Chapter 2

The History of Measuring Ocean Currents

Chapter Outline

The world came to know of the existence of ocean currents from the early mariners, who painstakingly crossed the world seas on their long and tiring trading voyages through the pathless ocean. As a matter of necessity in terms of navigational safety and in an attempt to substantially reduce the travel time to the destination ports, it began to be a routine practice among the early mariners to collect the experiences of every navigator about the ocean currents and winds he encountered, and then discuss their observations during leisure times. They realized that by systematically recording on a chart the tracks of several ships on the same voyage but at different times and in different years, and during all seasons, and by graphically indicating the currents and winds daily encountered by them on each track, these charts would eventually turn out to be fine expressions of the results of the combined experiences of all whose tracks were thus drawn.

The initiative for methodical documentation of all observations of all the navigators, as just mentioned, came from a veteran navigator named Lieutenant M. F. Maury of the U.S. Navy, and the charts so prepared came to be known as *Maury's Wind and Current Charts*. Eventually the charts describing the currents and winds in different seas and oceans became dependable guides to the early navigators. Maury's charts subsequently began to be considered as time-honored treasures by the maritime communities of the whole civilized world to guide them across the vast oceans, to save themselves from the wrath of the sweeping currents and winds of the oceans, in the best possible manner, for the improvement of commerce and maritime navigation.

A serious attempt at the systematic study of ocean currents began in the 18th century, primarily as a need to decrease travel time for cargo between England and America. In this attempt the first map was created of the notorious currents in the Gulf Stream in the Atlantic Ocean. This map showed the routes that ships should sail in order to decrease their travel time. According to Maury (1855), the National Observatory at Washington, D.C., showed immense interest in converting every ship that navigated the high seas into a floating observatory and a temple of

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science. Accordingly, more than a thousand navigators began to engage day and night, and in all parts of the ocean, in making and recording observations according to a uniform plan and in furthering this attempt to increase our knowledge about the currents and winds of the seas, and several other phenomena that manifest themselves at sea and that might have implications for safe and proper ocean navigation. This attempt proved a giant stride in the advancement of knowledge and a great step toward its spread upon the waters.

In the present era, ocean currents are monitored for several applications, such as port operations, coastal environmental monitoring, offshore explorations, and other commercial purposes; studies of climate change; and out of purely academic interest because, with proper knowledge of the ocean currents, it is possible to predict a variety of useful as well as damaging events in the oceans and effectively deal with the consequences.

With advances in oceanographic studies, application of measurements, together with modeling techniques, became more and more common in helping humans understand several oceanographic processes. Thus, in the context of ocean current circulation studies, there are now two kinds of approaches to understanding the state of the ocean: (1) the direct or indirect observation of current, and (2) model simulation based on the available knowledge about the governing laws. The difficulty in the former approach is that the number of observation points is usually insufficient to get adequate spatial coverage of the parameters of interest due to instrumentation cost and environmental regulation. Insufficient observation points lead to data being badly interpolated in space. Model simulation can represent only an approximated aspect of the particular problem under consideration and must therefore be validated appropriately by the field observation data. Fortunately, several methods of data assimilation have been developed to strengthen the performance of observation and model by combining these two approaches optimally.

2.1. SURFACE CURRENT MEASUREMENTS

As noted in Chapter 1, knowledge of sea surface currents is important for a variety of applications. Lagrangian method (i.e., a method that provides a quantitative description of both track and speed of water flow) is often employed to obtain an overall picture of water motions over large oceanic regions. In a Lagrangian sense, ocean currents are the channels through which the waters of the oceans flow. The Lagrangian method originally meant measurement of water movements by tracing the path of water parcels over sufficiently long time intervals. The combination of many such paths, termed *trajectories*, mapped on a chart (called a *current chart*) was then used to describe the overall pattern and speed of horizontal currents in a given oceanic region.

The study of ocean currents was important to mariners for several reasons. First, gaining insight into the weather pattern at sea involves knowledge of its currents, both cold and warm. Second, oceanic currents are the chief agents for distributing heat to the various parts of the oceans and thus play an important role in regulating the global climate. With advances in offshore exploration of marine resources, knowledge of ocean currents at various depth layers became important. Crude oil exploration and its maritime transport (via submarine pipelines or ships) resulted in occasional oil slicks. Timely mitigation of hazards arising from such unfortunate episodes required knowledge of surface currents and their trajectories over large areas. There are numerous other reasons that justify gathering information on sea surface currents. Consequently, several methods were attempted for the measurement of sea surface currents and their trajectories. Such methods threw much light on the nature of sea surface currents at different regions of the world oceans. It is interesting to examine the gradual growth achieved in this subject over the years with the use of more and more improved technologies. To appreciate these achievements, we first glance through the primitive methods and then skim through more and more sophisticated methods developed over the years. Detailed discussions on the sophisticated and the state-of-the-art technologies in each category of measurements are reserved for the subsequent chapters of this book.

2.1.1. Measurements Based on Motion of Drifting Surface Bodies

In the previous years of oceanographic studies, the trajectories traced by freely drifting seaweeds and driftwoods provided an indication of the approximate sea surface water circulation paths. An excellent example of the application of this method came from the Sargasso Sea, which is located in the Atlantic Ocean, off the west coast of North Africa. In past centuries, the Sargasso Sea was well known as a general receptacle of the driftwood and seaweeds of the Atlantic Ocean. Likewise, to the west from California a pool existed into which driftwoods and seaweeds generally gathered.

The natives of the Aleutian Islands (which are notorious for fogs and mists, as are the Grand Banks of Newfoundland), where trees hardly grow, depended on the driftwoods cast ashore for all the timber they used in the construction of their fishing boats, fishing tackle, and household gear. Among this timber, the camphor tree and other woods of China and Japan were said to have been often recognized (Maury, 1855). The drift, which brought the timber, was the result of the surface current of the China Stream.

Thus, driftwoods and seaweeds provided some of the earliest evidence of oceanic surface currents across the oceans.

The role of driftwoods in identifying surface current paths, although rudimentary in a practical sense, led to the notion that this idea can be effectively used for measuring surface currents and identifying surface current paths cost-effectively, although the precision in such measurements might be rather poor. Accordingly, one of the oldest methods of determining the speed and direction of oceanic surface currents was to trace the paths of floating objects that freely drifted with the currents.

Mariners have routinely noticed currents on the sea surface through ship drifts. Initially, observations of surface currents had been derived from ships' navigation logs (Sverdrup et al., 1942). In the ship drifts method, the ship itself is used as a tracer of surface currents. The vector difference between a ship's *dead reckoning* and its true position had long been used to provide a measure of sea surface current. In the early decades of maritime navigation, surface currents were determined from the difference between a ship's position by fixes from astronomical observations at least 24 hours apart and dead reckoning. This method was first used by Maury, about 1853, to examine surface currents of the Gulf Stream region, and the method was subsequently extended worldwide. *Dead reckoning*, i.e., deduced reckoning, is a method of estimating a ship's position from knowledge of the course steered and the speed maintained. The accumulating discrepancy between the dead-reckoning position and the true position is an indication of the average displacement of the surface layer of water through which the ship traversed. Over the years a large data bank of surface current statistics has been built up (e.g., Duncan and Schadlow, 1981).

A drawback of the ship-drifts method is that speed and direction are uncertain if the displacement is small, because an astronomical fix is usually not accurate to better than 1 or 2 nautical miles, and the position accuracy by dead reckoning is, as a rule, limited. Further, the ship's drifts are influenced partly by direct wind effects and partly by surface currents. In addition, wave motion can make it very difficult to maintain the ship's heading on the intended course. Even if wind speed, wind direction, and surface waves are recorded, it is difficult to fully assess their contributions to the drift of the ship. These inherent errors and limitations, together with those resulting from inaccuracies in fixing the true position of the ship, mean that observations made at intervals of 24 hours are insufficient. In olden days, the now-ubiquitous global positioning system (GPS) was unheard of, and therefore, for realistic assessment of sea surface currents using the ship-drifts method, the absolute position of the ship relative to the ground had to be very accurately determined at close time intervals. However, technology was not available for such measurements.

In coastal waters it was possible to obtain fairly accurate position fixes at fairly close intervals using navigational aids such as Loran, Shoran, Decca, Mini-Ranger, and so forth. However, further offshore, the navigator needed to rely on Omega and satellite navigation by the Navy Navigation Satellite System (see Joseph, 2000). Unfortunately, the data on sea surface currents obtained solely from ships' logs are often inadequate to construct detailed synoptic charts of surface currents over large areas because such data are concentrated solely along maritime trade routes. Furthermore, the average conditions are not represented because the number of observations is far too small. Nevertheless, several central agencies (for example, hydrographic offices of various countries) have accumulated large sets of such data from commercial shipping, thereby enabling charts to be constructed of surface currents, at least along navigation routes. Interestingly, a notable feature of the wind-driven surface layer circulation (namely, clockwise deflection in the northern hemisphere and counter-clockwise deflection in the southern hemisphere) was first observed from synoptic charts of currents prepared from navigational records.

