea will receive a return that has information about surface currents embedded in the Doppler shifts in frequency as a function of delay since the beam was sent. These radial components of surface current can be crossed with radial components of surface current from another antenna at a different location to make a vector map of surface currents over a bay, estuary, river, or coastal region.

Phased array antennas are one of the two systems used for HF radar. In this system, a set of antennas, poles connected to a base station, are erected along a shoreline over a distance of several hundred meters. The steering of the radio beam is done by the phase delays added to the antenna drivers. This system takes up substantial real estate. The other system consists of compact direction finding antennas for the receivers. This occupies only two specific locations along the shore and is more acceptable to local landowners.

The bands used by the HF radar select the water wavelengths from which Bragg scattering occurs and selection of different bands selects different wavelengths of the wind waves. Since the frequency relation of wavelength is defined for only the water that contains the circular or near circular orbits of the waves. Long wavelength waves average the current over greater depth than short wavelength waves. By using two different frequencies in the HF radar, depth dependence of surface current can be distinguished [14].

Shallow-water waves, those with a wavelength larger than the water depth, have a phase velocity proportional to water depth. This is a very different regime from deep-water waves. In this case depth information can be obtained since the Doppler shift is proportional to water depth. If there is current as well, this is added to the Doppler shift due to shoaling. Again, two frequencies can help distinguish the depth effect from the current effect.

HF radar has become one of the most active subjects in recent CMTC meetings although the technique was introduced more than 20 years ago. Intercomparisons with ADCP measurements in river applications and with microwave backscatter measurements have helped understand the signals and additional effects that are significant. The ability to remotely monitor harbors for surface current where there is ship traffic is valuable for docking and maneuvering. Systems to continuously monitor harbors and bays have gained favor. In Europe these observations are available to pilots in some ports.

V. PROFILING INSTRUMENTS

Single point measurements of current are still valuable but increasingly the choice for current measurement is a profile. A lowered instrument may give such a profile although the delay between readings at different depths may be convolved with variations in current with time. The acoustic Doppler profiler has made simultaneous measurements of current velocity over its depth range possible and these instruments have dominated the market for many applications, particularly where monitoring for high current events is needed. The first and still most common instrument is the ADCP or Acoustic Doppler Current Profiler made originally by RDI and now sold by Teledyne RDI.

A. *ADCP*

Acoustic pulses radiated from a fixed transducer are scattered from acoustic inhomogeneities in the water and return to the transducer shifted in frequency by the Doppler offset due to the velocity of the scatterer relative to the transducer. Four acoustic beams directed upward but at some angle off the vertical obtain profiles in depth of Doppler frequency shifts. When a pair is combined and the velocity components along the beam are differenced, the horizontal component in the plane of the beams is determined at each depth. The second pair can be differenced to obtain the other horizontal component of velocity at each depth. If all four beams are added the vertical component of velocity can be determined. If the beams are added pair wise, the difference between the two vertical estimates gives a measure of error in the observation.

The frequency used with the ADCP determines the range, since the attenuation of sound varies with frequency; and, at high frequency, fading below background noise limits the range. However, the Doppler shift is proportional to the frequency used and velocity resolution is limited by too low a frequency. Range bins from which samples of frequency shift are made become larger at lower frequency so spatial resolution is limited by too low a frequency. Finally, the repetition rate at which estimates of velocity can be made are proportional to frequency (inversely proportional to maximum range) because the first ping must die away before the next ping is transmitted and this depends on acoustic attenuation. In fact, a figure of merit for an ADCP is the product of resolution in velocity, resolution in depth, and resolution in time. The product of the three is a constant unless something else is done, in particular encoding additional pulses that can be transmitted before the earlier ones have decayed in intensity..

