Current, Waves, and Turbulence Measurements

Albert J. Williams 3rd
Woods Hole Oceanographic Institution
MS#12, 98 Water St.
Woods Hole, MA 02543, USA

***Abstract:* - Current transports material and properties such as temperature and salinity in the ocean. Waves suspend sediment in shallow water and propagate energy in deep water. Turbulence mixes heat, salt, and momentum between pairs of water parcels and keeps sediment in suspension from settling. All three processes- current, waves, and turbulence - are fluid motions and their measurement requires instruments designed to measure flow. Current measuring instruments rarely have moving parts today and are generally acoustic, either travel-time or Doppler, or are radio frequency radars. Current meters may drift as in Lagrangian sensors or be moored to the sea floor, the ice, or rigidly mounted to the bottom on tripods or jetted pipes. When mounted on drifting buoys or ships, surface velocity can be removed by GPS determinations or by Doppler bottom tracking in shallow water. Precision, resolution, and accuracy; calibration and validation; power requirements and data storage demands; difficulty in deploying or recovering the data; and even maintenance and initial cost are factors that influence selection of a current measuring system. The 50-kg current meter, the 500-m long antenna array, and the rotor and vane are proud achievements of the previous century but today's current, waves, and turbulence sensors are compact, lightweight, versatile, and well supported instruments. Yet there are choices of which a well informed user should be aware.**

Scale of flow, duration of deployment, frequency of measurement, resolution in time and space, and accuracy in speed and direction are considerations in selecting an instrument. Some of the most important flow consequences, such as global warming or ocean acidification, are difficult to measure directly and indirect indicators are needed. For climate time scales, historical markers from sediment or ice cores can indicate temperature, age of sediment, oxygen and pH, and biological composition of the age when the layer was deposited. Current may have been responsible for the global distribution of CO_2, heat, and oxygen but only the results of the movement of the water can be known from such indicators.

Global coverage from satellite may reveal wind from surface roughness, current from sea surface elevation, and movement of satellite tracked drifters – ARGO floats. Basin scale mixing can be deduced from diffusion and dispersion of tracers. But direct measurements of turbulence mixing from dissipation probes and shearmeters aids us in determining processes of mixing such as breaking internal waves over rough topography or resulting from wind stress events at the surface. Some mixing may be thermohaline with microscopic flow but even here, absence of significant shear is revealing. Continuing down the spatial scale is transport of sediment along continental margins by boundary layer currents. On the shelf are exchanges between shelf and slope water, response of the water column to hurricanes or other storm events, and even to tsunamis. In bays and estuaries and in rivers and harbors, knowledge of current is of practical value for navigation, environmental monitoring, and territorial security. Real time return of data is of greater value where the consequences are more immediate and cabled observatories to shore-based stations with connection to the Internet are becoming common in the US and Europe. Buoy-born flow measuring instruments can return data by radio near shore or by satellite far offshore. Wave observations are sought by fishermen and recreational users and the discontinuation of such wave reports from coastal buoys has been opposed by regional associations reflecting data users demand. Some systems remotely measure both waves and current and other instruments primarily measure current but can also estimate waves. Packaging such information for delivery to the public is an important but not simple task. Significant wave height, period, and wave direction is a short report, easily understood but sometimes deceptive. Finally there are very specific measurement needs for cooling water inflow, dredging environmental conditions, and marine construction where coastal conditions may threaten work due to waves or current. All of these issues can be addressed with a better understanding of current meters.

I. Introduction

River, estuarine, coastal, and deep-sea water motions are responsible for transport of sediment, heat, fresh water or salt, energy and momentum in the form of waves and tidal currents, and introduced materials from flotsam to chemical waste to biological invaders. Ecosystems depend upon flow for dispersion. Engineering projects are affected by current and waves during marine construction. Global climate is strongly affected by ocean currents and thermohaline convection. With so many consequences of flow, it is not unreasonable to consider how flow at scales from tidal current to storm waves, and to turbulent mixing can be observed, measured, and incorporated into models and predictions.