A rather primitive method for measurement of sea surface currents utilized the drift of free bodies such as drift bottles (Sverdrup et al., 1942; Merritt et al., 1969; Chew and Berberian, 1970; Wyatt et al., 1972). These methods were generally employed near coastal regions. The drift bottles were weighted down so that they would be nearly immersed, offering only a very small surface for the wind to act on, and they were carefully sealed. They contained cards giving the number of the bottle, which established the locality and time of release and requesting the finder (often fishermen and coastal dwellers) to fill in information as to the place and time of finding and to send this information to a central office in return for a small reward. Surface current speed could be determined from the range covered by the bottle and from its travel time. The straight-line distance between the positions of release and finding of a bottle were taken as the *range*, and the difference between the times of release of a bottle and its finding were taken as the *travel time*. Being relatively cheap, drift bottles were used in great numbers. Together with ship-drift observations, this simple method provided a practical means to describe many features of the general surface circulation in coastal regions. In certain studies of ocean currents, drift bottles could provide information that was unobtainable otherwise. This was especially true in shallow coastal regions and in areas abounding in many shoals and islands or those with an irregular coastline.

A disadvantage of drift bottles is that they are fragile and may break, either in handling aboard fishing boats and ships or when washed against rocky cliffs or beaches. To use them effectively, several bottles should be deployed on a single cruise. When used on the South African coast, their recovery rate was less than 1%, presumably because of the high breakage rate on the rocky coast. There are, however, instances in which nearly all the drift bottles were recovered after having been tossed about in a severe hurricane.

A substitute for drift bottle was the drift card, first used by F. C. W. Olson in the early 1950s. The *Olson drift card*, named after its inventor, consisted of a printed card rolled hermetically in a polyethylene envelope. The Olson card thus formed an inexpensive, compact, and convenient means for studying surface currents. Because drift cards are cheap and easy to handle, several hundred of them were usually released at a given point. The method of multiple releases provided more dependable data than would be obtained if the cards were released singly. In a series of trials conducted by Olson, the drifts indicated by these cards were found to be consistent with flow patterns determined by other methods such as water mass analysis and drift bottle studies (Olson, 1951). The results also indicated that drift cards were not at the complete mercy of the wind.

However, the Olson cards had some disadvantages. It was realized that the cards recovered from sandy beaches showed definite signs of sand abrasion, which in some instances acted through the polythene envelope, thereby scouring all identification marks. Because these cards were so light, they had also been, on some occasions, whipped along by strong winds. There were also instances in which the cards displayed marks that suggested attacks by fish and sea birds that were in search of food (Stander et al., 1969). This sometimes resulted in sinking of cards or the writing on them becoming illegible.

In an attempt to retain the advantages and reduce the disadvantages of the Olson cards, a solid polythene drift card (3 mm thick) was designed by Duncan (1965). In the *Duncan drift card*, the messages in several languages (English, Afrikaans, Portuguese, and German) were heat-embossed. The Duncan cards proved to be durable and withstood rough sea action that would normally break bottles and puncture Olson-style envelopes. The heat-embossed lettering withstood sand abrasion. Being heavier, the Duncan cards were not as susceptible to wind action as the Olson cards. Further, their conspicuous red color was advantageous in their recovery. In deployments along the South African coast, Duncan cards proved both durable and convenient.

Like drift bottles, the drift cards could be released from ships and aircraft. Usually hundreds of cards were released at each of the selected stations at both high and low tides. The adjacent beaches were then monitored at regular intervals immediately following each release. This approach considerably improved the card return rate. Duncan (1965) has graphically reported an example of drift card recoveries from the southern coastal waters of South Africa. Drift card studies by Dornhelm (1977) indicated that there was a significant correlation between drift card trajectories and the local winds. He observed that the role of the tides was also significant in the drift card motions, as evidenced by distinctive return patterns for the low- and high-tide deployments. Comparison of current velocities determined by a recording instrument, deployed at a depth of about 7 meters below the surface, with the current velocities inferred from drift card motions revealed reasonably good agreement for direction and a consistently low instrument-recorded current flow speed. This was natural because the drift cards responded to the flow in the upper few centimeters of the water column, which, in turn, was highly responsive to the surface wind stress. However, in situations where a major portion of the drifting body is exposed to wind, considerable care had to be exercised in interpreting the data, because often the wind rather than the surface current had carried the body through the water.

Several drift cards released by Stander et al. (1969) in the vicinity of Cape Town, South Africa, and at various locations in the Atlantic Ocean were recovered on the coast of North and South America and on some islands in the South Atlantic as well as in England, France, Nigeria, and Australia. Some cards released east of Cape Agulhas (on the southern tip of the African continent) traveled across the Indian Ocean and were recovered from the Australian coast after 23 to 31 months. The mean surface current velocities derived from the travel times of these cards were in reasonably good agreement with those obtained from drift bottles that were deployed four years before the drift card experiment. Stander et al. (1969) have reported the trajectories of the drift cards and the drift bottles in these experiments.

An obvious disadvantage in the use of drift bottles and cards was that, often, they remained undiscovered on a shore for some time, and in those cases it became impossible even to determine the magnitude of the average drift velocity between the start and the end points. Fortunately, in coastal waters off heavily populated localities, this problem would probably not be so severe. Interestingly, the data derived from drift bottle and drift card measurements often proved valuable in several unexpected ways. For example, drift bottle experiments could provide useful information such as the presence of eddies (Sverdrup et al., 1942). The drift bottles were also used extensively for the estimation of surface current circulation on the continental shelf off eastern North America and for observation of surface currents off Oregon state as well as those along South African coasts.

Interpretation of data obtained from drift bottle and drift card experiments presented some difficulties because the drifters, in most situations, were unlikely to follow a straight course from the place of release to the place of finding. Because only the end points of the trajectory were known, the drift bottle/drift card experiments provided only information on the average trajectories. The reconstruction of the paths taken by the bottles or cards could be aided by knowledge of the temperature and salinity distribution in

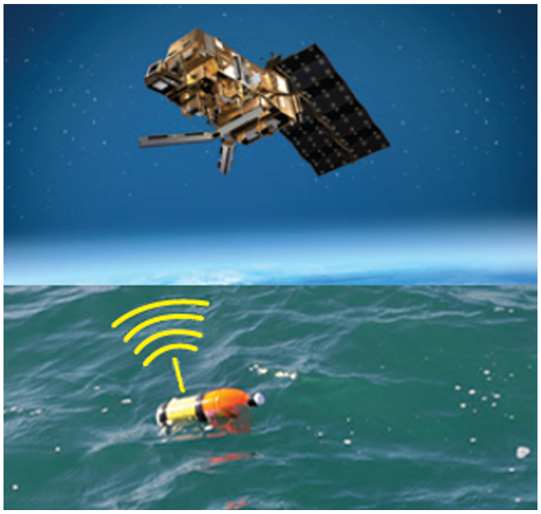


FIGURE 2.1 Application of satellite-tracked drift-bottles in the Pacific Ocean to determine the movement (trajectory and speed) of marine debris in the aftermath of the March 11, 2011 Japan tsunami. *(Source: Courtesy of CLS [France] and Dr. Koki Nishizawa, the Sustainability Research Institute, Tottori University of Environmental Studies.)*

the surface layers. In the absence of alternative methods, synoptic drift bottle/card experiments that were of immense value to fisheries were conducted especially in coastal waters.

A major drawback associated with the Lagrangian method (i.e., a method that provides a quantitative description of both track and speed of flow) just discussed was the time-consuming process involved in tracking given water mass over a large area, requiring many days and sometimes even months of painstaking effort. Further, tracking of water parcels during rough weather conditions and in remote areas was often impractical. This lacuna was removed in 2011 with Dr. Koki Nishizawa's judicious application of satellite-tracked drift bottles in the Pacific Ocean to determine the movement (trajectory and speed) of marine debris in the aftermath of the March 11, 2011, Japan tsunami (see Figure 2.1). Thanks to Collecte Localisation Satellites (CLS) in France and Dr. Koki Nishizawa of the Sustainability Research Institute, Tottori University of Environmental Studies, in Japan, perhaps the most primitive sea surface current-monitoring device has ultimately been resurrected as a modern, yet the cheapest, device for Lagrangian measurement of sea surface currents.

To determine surface currents close to the landmark, *drift poles* have also been used (Pickard and Emery, 1982). The drift pole, which was a wooden pole of a few meters in height and weighted to float, with only ½ to 1 meter emergent above the water surface, functioned as a simple Lagrangian surface current indicator with a minimum of surface exposed to the wind. The pole was simply allowed to drift with the water, and its position was determined at regular intervals, either from the shore or by approaching it in a small boat and fixing its position relative to the shore. The surface current speed was determined by timing the travel time (t) of the pole between its successive positions. If the distance between these two positions is D, then current flow speed is given by D/t in appropriate units. The trajectory of the current could be mapped by joining those successive positions at regular intervals. A concept diagram of this scheme is depicted in Figure 2.2.