B. *Broadband ADCP*

If more than one pulse can be put in the water at a time, the temporal resolution can be improved. This is not as easy as using two different frequencies since the phase tracking is not cognizant of the frequency but coded pulses can be distinguished and in the broadband ADCP this technique is used. The instrument is called broadband since in order to vary the phase encoding of the transmitted burst of sound, the phase of the transmitted burst of cycles must be inverted in a single cycle or two and this corresponds to an instantaneous frequency that is a multiple of the normal transmit frequency. Orthogonal strings of phase reversals, with low correlations between one another except for themselves, form these pseudo-random codes. With the broadband technique, the figure of merit can be lowered manifold over the limit previously cited [15].

Backscatter signal strength may be low in much of the open ocean where there are few organisms in small volumes of seawater. This has been a serious issue for single point Doppler current meters, which lose signal lock in the midwater far from ocean boundaries. With loss of signal they may lock onto a spurious backscatter signal from mooring hardware giving a zero Doppler offset or may do so intermittently and give an anomalously low average velocity. But for the large range bins of the ADCP, this apparently is not a problem except for the farthest range bins.

Scatterers are, however, generally marine organisms and these swim and migrate so there is often a difference between the Doppler measured velocity and an acoustic travel-time measure of velocity that is sensitive only to the velocity of the major contributor to the acoustic propagation, the water. These differences can be 10s of cm/s in the horizontal and several cm/s in the vertical. There have even been consistent locks onto fish swimming near moorings with errors much greater.

There is also a limit to the proximity to the surface to which acoustic Doppler measurements can be made since the bins at a range equal to the depth of the ADCP are blanked out from the specular acoustic return from the surface. But with these caveats, the ADCP is an excellent contributor to our knowledge of currents in the ocean as well as in harbors, rivers, bays, and estuaries.

C. *Moored Profiler*

If in addition to current measured over a substantial portion of the ocean's depth, salinity and temperature are wanted, then a profiling instrument that runs up and down a mooring cable is needed. The Moored Profiler does this with a vehicle adjusted to remain nearly neutrally buoyant and powered by battery to climb and descend the wire rope of its mooring from a station near the bottom to a station near a subsurface float at the top [16]. Along the way, a CTD measures depth by pressure and temperature and conductivity from which salinity can later be determined.

To this package is added an acoustic travel-time current meter such as the FSI Acoustic Current Meter [17] or the Nobska Modular Acoustic Velocity Sensor, MAVS [18]. Each of these instruments, not reliant on scatterers, has four acoustic axes to resolve vector velocity. Since there is a large vertical component of velocity due to the climbing velocity of the profiler, two of the axes are in a vertical plane where their vertical component can be subtracted by the pressure record from the CTD while the other two axes are in the horizontal plane where the current can be decomposed into that flowing into the axis of the faired body and another perpendicular to the faired body. The principal velocity of interest is that into the faired body since this is the current felt along the mooring. Lateral velocities have their origin partly from motion of the mooring in the current and partly from eddies immersed in the flow. Likewise, fluctuations in vertical velocity are partly from variations in climb or descent speed and partly by fluctuations of current velocity in the vertical. A plan is about to be implemented to moor a profiler to a hole through Arctic ice to measure shear, stratification, and internal waves and seiches during a winter in the Arctic Ocean.

VI. SUMMARY

Current sensors and current measurement techniques are developing at a continuous rate, being tested by intercomparison, and used to make observations of oceanic, near-shore, and bottom currents along with ancillary water properties. There are a number of commercial sources for these devices. Research on them and with them is vigorous and the current measurement technology community meets regularly to present their advances and discoveries; at Oceans and other conferences and symposia and at the CMTC workshops every four or five years. Precision and capability increase but applications increase faster so that there is a continual chase of technology after problems. We learn about circulation and mixing of the ocean, about wave propagation and interaction of flow with the boundary, and about cascades of energy from overturning scales to dissipation. Current and flow measurements support other measurements of sediment transport, larval distribution, acoustic communication, environmental quality, and nearly anything that depends on seawater for its characteristic behavior.

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