II. Flow

A. Currents, Waves, and Turbulence

The scale of flow varies from currents at the largest scale, to waves at an intermediate scale, and to turbulence at a scale only slightly greater than the diffusion scale where molecular processes finally remove velocity differences in the fluid.

B. Current

Current is responsible for transport of heat and materials and thus is of great significance to us. Western boundary currents carry heat to higher latitudes, western boundary undercurrents carry return flows back towards the equator, equatorial currents are strongly influential in climate and weather (El Niño and La Niña, for example) and bottom currents close the global thermohaline circulation. Point measurements of velocity in these global flows are suggestive but rarely capture the total volume of water transported. The flows are simple rivers in the sea only when averaged because such open ocean currents contain eddies and barotropic waves that compromise the significance of an instantaneous observation of the current. Even in rivers, there are eddies, seiches, tidal influences near the mouth, and hydrologic influences up river that complicate a simple current determination. So in an effort to obtain a mean flow, it is often necessary to observe at a point for a prolonged duration or over an extended region at an instant of time, or better yet, both. In practical terms, the capability to do these has given rise to modern current meter and current sensing systems. A point current meter is most commonly able to record the instantaneous flow for an extended time. This permits removal of fluctuations due to waves, vibrations (in most cases) and eddies (again if not aliased by some unfortunate peculiarity of the installation) and a mean current in time is obtained.

But flow is often stratified and the location in the water column where this time series measurement is made will affect how representative the observation of flow is to the total transport in the current. A profiling current meter extends the depth range that might be observed, either for averaging the stratification effects or to resolve the stratification effects for a more complex representation of the current. For example, in an estuary, salty flow frequently proceeds upstream at depth while fresh flow proceeds seaward near the surface. Profilers have become standard for coastal current measurements, the ADCP (Acoustic Doppler Current Profiler) having captured the major part of the market for these measurements as of 2010 [1].

Eddies and barotropic waves in ocean currents add complexity through inhomogeneous flow in the horizontal. Vertical profiles cannot sample such variability with much precision. The classic way to deal with this problem is either to spread a spatial array across the region of interest to resolve the horizontal scale of variability (a section) or to make a long time series and invoke the ergodic hypothesis, which replaces a spatial average with a temporal average if the flow is stationary (doesn't accelerate or decelerate) and homogeneous (doesn't have cross stream or downstream gradients in average velocity). Many flows are ergodic over some range in time and space and so it is not uncommon and certainly less expensive to place a few current meters in a current and sample for a long time and then average to obtain the mean flow than to put out a large array of moorings.

But there are some current measurement systems that are able to resolve horizontal scales of flow with significant resolution and to do so over extended time, which permits removing the dependence on the ergodic hypothesis. HF radar is such a system.

Tidal currents can be strong, responsible for significant transport of materials, yet have no net displacement and thus are on the average, not a current at all but rather a wave. On a spatial scale significant for coastal or estuarine and certainly riverine boundaries, the displacement over half a tidal period is significant and current measurement techniques are appropriate even if the mean tidal flow is zero. In addition, there are rectification effects that make tidal flows often not zero mean. And for many practical purposes such as navigation, tidal currents are the most important flow affecting us. There is the added benefit that tidal currents are eminently predictable (once studied and modeled) so we depend upon current tables and charts as much as we depend on tidal elevations from similar tables and charts.

There has been an implication in this presentation that current flows in the horizontal plane and it generally does due to stratification but some of the most significant current flows are upwelling, downwelling, or in a few places on the globe, deep convection where surface water sinks to the bottom contributing to the thermohaline conveyor belt. Upwelling and downwelling are responsible for nutrient enrichment or surface water impoverishment, generally due to wind forcing or failure of wind forcing. Deep convection is vitally important for whole earth climate but is locally uncertain and can be inhibited by fresh water capping. Such flows require a different current sensing system, vertical current meters, and plume sniffing AUVs for example. These currents deserve detection and measurement too.