Although drift poles may appear to be primitive devices, their modified version, incorporating an antenna, are frequently deployed today. For example, Lobel (2011) deployed such current-drogues offshore of the Kona coastline (Island of Hawaii) and over reefs as Lagrangian tracers of surface currents during cyclonic eddy events. The drift pole drogues used by Lobel (2011) were made of polyvinylchloride (PVC) pipe with a radio transmitter attached to the emergent section (see Figure 2.3). Cross vanes of plastic sheets (0.7 × 1 m) were used as sea anchors below the surface (see Figure 2.4a). The overall length was about 6 m. The drogues were tracked from the nearby coast (tracking distance was about 50 km) using trucks equipped with directional 12-element yagi antennas (see Figure 2.4b). Drogue positions were determined by a running-fix calculation. Figure 2.5 indicates the date-wise total time that each drift pole drogue remained within transmitter signal range of the shoreline. The points indicate the total duration (days) that a drogue, deployed on a given date, remained within the Kona coast domain.

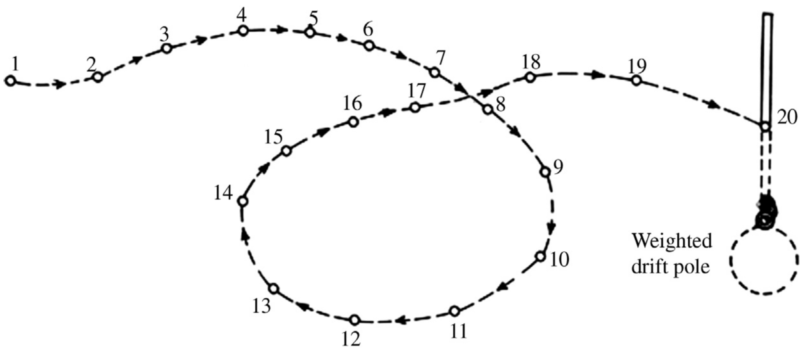


FIGURE 2.2 Concept diagram of the use of a drift-pole as a simple Lagrangian surface current indicator with a minimum of surface exposed to the wind.

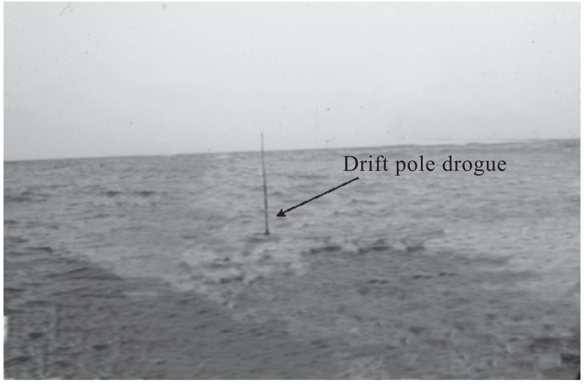


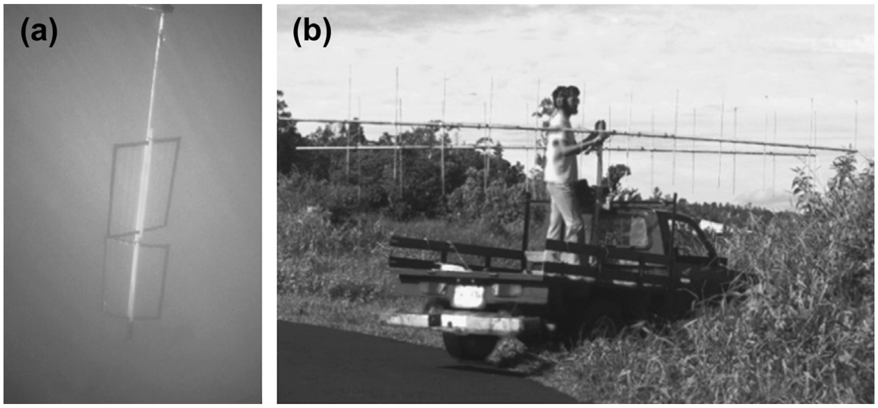
FIGURE 2.3 Drift pole drogue fitted with antenna. *(Source: In part from Lobel, 2011.)*

Retention was greatest during the June to September 1982 period, when the eddy field formed and remained resident. One drogue released on July 25, 1982, in the core area of the cyclonic eddy, circulated within the eddy as the eddy remained near the Kona coast from July 25 until September 13, 1982, at which time the eddy drifted away from the Island of Hawaii. Satellite infrared photographs and bathythermograph measurements of the eddy field confirmed these patterns of the eddy (see Lobel and Robinson, 1986, 1988). Information gathered from the track and motion of the drift pole drogues demonstrated the transport from the offshore eddy to very near the coastline coral reefs and provided valuable information on the role played by passive advection in larval fish recruitment patterns. Examination of drogue drift tracks provided additional evidence that oceanic zooplankton were being transported near-shore by the cyclonic eddy currents.

Despite the vital importance of closely monitoring the sea surface circulation in polar regions in terms of climate change studies, such measurements have been one of the most difficult tasks encountered by oceanographers. Over the years, application of the Lagrangian approach with the aid of drifting ice floes as tracers of water movement proved helpful in determining surface circulation in Arctic areas. Evaluation of transport of water, salt, and heat in polar oceans, as well as study of the response of sea ice to climate changes, all require an understanding of the movement of sea ice over long periods of time. The observational basis for our present understanding of sea ice motion has been accumulated over the past several decades by tracking icebergs marked by manned research stations or, more recently, by unmanned automatic satellite transmitting stations for long periods. The trajectories of these ice floes were then used to define a mean circulation pattern, which was often considered as the response of the ice packs to the long time-average circulation of the atmosphere and ocean. Motion of an ice island in the Arctic Ocean is said to have been tracked for more than 40 years. Knowledge of the position and movement of icebergs is needed daily for safe and efficient operation of drill rigs and oil tankers in the Arctic Ocean and the Greenland Sea. In situations in which data on sea ice movement over long periods were not available, observations of sea ice displacement over short periods of time were used to deduce some statistics of the ice motion over long periods of time.

With rapid advancements in technology, the concept of Lagrangian measurements took on new dimensions and underwent significant leaps. For example, pairs of pulse-radar transponders located at fixed reference points, a few km apart on the coast or on fixed platforms in the sea, have been employed to track radio buoys and thereby to determine surface currents (see Section 3.1.1). Application of the Doppler effect brought about a radical improvement in ocean current measurements. Incorporation of a drifter-borne Doppler transponder for surface current measurements from coastal waters, regardless of weather conditions (i.e., in fog, high winds, rough seas, and at night; see Section 3.1.2), is just one example. Combined use of polar-orbiting satellite technology and the Doppler effect gave birth to an advanced method of determining surface currents and their trajectories over long distances in the

FIGURE 2.4 (a) The underwater section of the drift pole drogue with antenna; (b) Tracking using a directional radio antenna. *(Source: Lobel, 2011.)*



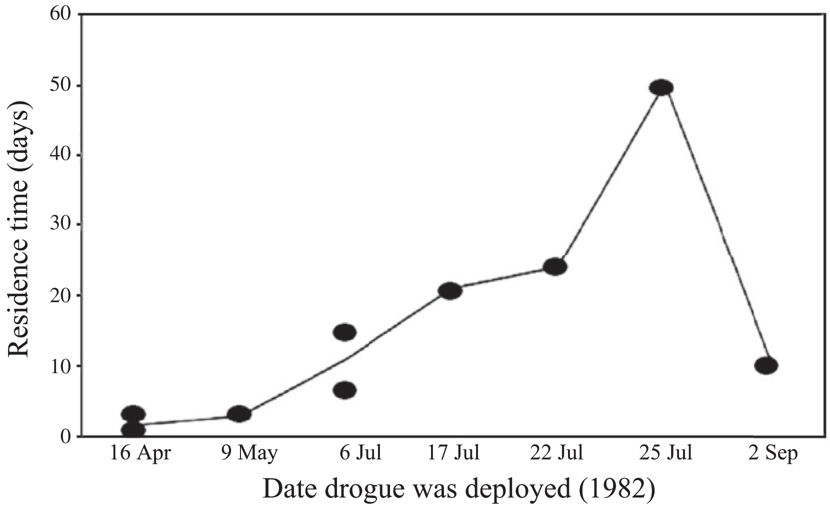


FIGURE 2.5 Residence time of drift pole drogues (i.e., the number of days that a drogue was tracked) along the Kona coast, Hawaii, in 1982, covering the times of summer eddies. *(Source: Lobel, 2011.)*

open ocean regions for long periods of time (see Section 3.1.3). There are several other examples where the Doppler effect is widely used for measurements of surface and subsurface oceanic currents, and discussions of these are spread over various chapters in this book. Nondifferential GPS, which was initially developed for military purposes and released in May 2000 for civilian application after removal of Selective Availability (SA), proved to be a valuable device for position-fixing applications for the purpose of sea surface/subsurface current measurements. Availability of small and low-cost standard GPS receivers with the capability to fix their position to an accuracy of within a few meters, and anywhere in the world, led to the development of GPS-tracked sea surface drifters for surface current measurements (see Section 3.1.4).

Introduction of such cost-effective Lagrangian drifters stimulated renewed interest in coastal sea surface current measurements, and these came as a great relief to oceanographers, ocean engineers, and environmentalists in tracking surf zone currents, for which a suitable device was hitherto unavailable. Advancements in cellular phone technology in the 1990s and the rapid spread of cellular towers almost all over the world began to exert considerable influence in the realm of sea surface current measurements from coastal and land-locked regions as well by way of availability of telephonically tracked drifters (see Section 3.1.5).

2.1.2. Imaging of Surface Water Motion Trajectories and Patterns

Imaging provides an important means of deriving a visually comprehensible picture of oceanic surface circulation trajectories and their shapes. Apart from academic interest, such images are vital for several operational applications such as oil slick monitoring and commercial applications such as fishing. Generation of such images involves photography and microwave imaging.

2.1.2.1. Aerial Photography

Aerial photography was one of the earliest methods used for identifying seawater motion in coastal water bodies. For example, Inman et al. (1971) obtained excellent aerial photographs of surf zone current patterns, clearly indicating the dangerous and evenly spaced jet-like rip current paths carrying material from the surf zone and producing vortex pairs. Aerial photography has also been successful in identifying strong tidal currents from straits and tidal vortex pairs generated in tidal channels (e.g., Yamoaka et al., 2002). Images such as aerial photographs are used in the identification and study of sea surface currents because the human brain is especially good at pattern recognition. Images of seawater motion signatures (e.g., tidal vortex, gyres) are constructed based on the characteristics of electromagnetic radiations that are reflected or scattered from or emitted by the sea surface.

Sea surface roughness and color contrasts are the two major types of signatures that are often utilized in the detection of sea surface current patterns with the aid of aerial photography in the visible and infrared bands of the electromagnetic spectrum. These contrasts provide visual indications of the surface manifestations of seawater motion. Sea surface roughness often changes from the combined effect of varying wind stress in the marine atmospheric boundary layer (induced by sea surface temperature front) and surface current convergence and divergence (induced by the meandering current). In particular, the changes in the stratification of the marine atmospheric boundary layer (MABL) and subsequent wind stress changes produce a step-like drop of the sea surface roughness at the downwind side of the front (Johannessen et al., 2005). The color signatures are usually those of chlorophyll, algae, and suspended-sediment plumes.

Whereas chlorophyll and algal blooms are often indicative of upwelling motions, the suspended sediment plumes often arise from river discharges into the bluer, clearer seawater. The plume of turbid brown water is easily detectable in the visible wavelength photographs. In the initial years of oceanographic studies, time-lapse aerial photography from overhead was employed for obtaining such images. Photographic cameras produce black-and-white or color images by a simple and relatively inexpensive process that, like the human eye, is limited in wavelength response. In the past, the most commonly used aerial photographic camera was the multiband camera, which contained four to nine lenses and carried many rolls of photographic film. Different films and filter combinations permitted simultaneous photography in different optical spectral regions.

Remote sensing of circulation features in coastal and estuarine regions is a valuable complement to *in situ* observations. In the study of fluid motion, flow visualization techniques have often been used to estimate intuitively the spatial dimensions of the flow field. In fact, visible wavelength photography was historically the first remote-sensing technique developed to study the ocean from above the sea surface. This is also one of the very few techniques that "sees" directly from the surface layers of the sea down to a depth of several meters. Visible wavelength photography is particularly useful in studies of various kinds of sea surface manifestations of seawater motion such as upwelling, intense tidal currents, vortices, and surf zone circulation cells. Such photographs provide an overview to help preliminary evaluation and interpretation of these dynamic processes, which occur in a given region, before any attempt is made at field studies incorporating *in situ* measurements. In some cases, shapes or patterns of seawater motion are equally, or sometimes more, important than their speed and direction values. A typical example is the surf zone circulation cells, the dimensions and locations of which are valuable to give warning to swimmers at a beach that is characterized by this dangerous circulation.

In the initial years of oceanographic studies, aerial time-lapse photography was used for imaging of sea surface circulation patterns employing two different concepts. One was the just-mentioned truly remote-sensing technique whereby the surface circulation pattern is detected and identified from the color or roughness contrasts of the sea surface. The other was a quasi-remote-sensing technique whereby the mean flow velocities at small scales were estimated from the travel times of surface drifters such as floats, drogues (i.e., weighted floats), and fluorescent dye patches. Travel times were determined from a series of time-lapse aerial photographs taken from overhead.

Because turbulent currents play an important role in mixing processes, it is essential to measure such currents. One method of mapping turbulent surface currents is aerial photography using fluorescent dye. The dye method has been used successfully by several investigators for flow visualization and measurement of current speeds in the surf zone. Richardson et al. (1972) and Flynn and Cook (1978) mapped sea surface currents by aerial photography of surface current markers, such as fluorescent dye, using aircraft outfitted with position-fixing equipments. Radioactive or dye tracers indicate surface current as well as turbulence. In this method, dye markers or phosphorescent tracers are dropped from an aircraft or a vessel at selected locations. Currents transport the dye/tracer patches while horizontal diffusion due to the turbulence spreads them. Current velocities and diffusion coefficients are determined, respectively, from the temporal changes in position and size of the dye/tracer patches between successive photographic flights over the measurement site.

For economy in such experiments, flights can be replaced by balloons. Calibration of the photographs can be carried out using simultaneous measurements of the dye concentration by a fluorometer. High contrasts in aerial photographs can be obtained by filtering the camera, either to the band of maximum light absorption of the dye or to the band of maximum fluorescence of the dye. For the first case, on a positive black-and-white print, the seawater would appear light in tone, whereas the dye patch would appear dark. For the second case, the dye patch would be light in tone, whereas the seawater would appear dark. The dyes usually used for these investigations are Rhodamine B (red color) and Rhodamine 5GDN (yellow-red color). One of the primary problems encountered in processing the photographs obtained from vertical photography is the direct sunlight reflection from the sea surface. To avoid this problem, aerial photographs are usually taken with an oblique camera mounting.

Several investigators have observed that during the early stages of diffusion of the dye, the patch shape is very close to a circle. At later stages, the patch becomes elongated. The elongation of the dye patches occurs in the direction of the current in the absence of wind. If the directions of the current and of the wind are different, the axis of the patch can be aligned with yet another direction. Depending on the state of the sea and the associated circulation features, striation, curvature, elongation, and stripe formation of the dye patches are common. As the sea becomes rough, the finely mottled tone changes to a coarsely mottled pattern. When the wind velocity exceeds 25 knots, streaks parallel to the direction of the wind begin to appear. The elongation of a dye patch can be influenced by horizontal and vertical velocity shears. If Langmuir circulation is predominant, the dye patches will converge into parallel stripes. For photographic studies of dye plumes, the aircraft is generally flown at altitudes of 500 to 5,000 feet above the sea surface.

Sea surface current measurements using dye-patch photography method has merits and limitations. An important advantage, over other methods of circulation studies, is that this method enables measurements of turbulent fluctuations in the flow velocity field. The growth, elongation, change of shape, and breakup of dye patches are related to the nature of turbulent surface currents. Measurement of turbulence in the upper layers of the oceans is important in understanding the mechanism of surface phenomena such as slicks, streaks, and foam lines as well as such other phenomena such as heat exchange between the atmosphere and the ocean, the flushing and disposal of polluted water, mixing of different water masses, and sedimentation.

The study of turbulence has been handicapped by the lack of suitable measuring devices. The float method was inadequate in obtaining information on detailed structures of small-scale eddies owing to difficulties in simultaneously tracking a large number of floats. In contrast, studies of dye patches in the ocean were found to be much simpler in practice and yet gave more detailed pictures of turbulence and small-scale eddies. Dye patch photography has been found to be an excellent technique for detection and quantification of rare circulation phenomena such as Langmuir cells and Ekman spirals. From an operational point of view, the dye method is routinely applied in studies related to pollution monitoring and control. In designing an outfall for discharge of waste, one has to select such an outfall length that harmful concentrations do not reach the coast. The prediction of concentration near the shore for different outfall lengths is often carried out by observing the spread of radioactive tracers or fluorescent dyes such as Rhodamine released at a chosen point in the proposed disposal area. The concentration of pollutants at the shore arising out of a continuous source is determined by superposition of results from different successive releases. The fluorescent dye Rhodamine is also traced by *in situ* measurements of fluorescent concentration with the aid of a fluorometer.