C. Waves

The sun warms the earth and the ocean unevenly and the rising air is a flow in the atmosphere that produces wind. Wind exerts a stress on the water surface and this builds waves. Waves, once developed, propagate great distances, losing energy only slowly through breaking or spilling and dispersion. There are several serious consequences of waves. The restless surface shape and locally variable velocities are a threat to marine construction and comfortable sea voyaging, but can be invigorating to surfers and beach goers. NOAA wave buoys report significant wave height and are a popular data feed for mariners and fishermen. Waves in shallow water produce a stress on the bottom that erodes and suspends sediment and thus can be a threat to shore installations. Geologically, waves straighten shorelines by moving sand and stone from rocky points to embayments in their lee. Waves serve to move sediment into harbor channels, causing shoaling. And because waves dissipate their energy and momentum slowly except where they encounter a shore, distant storms are often the source of local waves.

Directional wave spectra are the standard way to characterize waves [2]. Each frequency component has amplitude and a direction of propagation. This characterization can have predictive value either by showing where the particular event producing the wave was or by telling where the wave will go next. Development of a wave event from a storm is interesting in it own right since the long wavelength waves propagate faster and run ahead of the storm and the shorter wavelength waves follow later. Although there is no mean displacement of water in a wave, the energy content may be very great and serve to generate power. It is then another way to harvest the energy from the sun, localized along a shore for example rather than from solar collectors in a field or wind turbines in a sound.

Velocities from a current sensor can provide a directional wave spectrum either through three axes of velocity or from two horizontal axes and pressure. Near the surface, all of these quantities are large and the measurement can be made with high accuracy. But supporting a sensor of velocity near the surface is often difficult. If on a floating buoy, the motion of the buoy must be determined and the fluid velocities measured must be corrected. Or the velocity and displacements of the surface buoy can be used in place of the fluid velocities to determine the directional wave spectrum. Wave buoys that have been characterized for response to frequencies of waves are one of the oldest and most trusted ways to determine directional wave spectra. Surface slope is another well trusted way to determine directional wave spectra with an array of wires supported from a spar buoy or a tower or with stereo photographs of the surface or reflective slope measurements captured by video. But the current meter can do a pretty good job if rigidly supported. This is most easily done on the bottom or near the bottom, either from a tripod or from a jetted in pipe [3]. If the water is too deep for good vertical velocity from the wave orbits, a pressure sensor can be the third variable needed for a directional wave spectrum.

Waves are sensitive to depth, being refracted towards shallows, steepening, slowing, and eventually breaking as the fluid speed exceeds the wave speed. But in deep water the attenuation of the wave orbital velocity with depth makes it difficult to measure directional wave spectra on the bottom, though the pressure signal can provide the non-directional spectrum. Recently there have been current meters introduced that measure surface height fluctuations from a bottom mounted Doppler profiler to couple to near surface horizontal orbital wave velocities and thus obtain a directional wave spectrum. The instrument is Nortek's AWAC [4], an acoustic Doppler profiler with vertical beam. When the surface is sufficiently rough to get a reliable surface scattered acoustic signal, this instrument measures directional wave spectra very well.

D. Turbulence

Mixing, wherein two parcels of water differing in temperature, or salinity or any other dissolved or suspended property interpenetrate and diffuse to an intermediate state, is accomplished at the earliest stage by turbulence. The final stage is molecular diffusion that is responsible first for erasing velocity differences, then temperature differences, and finally for removing salinity or other dissolved concentrations gradients. Suspended materials are left where they were, not being susceptible to molecular diffusion. In a way, they may leave a trace of where the two disparate fluids were brought into close proximity so that the molecular processes could do their work. But the first stage is the stirring that puts the fluid into close proximity and this is the turbulence that can be measured as velocity.

Turbulence is chaotic and can only be represented statistically. Certain critical processes are turbulent and not accessible to measurements at large scale. One of these is Reynolds stress wherein momentum from a flow displaced some distance from a boundary is conducted to the boundary through exchange of fluid with that close to the boundary. The details of this are sometimes represented as burst and sweep. A burst is the sudden departure of nearly stationary fluid at the boundary to be replaced by higher velocity fluid farther away from the boundary in a sweep. At any given time, there may be many of these bursts and sweeps over an extended plane parallel to the boundary but at a single point, the burst and sweep is an infrequent event. To obtain a reasonable estimate of Reynolds stress at a point, a long time series of fluctuations in velocity parallel to the boundary correlated with velocity perpendicular to the boundary must be made [5]. This invokes the ergodic hypothesis again and demands that the flow be stationary and homogeneous. The alternative of measuring the bursts and sweeps over the parallel plane is one that is considerably more difficult although it may be possible with PIV (particle imaging velocimetry).

The essential requirement for measuring turbulence with a point current meter is to obtain accurate three-axis flow over a small volume fast enough to avoid aliasing the turbulent eddies that produce the bursts and sweeps.

There are other turbulence flows such as turbulent kinetic energy and in the water column away from boundaries, there is a decay of shear to mixing through Kelvin-Helmholtz instability, a kind of breaking internal wave, wherein stratification in the water column is insufficient to stabilize the vertical velocity shear against rolling up and breaking followed by mixing. The dissipation of shear though such processes is important for mixing and for following the energetics in the interior of the ocean. Special shear probes are used in these studies, probes that respond to transverse velocity fluctuations as the probe is propelled ahead in a profile or along a tow track.

The results of turbulent mixing can be determined with tracers injected along an isopycnal surface. As the surface is overturned by turbulent events, the tracer is spread to shallower and deeper depths and can be detected over a range of depths after months or a year, revealing how much dissipation and mixing is at work at that location. The mixing is driven by such things as inertial oscillations generated by surface input of momentum through wind or by bottom generated waves over rough topography from tidal flows. As one of the two possible internal mixing processes, (the other being double diffusive convection, salt fingers for example) the tracking of what is happening where and what causes it is important for understanding what mixes the ocean, where and how.

III. PLATFORMS

A. Moorings

Current meters have been supported on moorings to permit measurements of velocity to be made at depths that are representative of current in a stratified ocean. When a deep current is under study such as the western boundary undercurrent or the flow of Antarctic Bottom Water through the Kane Fracture Zone, current meters are spaced along the deepest part of the mooring. When measurements of equatorial currents are made, the current meters are closer to the surface. Since each mooring is costly due to the release, anchor, mooring line, buoyancy, and recovery buoy, it is less expensive to put current meters on a few moorings spaced at different depths than to spread them out on many moorings at the same depth. This does not address the need to obtain a section of current at a spacing that resolves the spatial scales of variability such as the RAPID section at 26.5ºN to capture the meridional return flow of the Gulf Stream [6].

While subsurface moorings are standard due to their greater reliability than moorings with surface expressions, many moorings now have either meteorological buoys at the surface or a satellite transmitter at the surface. Fig. 1 illustrates these two surface moorings. The mooring can be taut as is illustrated for the meteorological mooring with an elastic length of nylon line and the total mooring length cut for slightly less than the depth of the water to prevent the line from ever becoming slack. The motion of the surface buoy, approximately following the sea surface slope, presents a challenge to the connection to the mooring line and this has been solved with a bushed universal joint to reduce wear and is made with corrosion resistant materials. The nylon section is below the fish bite zone which experience has taught is greater than 600 m or so. If a surface expression is needed for real time data return by satellite, a smaller surface buoy is acceptable and one solution to this need is the S-Tether in which a subsurface mooring is connected to the surface buoy by a buoyant line spliced to a weighted line such that the buoyant line is too short to reach the surface and the weighted line is too short to reach down to the subsurface buoy. Data are transmitted inductively to the surface buoy.