Although aerial photography of dye patches in the sea is a comparatively simple remote-sensing technique, the quality of the result depends on various environmental and flight-related factors. For example, when the sea is rough, suspended sand and silts in the coastal waters can make identification of a dye patch difficult. Shadows from scattered clouds cause uneven lighting on the sea surface, and this interferes with quantitative data processing. Whitecaps and spray generated from strong winds can also interfere with the effectiveness of photographic techniques. From a flight-related point of view, side winds and turbulence make it difficult to maintain straight flight lines. These factors may also cause the camera axis to deviate from the vertical. Camera axis tilt results in distortion and variations in scale across the photograph. To obtain better-quality aerial photographs, a variety of expensive equipment, such as gyro-stabilized camera mounts, auxiliary viewfinders, radar profile recorders, and inertial guidance systems, must be used. The feasibility of large-scale current measurements in the open ocean using aerial photography is often limited because the quantities of tracers required to "tag" open-ocean water masses would be impractically large. Furthermore, both advection and diffusion act three-dimensionally to spread the tracers; therefore, the results cannot be interpreted solely in terms of advection by currents (Pickard et al., 1982).

Aerial photography of floats for circulation studies has some advantages as well as some limitations. Whereas turbulent characteristics of turbid waters are difficult to investigate using conventional dye techniques, aerial photography of clusters of floating objects gives reliable information about turbulent dispersion. It is assumed that motions of a sufficiently large number of floats adequately represent the turbulent motions in the flow field. The float method, although simple in analyzing the results, may, however, be inadequate in obtaining information on the detailed structure of small-scale eddies, owing to the limited number of floats deployable in practice. In contrast, the release of dye in water is much simpler in practice and yet gives a more detailed picture of small-scale eddies in the ocean. Another disadvantage in the use of float clusters is that they cannot be used to assess vertical mixing and the vertical distribution of horizontal turbulent components because the positive buoyancy of the float does not allow its vertical motion. For these reasons, photography of dye patches is often employed, especially in clear water, in studies of turbulent motions.

Aerial photography has been used to distinguish water masses, delineate circulation patterns, identify upwelled waters along the coast, and trace thermal plumes in the ocean. Circulation patterns in the coastal regions have been obtained from photographs taken from aircraft that are usually used by the Coast Guard and the Air Force. Aerial photographs of the sea surface, taken from Earth-orbiting satellites and manned spacecraft, have also provided useful information. For example, color photographs taken by *Skylab* astronauts using handheld cameras revealed oceanic features such as algae blooms, which are often indicative of upwelling. Photographic surveillance has played a major role in pollution monitoring of estuaries and coastal waters.

High absorption of light energy in the infrared band by clear water makes infrared black-and-white photographs of clear water surfaces normally appear black. In contrast, muddy water shows up in lighter tones than clear water. This is because suspended sediments or algae in the muddy water have high reflectance in the infrared band. This property of muddy water is often used for the investigation of transport of suspended sediments in estuaries. Sediment patterns reveal residual transport, tidal streams, and small gyres (Robinson, 1985). It may be noted that sediment transport in a tidal flow takes place as a result of residual tidal flows. Data on sediment movements have potential applications in civil engineering studies related to harbor management.

Monitoring algae blooms with the aid of infrared photography helps in the detection of a special kind of circulation signature, known as *upwelling*. Furthermore, the property of high reflection in the infrared region by muddy waters might be applied in clearly delineating patches of floating plants in turbid waters. Because floating plants are excellent Lagrangian tracers of surface circulation in coastal waters and estuaries, infrared photography may be a promising remote-sensing tool for measuring surface circulation in these regions. Once a feature has been identified, the speed and direction of its movement over time may be studied from a sequence of photographs taken in the area.

The purpose of most infrared photography is that of mapping a pattern. The technique is especially useful for detection of circulation patterns involving some kind of signature that can be detected using infrared photography. An excellent example is the detection of chlorophyll in the ocean. The property of fluorescence of chlorophyll in the infrared region of the electromagnetic spectrum permits infrared photography of these patches. The importance of chlorophyll in the detection of certain circulation features (e.g., cold-core eddy; upwelling) is briefly mentioned in Chapter 5.

A great advantage of infrared photography over conventional photography is that atmospheric dust and vapor can be penetrated to a great distance by infrared rays. These rays also have the ability to penetrate in the dark. Infrared photography requires special films and lenses. Infrared-sensing lenses use materials such as magnesium fluoride and zinc sulfide. These lenses, however, generally suffer from the problems of chromatic aberration. Infrared lenses have special coatings designed for transmission of maximum infrared radiation. To avoid the problem of aberration, lens systems that use reflective surfaces only are sometimes used. Usually a combination of reflective and refractive components is used in infrared photographic work. These lenses do not suffer from chromatic aberration and do not absorb infrared radiation.

2.1.2.2. Radiometry

In the past, radiometers of varying resolution and spectral bands were used from various satellites. They are the scanning radiometer (SR), visible and thermal infrared radiometer (VTIR), visible and infrared radiometer (VIRR), visible and infrared spin-scan radiometer (VISSR), medium-resolution infrared radiometer (MRIR), high-resolution infrared radiometer (HRIR), very high-resolution radiometer (VHRR), and advanced very high-resolution radiometer (AVHRR). The SR was flown on the National Oceanic and Atmospheric Administration (NOAA) series of Improved TROS Operational Satellites (ITOS), which began in 1970. The SR was a dual-channel, line-scanning radiometer that measured radiation in the range 0.5−0.7 μm (visible band) and in the range 10.5−12.5 μm (thermal infrared band). The ground resolution of the data at nadir was about 4 km for the visible channel and 8 km for the thermal infrared channel.

On board Seasat-1, the VIRR was a scanner for collection of digital data in the visible and thermal infrared portions of the electromagnetic spectrum over broad swaths of the Earth's surface. Scanning was accomplished by means of a rotating mirror mounted at 45° to the optical axis of the collecting telescope. The mirror rotated continuously, creating a line scan perpendicular to the motion of the spacecraft. The motion of the spacecraft provided the second dimension of scan. A relay optical system transmitted the radiation to a dichroic beam splitter, which separated the visible and infrared wavelengths. The visible energy was then focused onto a silicon photodiode and the infrared onto a thermistor bolometer. On board the GOES satellite, the VISSR also provided visible and thermal infrared images of the sea surface. The VISSR data were transmitted from the satellite in digital form. The best ground resolution at nadir was 1 km for the visible channel and 8 km for the thermal channel data.

The VHRR, a second type of radiometer on the ITOS, was also a two-channel line-scanning radiometer. The VHRR was sensitive to energy in the 0.6−0.7 μm and 10.5−12.5 μm bands. The VHRR had many similarities to the SR. The VHRR, however, had substantially better ground resolution than the SR, about 1 km at nadir for both channels. The limited capacity of the VHRR's on-board tape recorder permitted a maximum of only 10 minutes of stored data per pass to be acquired when the spacecraft was remote from the two Command and Data Acquisition Stations. The AVHRR on board the NOAA satellite scanned at a rate of 360 swaths per minute with an effective ground resolution of 1.1 × 1.1 km at nadir (Smith et al., 1987). With the sensor cooled to 105°K, the AVHRR achieved sensor noise levels of around 0.05°K in the very short integration time of less than 25 μs of the scanning process (Robinson, 1985). See Section 5.2 for details.

The AVHRR images have been of great value in exploring the mighty western boundary currents (WBCs) such as the Gulf Stream and the Somalia currents and in detecting large-scale oceanic circulation features such as rings, thermal jets, and frontal currents. The WBC in the Bay of Bengal (Indian Ocean) and its unstable nature were first explored using AVHRR images (Legeckis, 1987). These images played an important role in monitoring drifting gyres associated with the Somalia current system and in studying their relationship to the Indian southwest monsoon.

2.1.2.3. Active Microwave Radar Imaging

It has been noted that sea surface roughness contrast is a good indicator of sea surface circulation patterns. Some of the merits and limitations of photography and radiometry were indicated in the preceding sections. An alternative microwave device that was born out of sheer necessity is synthetic aperture radar (SAR). This device was initially developed to aid Lunar missions but was subsequently released for terrestrial imaging. SAR has been successfully used for several oceanographic studies. For example, the surface signatures of meandering fronts and eddies have been regularly observed and documented in SAR images. Wave-current interactions, suppression of short wind waves by natural films, and the varying wind field resulting from atmospheric boundary layer changes across oceanic temperature fronts all contribute to the radar image manifestation of such mesoscale (order 100 kilometers) features.

A new radar imaging model developed by Johannessen et al. (2005) provides promising capabilities for advancing the quantitative interpretation of oceanic water motion features manifested in SAR images. An example of such a SAR image expression of a 10-km-in-diameter cyclonic eddy in the Norwegian Coastal Current that generally depicts the eddy boundary has been reported by them. Due to the convergence, the passive surface-floating material accumulates to delineate the eddies. In addition, the enhanced wave breaking of intermediate waves in the vicinity of the zones of surface current convergence is the dominant source for the radar cross-section modulation and subsequent SAR image manifestation. Studies by Johannessen et al. (2005) emphasize the crucial role of current convergence and divergence that occur along meandering fronts and eddies as well as the wind direction versus the SAR look direction. In the case of convergence, the sea surface roughness modulation comes from the direct and indirect effects of the breaking of intermediate scale waves that takes place within the converging zone due to wave current interaction. This, in turn, produces the sharp delta-like intensity changes in the radar cross-section.

Topographic maps have a long history, and the advent of stereo aerial photography in the first part of the 20th century made possible photogrammetric measurements of surface elevations over substantial areas; many regions have been mapped at various scales by these means. Stereo images or photographs taken by satellites are also used to construct topographic maps. Such topographic maps have the ability to reveal sea surface roughness contrasts and, therefore, sea surface circulation signatures. A major problem for optical imagery in tropical areas is cloud cover that prevents imaging of the ground surface from space. The Interferometric Synthetic Aperture Radar (InSAR) technique has emerged as the state-of-the-art technique of measuring dense points in an area accurately, economically, conveniently, efficiently, and without any effect from cloud cover (Gabriel et al., 1989; Massonnet et al., 1993). Studies have demonstrated the potential of the interferometric technique to produce high-resolution topographic maps, as found by Zebker (1994) in tests with three-day repeat-pass ERS-1 imagery.

The use of space-borne SARs as interferometers became popular only recently, although the basic principle dates back to the early 1970s (Graham, 1974; Richman 1971). Today it is generally appreciated that SAR interferometry is an extremely powerful tool for mapping the sea surface topography. The so-called differential InSAR method (D-InSAR) represents a unique method for detection and mapping surface displacements over large temporal and spatial scales with precision in the centimeter and even millimeter range.

Since the early 1990s, InSAR has developed from theoretical concept to a technique that is being utilized at an increasing rate for a wide range of Earth science fields. Despite the fact that none of the currently deployed imaging radar satellite platforms was designed with interferometric applications, the high quality and vast quantity of exciting results obtained from the InSAR technique have demonstrated their potential as powerful ground deformation measurement tools (for millimeter-scale ground deformation characterization). Their capability has been further considerably improved by using large stacks of SAR images acquired over the same area (multi-image InSAR technique) instead of the classical two images used in the standard configurations (Ferretti et al., 1999, 2000, 2001). With these advances the InSAR techniques are becoming more and more quantitative geodetic tools for deformation monitoring rather than simple qualitative tools.

In judging the progress made so far in SAR interferometry, it should be kept in mind that neither of today's space-borne SARs have been designed explicitly for interferometry. The first Earth observation satellite to provide SAR data suitable for interferometry was the Seafaring Satellite (SEASAT). Launched in 1978, it was operated for 100 days, whereas SAR data collection was limited to a period of 70 days. The real breakthrough in SAR interferometry was achieved through the European ERS-1 satellite and its follow-on, ERS-2. The ERS-1 mission was officially terminated in 1996. The ERS-2 SAR, identical to the ERS-1, was launched in 1995 and has the same orbit parameters as ERS-1. It continues the ERS-program with the 35-day repeat period. Most important, from the SAR interferometry point of view, was the TANDEM mission (Duchossois and Martin, 1995), during which ERS-1 and ERS-2 were operated in parallel. ERS-2 followed ERS-1 on the same orbit at a 35-min delay. Together with the Earth's rotation, this orbit scenario assured that ERS-1 and ERS-2 imaged the same areas at the same look angle at a one-day time lag. The orbits were deliberately tuned slightly out of phase such that a baseline of some 100 m allowed for cross-track interferometry. This virtual baseline between ERS-1 and ERS-2 could be kept very stable because the two satellites were affected by similar disturbing forces. The first of several TANDEM missions was executed in May 1996. The instrument was designed for oceanographic imaging and, hence, uses a very steep incidence angle of only 23°. (See Section 5.4 for details.)

2.1.3. Vector Mapping Based on Current-Driven Sea Surface Wave Transport

Imagery basically provides patterns. Although sea surface current patterns have great value in themselves, time-series images are needed to yield quantitative estimates of sea surface currents. Thus, oceanographers were badly in need of some devices that would provide time-series quantitative information directly on sea surface currents. An exciting discovery by D. D. Crombie in the early 1950s ultimately paved the way for remotely acquiring high-resolution, real-time time-series vector maps of sea surface current fields over large areas by processing the backscatter returns from the sea surface. The device used for this purpose is a Doppler radar system, which operates in the high-frequency/very high-frequency (HF/VHF) band of the electromagnetic spectrum. The functioning of HF/VHF Doppler radar systems is based on the principle of the Doppler shift of the backscattered electromagnetic radiation, caused by Bragg-scattering sea surface waves that are transported by the underlying water currents (details given in Chapter 4). In this method, radio-wave propagation is mainly accomplished by ground-wave propagation scheme. Looking at the usefulness of these systems, these devices can be legitimately termed as enduring resources for generations of oceanographic researchers to come.

Although the landmark discovery of the concept embodied in the application of the backscattered Doppler radar signal from the ocean surface for remote mapping of sea surface currents and waves was published by Crombie in 1955, his *Nature* publication (Crombie, 1955) did not elicit citation by the oceanographic researchers of his time. It is surprising that Crombie's pioneering discovery remained in the dark until the theoretical investigations on the retrieval of wave information from HF radar backscatter were reported by Hasselmann in 1971 (see Hasselmann, 1971) and Crombie himself reported the practical application of his discovery to physical oceanography at the IEEE Oceans '72 Conference (see Crombie, 1972) after a long gap of approximately 17 years, based on his "self-cited" publication!

With the reporting of the practical value of Crombie's discovery, his *Nature* publication and his conference paper began to attract considerable attention in the oceanographic community. The realization that HF Doppler radar estimates, derived based on Crombie's "Bragg scattering" principle, are capable of providing quasi-real-time information about several oceanographic parameters such as sea surface currents, sea states, and wind direction led to vigorous research and developmental activities in subsequent years. For example, Barrick and co-researchers at NOAA in the United States developed the coastal ocean dynamics applications radar (CODAR) system, which proved to be the first commercial application for remotely mapping the sea surface current fields. Since then the technology of HF Doppler radar systems has become a rapidly expanding field. Decades of technological developments have resulted in a variety of HF Doppler radar systems capable of producing current vector maps of the coastal zone over spatial scales ranging from hundreds of meters to about 200 kilometers and on time intervals from tens of minutes to days. Within a relatively short interval, the technology emerged as a viable commercial product, and radar systems of different constructions to suit installation at different coastal locations (Figure 2.6) became available. Based on the same basic technology as that used in CODAR, other systems have been developed, such as the SeaSonde, which employs broad-beam antennas and direction finding to produce maps of radial current velocity vectors. Each vector produced is the average over a radial cell, the area of which is primarily determined by the carrier frequency of the radar systems. Figure 2.7 shows a Long-Range SeaSonde surface current vector map spanning 200 km offshore, overlain on SeaWIFS imagery, capturing the complex Kuroshio Current as it meanders off the coast of Japan.