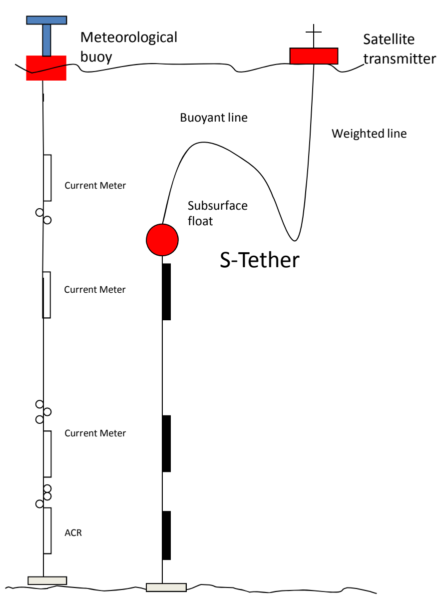

Fig. 1. Surface mooring with current meters.

B. *Moored Profiler*

For the cost of a single mooring and a single instrumented profiler, the entire length of the mooring can be monitored if the profiler can crawl up and down the mooring line [7]. A design using an electric motor and rollers to move the profiler has been built by McLane Research Lab. This moored profiler system has revealed transient phenomena undiscovered before, intrusions of tongues of water at depth that swept by briefly and would almost certainly have been missed by discrete current meters with CTDs (conductivity, temperature, and depth recorders). In some instances, real-time telemetry of moored profiler data have been returned by satellite and this requires a surface expression as in the Fig. 1 illustration with an inductive modem returning the data from the profiler to the top buoy. The McLane Moored Profiler or MMP is shown being deployed in Fig. 2. In this deployment, current is measured with an FSI acoustic travel-time current meter seen extending outward. Since current is measured as the profiler moves, the pressure rate must be subtracted from the measured vertical velocity to obtain the true vertical component of current. The body of the profiler acts as a wing or fin to keep the current sensor pointed upstream where flow is least disturbed by the body of the profiler. CTD sensors, battery, motor, logger, and controller are housed inside the body, some of the items in glass spheres in this MMP.

Fig. 2. McLane moored profiler being deployed.

C. *Ice Tethered Profiler*

Arctic studies have turned the MMP upside down with a mooring hung from the surface to a buoy frozen in the ice. The Ice Tethered Profiler (ITP) uses an inductive modem to transmit data from the profiler to the surface for satellite transmission to shore. The bottom of the mooring, at 800 m in the installation in October 2009 is weighted and becomes the turning point for the profiler. As the ice moves, the GPS position of the buoy is tracked and the mooring may be recovered a year later if it is convenient.

Current measurements from the ITP present a new problem in that the hole in the ice is smaller than needed for the full sized MMP body. A new housing of aluminum contains the current meter, CTD, batteries, and controller. The electric motor is clamped to the side as shown in Fig. 3, where the ITP is being lowered through the hole in the ice.