The ocean surface current radar (OSCR) developed in the United Kingdom (Prandle et al., 1993) was another milestone in the rapid expansion of the HF/VHF Doppler radar technology. The University of Hamburg, Germany, started its work on HF radars in 1980 by modifying the CODAR technology (Gurgel et al., 1986). By 1985, both hardware and software had been modified to reduce internal noise, increase sensitivity, and optimize processing algorithms, and they brought out a new system called Wellen radar (WERA) (Gurgel et al., 1999). At present, these commercial products adorn a prime position in coastal observing systems in many parts of the world. Independent of CODAR systems, other developments have been made, such as coastal ocean surface radar (COSRAD) at James Cook University in Australia (Heron et al., 1985), VHF Courants de Surface MEsures par Radar (COSMER) at the University of Toulon in France (Broche et al., 1987), PISCES at the University of Birmingham, United Kingdom (Shearman and Moorhead, 1988), high-frequency surface wave radar (HF-SWR) at C-CORE and Northern Radar Systems in Canada (Hickey et al., 1995), high-frequency ocean surface radar (HFOSR) at Okinawa Radio Observatory/Communications Research

FIGURE 2.6 HF Doppler radar systems of different constructions to suit installations at different coastal and offshore locations. *(Source: CODAR Ocean Sensors brochure, May 2003, Volume 7, Number 4; and CODAR CURRENTS newsletter, Spring/Summer 2011.)*

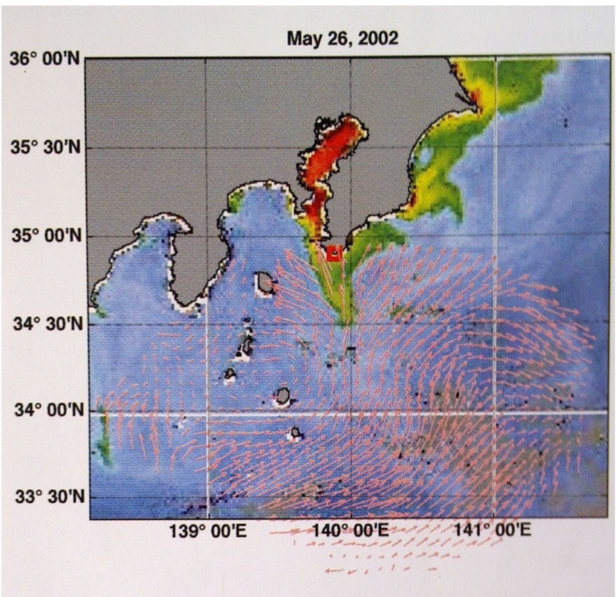


FIGURE 2.7 Long-range SeaSonde surface current vector map spanning 200 km offshore, overlain on SeaWIFS imagery, capturing the complex Kuroshio Current as it meanders off the coast of Japan. *(Source: Hydro International; CODAR Ocean Sensors, May 2003, Vol. 7, Number 4; SeaSonde data courtesy of Tomotaka Ito, Japan Coast Guard; SeaWIFS image courtesy of Dr. Robert Arnone, Naval Research Laboratory.)*

Laboratory (ORO/CRL) in Japan (Takeoka et al., 1995), multifrequency coastal radar (MCR) at the University of Michigan at Ann Arbor (Teague et al., 2001), Ocean States Measuring and Analyzing Radar (OSMAR2000) at the Wuhan University in China (Huang et al., 2002), and PortMap at James Cook University in Australia (Heron et al., 2005).

The concept of HF/VHF Doppler radar-based measurements received considerable attention in coastal oceanographic measurements to extract ocean surface parameters such as surface currents, waves, and winds. The reason for the considerable importance attached to this technology stems primarily from its ability to map coastal ocean surface currents in real time over relatively large areas (covering a radial distance of ~200 km from the radar) with high temporal and spatial resolution, which offers the possibility to track a variety of oceanographic phenomena (e.g., tidal vortex, gyres). HF/VHF Doppler radar systems do not provide a global coverage like that obtainable from the well-known satellite-based systems; however, they have the advantage of providing continuous observations in limited areas with high spatial resolution (a few kilometers down to a few hundred meters) and with high temporal resolution (30 min down to 10 min) in contrast with a repeat cycle of several days for the satellite systems (Cochin et al., 2006). Consequently, HF/VHF Doppler radar systems have now become an important technology for studying coastal circulation processes. Good spatial and temporal resolution make the HF/VHF Doppler radar technology particularly suitable for aiding search-and-rescue operations, studying pollutant and larval dispersal (e.g., Bjorkstedt and Roughgarden, 1997; Graber and Limouzy-Paris, 1997), and analyzing the physical forcing of coastal flows (e.g., Shay et al., 1998).

The applicability of HF/VHF Doppler radar systems for detecting the arrival of tsunami-induced amplified currents from as far away as the continental edge and subsequent monitoring of tsunami propagation over the continental shelf and toward the coast is expected to be a landmark achievement in the technology of tsunami early warning in the coming years. This ability comes from the fact that in case of an open-ocean tsunami entering the shelf edge and heading toward a coast, the strong ocean currents generated as a result of the considerable decrease in water depth of the continental shelf can be observed by the HF/VHF Doppler radar systems. Such systems, programmed to make measurements at fine temporal resolution, could therefore contribute immensely to the development and improvement of tsunami early warning systems.

HF/VHF Doppler radar systems are primarily operated from the seacoast (of course, there are instances in which a few deployments have been made from offshore platforms and buoys), and therefore the sea surface current maps derived from them are generally limited to the coast (extending up to a maximum distance of ~200 km from the coast). There was a clear need for a device that would provide quantitative estimates of sea surface currents from offshore and polar regions. Satellite altimetry paved the way for such measurements (see Chapter 12 for details).

2.2. SUBSURFACE AND ABYSSAL CURRENT MEASUREMENTS

In ancient times, the oceans were ruled exclusively by fishing folk and mariners. They considered the oceans vast ponds of blue water that is turbulent at the surface and stagnant in the deeps. However, purely accidental observations by the early mariners brought to light the folly of previous notions about the stagnancy of the deep oceans.

2.2.1. Early Mariners' Contributions

Ancient mariners began to realize the existence of subsurface and abyssal currents in the ocean through rare incidents during their seafaring careers. For example, Maury (1855) mentions a shipwreck incident that took place in the year 1712, which a Dr. Hudson communicated to the Philosophical Society in 1724. This wreck pertains to a Dutch ship, with her cargo of brandy and oil, which sunk in the deep water at Ceuta Point, Spain. Surprisingly, the sunken ship arose on the shore near Tangier directly *against* the strength of the *surface current* in that region. This incident clearly demonstrated the existence of a strong *undercurrent* in the same region, in the opposite direction of the surface current, which dragged the sunken ship to the shore.

Maury (1855) mentions another incident on the discovery of oceanic subsurface currents. According to this story, an able seaman who was navigating in the midstream of the Baltic Sound from one of the king's frigates observed that the boat was carried violently by the surface current. He sunk a bucket with a heavy cannonball to a certain depth of water to give a check to the boat's violent motion. Surprisingly, sinking the weighted bucket still lower and lower, the boat was driven ahead to the windward *against* the upper current. The lower the bucket was let fall, he found the undercurrent was the stronger.

Further evidence for the presence of oceanic subsurface currents emerged when Lieutenant J. C. Walsh and Lieutenant S. P. Lee of the United States were carrying out a system of observations in connection with the *Wind and Current Charts*. They made some interesting experiments on the subject of submarine currents. In their experiments, a block of wood was loaded to sinking and, by means of a fishing line, they let the weighted wood down first to the depth of 600 feet and then to 3,000 feet. A small float, just sufficient to keep the block from sinking deeper, was then tied to the fishing line, and the combination was let down from the boat. It was wonderful indeed to see the subsurface float moving off *against the surface currents*. For the men in the boat, it really appeared as if some monster of the deep had hold of the weight below and was walking off with it, although what they witnessed was an interesting manifestation of an under-current.

Much light had been thrown on the subject of subsurface currents by the ancient mariners, based on several of their experiments in deep-sea depth measurements. It may be noted that in the early eras of navigation, ancient navigators conducted water depth measurements using a plummet fastened at the end of a roll of twine. They reckoned that there was reason to believe that undercurrents existed in almost all parts of the deep sea because during deep-sea depth measurement operations, the plummet line never ceased to run out, even after the plummet had reached the bottom. Lieutenant J. P. Parker's deep-sea depth measurement experiments off the coast of South America in 1852 also provided reliable indications that the plummet line was swept out by the force of one or more undercurrents; but their directions remained unknown. The navigators also discovered the existence of an undercurrent in the Arctic Ocean; they noticed immense icebergs drifting rapidly against a strong surface current. These icebergs protruded above the sea surface, and their depth below was approximately seven times greater than their height above the sea surface.

2.2.2. Spatially Integrated Measurements Based on Earth's Magnetism and Oceanic Sound Speed

A class of oceanic subsurface current measurements that have been found to be of immense practical value is spatially integrated measurements. Such measurements became particularly useful for investigating the transport of water through channels, straits, and ocean basins.

2.2.2.1. Electromagnetic Method

Although the earliest sign of the existence of subsurface currents in the ocean was communicated to the world as far back as 1724, an attempt to measure such currents started in 1832 with von Arx's measurement of water-flow-induced electric current flowing over a short range (see von Arx, 1950). However, little was accomplished until 1918, when F. B. Young and his associates used both moored and drifting electrodes to measure electric currents generated by tidal motions.