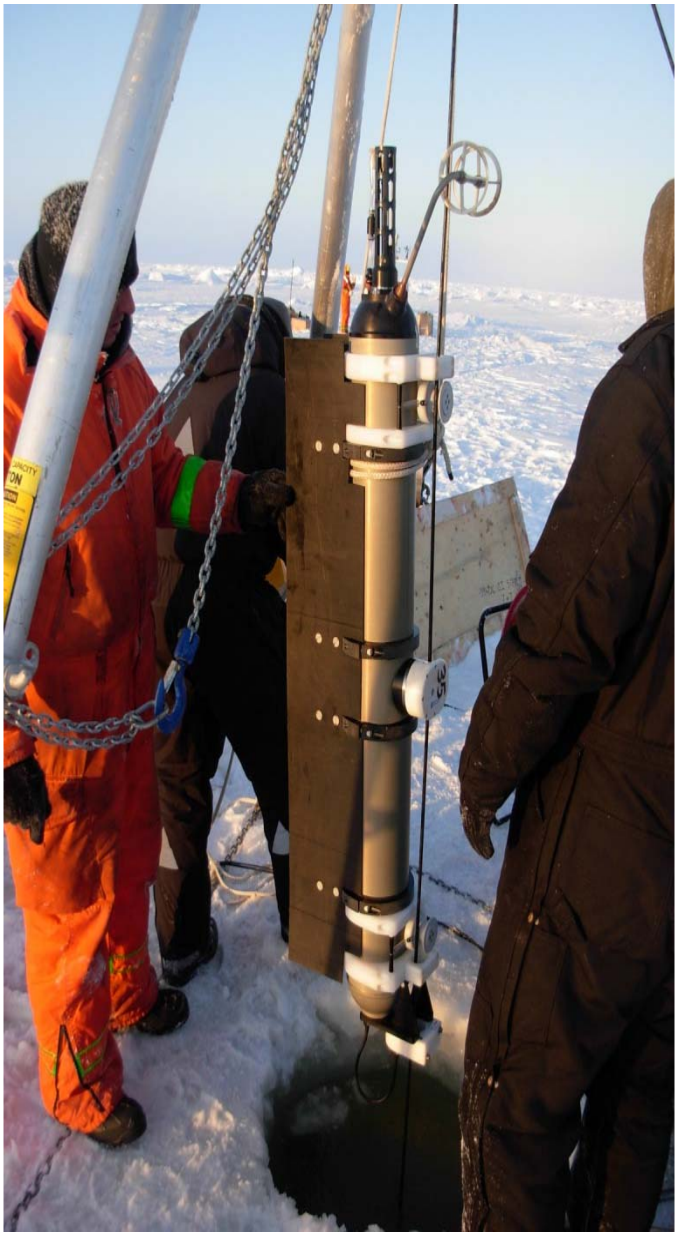

Fig. 3. Ice Tethered Profiler being lowered through a hole in the ice.

Since the hole size limits the body size of the profiler, a short split fin has been strapped to the housing but this fin is insufficient to entirely remove rotations about the body of the profiler. The velocity sensor in this instrument is the MAVS acoustic travel-time sensor made by Nobska Development, Inc. The two rings support eight acoustic transducers that define four acoustic axes, two in the vertical plane and two in the horizontal plane. At the top end there is a set of CTD sensors: conductivity and temperature in the cage and a pressure sensor ported through the endcap. This instrument is expected to flutter if the current is strong and the rotations of the housing about the center of rotation despite the fins will contaminate the velocity measurement so a three-axis rate gyro has been incorporated in the MAVS current meter to correct for body rotation.

D. Other Platforms

Ships have supported ADCPs (Acoustic Doppler Current Profilers) for obtaining current profiles along their track, the ship motion being removed by GPS navigation or in shallow water, by the Doppler tracking of the ADCP signal from the bottom. AUVs also have used ADCPs with bottom tracking when near the bottom or under-ice tracking when near the underside of ice. If neither is within range, inertial guidance removes the vehicle velocity until a surface exposure allows a GPS correction to reset the track.

Bottom mounted tripods are necessary if rigid support is required for turbulence measurements near the bottom. Wave measurements also benefit from rigid mounts but jetted pipes are can be used for beach studies where the water is shallow and there is a hard sand bottom. Small tripods are easy to deploy and the tripod shown in Fig. 4 has been used extensively for studies of bottom turbulence, waves, and currents near Woods Hole. Recovery of this tripod is by pop-up floats carrying Spectra lifting line of small diameter.

Fig. 4. Small tripod to support ADCP and MAVS current sensors with Pop-Up floats for instrument recovery carrying Spectra line.

IV. HF RADAR

The problem of obtaining a current map of the surface of an estuary, embayment, or coastal region is very difficult to solve with discrete current meters. Remote sensing by satellite, aircraft, or conventional radar gives some assistance but still requires successive images of the surface to obtain velocity vectors. HF radar on the other hand, obtains a velocity vector from each point within range of the radar, typically out to 30 km. The principle is that Bragg scattering of HF radio waves from surface water waves selects one water wavelength from which the returned signal is received. This water wave has a speed in deep water that is known and thus the Doppler shift in the returned radio wave has an expected value. If the received radio wave return is other than the expected Doppler shifted frequency, it is due to advection of the water wave by current. A single HF radar antenna obtains a map of radial current velocities. But a pair of antennas crossing a body of water and thus obtaining a pair of radial current components is sufficient to make a current vector map. Fig. 5 is such a map made in Monterey Bay by Don Barrick of CODAR, Inc. [8].

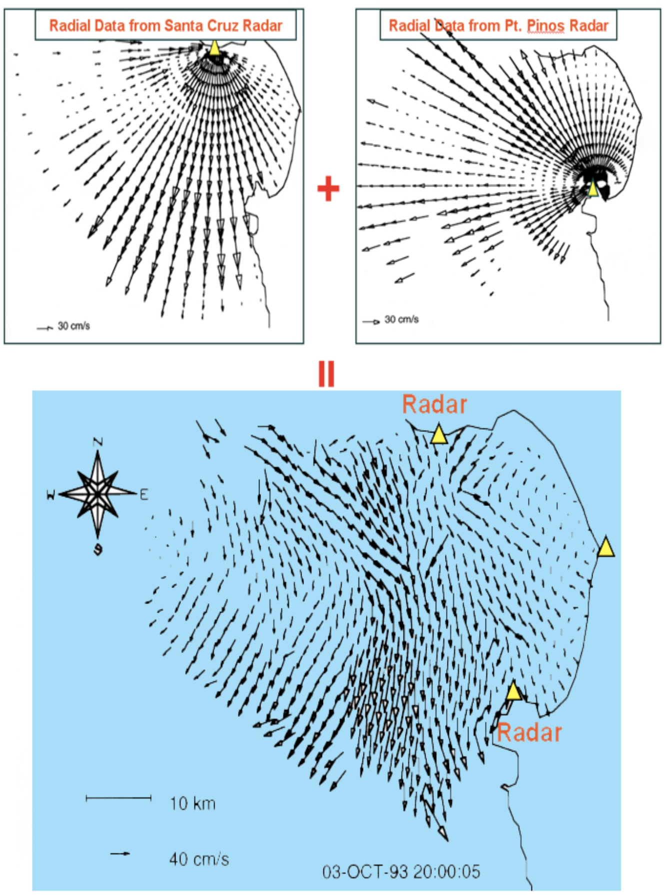

Fig. 5. HF radar from two antennas in Monterey Bay California. The crossed radial current components produce a vector current map.

UFH radar (CODAR RiverSonde) has been developed to map surface velocity in rivers [9]. The backscatter is from capillary waves instead of deep water gravity waves. The size of the cells resolved by the radar is appropriate to the smaller size of a river where 30 km range is not needed.

Real-time data return is available with HF radar. Being shore based, information is available for fishermen, mariners, Coast Guard, and other agents with need for immediate information concerning current near shore. The US is in the process of installing HF radar to cover the entire coast of the contiguous states and much of Alaska, Hawaii, Guam, and the US Caribbean islands by 2015.

V. PROFILING INSTRUMENTS

Vertical profiles of velocity can be obtained with a moored profiler containing a point-measuring current sensor. But the most common approach to obtaining a vertical profile of velocity uses an acoustic Doppler profiler (ADP). The ADP can be bottom mounted looking up, mounted beneath a surface buoy looking down, or on a mooring in mid-water looking either up or down. In the Gulf of Mexico, such mooring supported ADPs are commonly used near oil platforms where they can give warning of loop current incursions, dangerous to platforms throughout the region. MMS has mandated these observations and the sharing of data to forestall platform and environmental damage

A. ADCP

The first commercially produced ADP was RDI's Acoustic Doppler Current Profiler (ADCP) and this instrument has a dominant influence on the current measurement world. The principle of Doppler current measurement is that sound scattered from particles or other acoustic inhomogeneities in the water is Doppler shifted by the relative velocity of the scatterer towards the transmitter and receiver.

By transmitting a burst of sound and then receiving the scattered returns on the same transducer, a time dependent Doppler frequency shift becomes a range dependent velocity component of scatterers towards the transducer. Using four or three acoustic paths inclined to the vertical, different components of velocity are determined and these can be combined into a vector current profile. When this is done by the RDI ADP, it is an ADCP.

There is a brief time after the acoustic pulse is transmitted when the transducer is still ringing and unable to detect a received scatter signal but after this blanking period, signal is received until attenuation from absorption and spherical spreading brings the signal level down to the noise floor and this is the range of the ADP. High frequency gives reduced range but better spatial resolution (smaller bin size) and more rapid repeat pulses so that velocity fluctuations can be tracked out to a higher frequency of current variation. It is necessary to wait for the scattered signal received on the transducer to drop to this cutoff before the next pulse is transmitted. This presents a limit on the combination of resolution of current resolution, current fluctuation frequency resolution, and range that is fixed for a single frequency ADCP. But a way around this limit was discovered that codes the acoustic pulses that are transmitted and then allows several coded pulses to be present at the same time for greater current frequency resolution.

B. Broadband ADCP

The coded pulse technique is called the broadband technique and it is patented by RDI (now Teledyne RDI) [10]. As the frequency to be transmitted is generated for the power amplifier, the phase of the signal is reversed in a pattern that is unique or at least poorly correlated with the other codes to be transmitted. This reversal of phase represents an instantaneous high frequency and thus the power amplifier must be broad band to handle the coded pulses.

VI. SUMMARY

Flow measurement for current, waves, or turbulence requires velocity sensors and systems that support them or that permits them to profile or observe the surface. Trade off between continual time series, spatial profile, and surface mapping dictate which technology is most appropriate. Real-time data return is often required and this mandates a surface expression for a moored current meter. Development of current measuring technology continues while installation of current monitoring arrays is ongoing.

ACKNOWLEDGEMENT

The National Oceanic and Atmospheric Administration provided support to participate in the US Argentina Symposium.

REFERENCES

[1] http://www.rdinstruments.com/

[2] Morrison, A. T., III, "MWAVES - Software for Calculating the Directional Spectra and Statistical Properties of the Wave Field From MAVS-3 Triplet Measurements", Proceedings of the IEEE Seventh Working Conference on Current Measurement, IEEE/OES, March 2003, pp. 128-134.

[3] Williams, A.J. 3rd, A.T. Morrison III, and J.E. Farrel, 2007. Measurements of Surf Zone Currents and Waves In Support of Madaket and Sankaty Head, Nantucket, Beach Nourishment. *Oceans '07 IEEE Aberdeen*, ISBN CD-ROM 1-4244-0635-8, IEEE Aberdeen, Scotland June 18-21, 2007, 6 pages.

[4] http://www.nortek-as.com/en/products/wave-systems/awac-1

[5] Grant, W.D., A.J. Williams 3rd, and T.F. Gross, 1985. A description of the bottom boundary layer at the HEBBLE site: Low frequency forcing, bottom stress and temperature structure. Marine Geology, 66, pp. 219-241.

[6[http://www.noc.soton.ac.uk/rapid/

[7] Doherty, K.W., D.E. Frye, S.P. Liberatore, and J.M. Toole, 1998. "A Moored Profiling Instrument," Journal of Atmospheric and Oceanic Technology, (1998) v. 16. pp. 1816 – 1829

[8] Barrick, D.E., 2008. "30 Years of CMTC and CODAR," Proceedings of IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology, IEEE Cat. No. 08CH37931, pp.131-136.

[9] http://www.codar.com/bib_RiverSonde.shtml

[10] Brumley, B., R. Cabrera, K. Dienes, and E. Terray, 1991. "Performance of a Broad-Band Acoustic Doppler Current Profiler," IEEE J. of Oceanic Engineering 16 no. 4, Oct. 1991 pp. 402-407, ISSN: 0364-9059.