The duplication of Young's experiments in the autumn of 1946 led to the development of the geomagnetic electrokinetograph, or GEK. The electromagnetic principle on which the GEK operates is the following: Because every point on the Earth's surface that is located away from the equator is permeated by a vertical component of the geomagnetic field, moving seawater mass generates a velocity-dependent potential gradient on a pair of electrodes inserted into the ocean, obeying Faraday's principle of electromagnetic induction (EMI). Note that seawater, being a solution of electrolytes, is a good electrical conductor. Although the theory is attractive in principle, there were several hurdles to be surmounted before the theory could be successfully applied for water current measurements in the ocean. The hurdles encountered were the following: Because the potential gradient developed across the pair of electrodes is of the microvolt order, a necessary requirement for the application of the electromagnetic method is the use of stable electrodes so that electrochemical effects do not complicate the measurements. The biggest problem in measuring electromagnetic potentials in the ocean by means of metallic electrodes arose from the fact that, unlike metals that conduct electricity by means of free electrons, seawater is an electrolyte solution that conducts by means of "assorted" ions (i.e., both positive and negative ions). Any metallic electrode inserted into the ocean as a probe can only function with the occurrence of "electrode reactions" involving both ions and electrons. Such electrode reactions are sensitive to the ambient temperature, pressure, ionic concentration (i.e., salinity), and contamination (i.e., oxygen tension). In effect, changing environmental conditions would give rise to changing electrode potentials, thereby resulting in "base-line drifts" and possibly irregular potentials that vary with changes in the chemical environment of the seawater surrounding the electrodes. A sensor based on the EMI principle was investigated by Michael Faraday as early as 1832. However, due to several practical difficulties just mentioned and the resulting unsteady response of the copper electrodes with which Faraday experimented, he could not succeed in applying his ideas to accurately measure oceanic water currents.

As a result of untiring experimentation by several researchers, it was found that electrode noise can be reduced by the use of Ag-AgCl electrodes that are reasonably reversible to chloride ions in seawater. The Ag-AgCl electrode, which is a thin layer of silver chloride electrochemically deposited on the silver electrode surface, can also pass on electric current without changing the chemical environment in the vicinity of the electrode and provides high porosity to the electrode surface (Offner, 1967). With the use of suitable electrodes, Faraday's EMI principle was successfully applied by von Arx in the development of a practical device that he named the geomagnetic electrokinetograph (GEK) for measuring motionally induced potentials in the ocean.

In the GEK method, the seawater is the conductor, and when it flows horizontally across the vertical component of the lines of force of the Earth's magnetic field, a potential gradient given by $E = (\bar{V} \times \bar{B})L$ is generated across a pair of electrodes. In this, $\bar{V}$ is the horizontal component of the water current flowing perpendicular to the line joining the electrodes, L is the electrode separation, and $\bar{B}$ is the vertical component of the Earth's magnetic field. When the GEK method is utilized for seawater current measurements, the electrodes are placed on either side of the current flow path. Through measurements of the potential differences on two courses at right angles, the velocity components in these two directions are determined, and the vector sum or resultant of these velocities is the surface water current vector for that locality.

An advantage of the GEK method is that it permits measurements of comparatively large-scale water currents across straits, rivers, and channels where logistics of deploying and operating moored current meter arrays may be difficult. The GEK method has successfully been used for measurements of the Florida Current as well as tidal currents in the English Channel (Gonsalves et al., 1981). In practice, the silver-silver chloride electrodes are spaced about 100 meters apart and are streamed astern, away from the magnetic and electrical influences of the ship. The shipboard end of the cable is connected to an industrial-grade recording potentiometer.

A practical consideration in the application of the GEK method for seawater current measurements is the small magnitude of the Earth's magnetic field, together with ambient electrical noise present in nature. These hurdles limit the applicability of the GEK method to situations where electrode separations of tens of meters or more are feasible. Furthermore, because this method relies on Earth's magnetic field, the electrodes tend to be sensitive to magnetic storms as well as the electrical fields produced by passing ships. Such effects have been reported by Mangelsdorf (1961). Sensitivity to interference due to ships limits the application of the GEK method for water current measurements to areas away from harbors.

For shore stations, the GEK may be adopted for use in channel, pass, or open arms of any estuary where turbulence is slight and where upwelling and sinking are negligible. Because the electrodes may be mounted on each side of the channel and connected by a cable, the horizontal velocity of the water passing through the channel (i.e., between the electrodes) may be measured. Because it is awkward to reverse the electrodes to calibrate the instrument when making measurements at a fixed station, it is necessary to consider the measurements of electrical potential recorded during times of zero tidal flow. This is computed using the measurements made during slack water. This comparison is then used to determine the cross-sectionally averaged water current flow through the channel.

The use of the GEK instrument is limited to areas located beyond 20° latitude from the Earth's magnetic equator because the vertical component of the Earth's magnetic field is involved in the computation of water current flow based on the measured electric potential difference across the pair of electrodes. In addition, highly industrialized areas are to be avoided for installation of the GEK instrument because stray grounds and intermittently operating electrical machinery may mask the signals from natural sources.

2.2.2.2. Acoustic Tomography

Ever since humans realized that the oceans exhibit mesoscale (order 100 kilometers) water current circulation features such as cold-core/warm-core gyre systems, just as the atmosphere exhibits storms and tornados, a great deal of effort has been expended in inventing some means to track and measure such large-scale ocean circulation features. Ocean acoustic tomography (OAT) has been identified as a probable vital tool for such measurements. Beginning in 1975, Walter Munk and Carl Wunsch of the Massachusetts Institute of Technology (MIT) pioneered the development of acoustic tomography of the ocean (see Munk and Wunsch, l979). With Peter Worcester, Munk developed the use of sound propagation, particularly sound arrival patterns and travel times, to infer important information about the ocean's large-scale temperature and current. Since the concept of acoustic tomography for mapping ocean mesoscale variability was first articulated by Munk and Wunsch in l979, there has been a continually growing research program aimed at understanding the capabilities and limits of acoustic tomographic techniques in the ocean and an evolving technology program to develop instruments for tomographic measurements. A significant aspect of the development of OAT has been to exploit the integrating features of acoustic measurements (see Chapter 7 for details). Acoustic transmissions inherently average observations and as such they constitute a unique ocean measurement. There is no comparable way to extract integral or large-area average information about fields of fundamental importance to large-scale ocean physics such as temperature, heat flux, horizontal velocity, vorticity, and open-ocean upwelling.

Ocean tomography, as conceived by Munk and Wunsch and as currently practiced, consists of measuring the travel time of acoustic signals transmitted between multiple points. Usually appropriate source-receiver geometry can be found that produces multipaths with good vertical distribution. Upon reception, the multipaths are distinguished by their unique arrival times and angles, thus identifying them with the path they traversed. Acoustic travel time data provide an indication of the average sound speed in the water body bounded between the source and receiver along the acoustic ray. Inversion of acoustic travel time data reveals the intervening sound speed structure, which in turn provides water temperature structure, thus shedding light on mesoscale ocean current circulation features such as cold-core/warm-core gyre systems.

One of the major early accomplishments of the tomography program was to settle some ocean acoustic issues regarding the stability of multipaths. A 1978 experiment in which pulse-like signals were transmitted over a 900-kilometer distance in the Atlantic, south of Bermuda, for a 48-day period showed a stable arrival structure. Furthermore, most of the arrivals corresponded almost exactly to those predicted by ray theory. Munk's investigations, together with the work of Spiesberger and Metzger (1991), eventually motivated the 1991 Heard Island Feasibility Test (HIFT) to determine whether man-made acoustic signals could be transmitted over antipodal (point on the Earth's surface that is diametrically opposite to another point) distances to measure the ocean's climate (water circulation and temperature). The experiment, perhaps the most ambitious program at least in terms of spatial scales and designed to see if it would be possible to measure changes in acoustic travel times over paths as long as 16,000 kilometers to estimate the magnitude of global ocean warming or cooling, came to be called "the sound heard around the world."

During the six days of the Heard Island Experiment in January 1991, acoustic signals were transmitted by sound sources lowered from the M/V Cory Chouest near Heard Island, an uninhabited island in the southern Indian Ocean located approximately 1,630 km north of Antarctica. These signals traveled halfway around the globe to be received on the east and west coasts of the United States as well as at many other stations around the world (Munk and Baggeroer, 1994). This idea of using acoustic signals as the basis for an ocean thermometer arose early in the tomography program. Unfortunately, the follow-up 1996–2006 Acoustic Thermometry of Ocean Climate (ATOC) project in the North Pacific Ocean (ATOC Consortium, 1998; Dushaw, et al., 2009) engendered considerable public controversy concerning the effects of manmade sounds on marine mammals.

Several demonstrations of mesoscale tomography followed the 1978 propagation experiment. An early, rather crude demonstration using limited bandwidth acoustic transmitters was conducted south of Bermuda in 1981. Acoustic transmissions were in one direction only, thus allowing inversion for the sound-speed field but not the absolute water current field. Maps of the changes in the sound-speed field were produced both by initializing the inversion with sound speed data acquired by conductivity-temperature-depth (CTD) casts and by using only a single historic sound-speed profile. Two experiments in 1983, one by the University of Miami in the Straits of Florida and the other by Woods Hole and Scripps institutes of oceanography, respectively, showed that subsurface ocean currents could be measured on 20- to 50-kilometer scales and 300-kilometer scales. A long-range, reciprocal transmission experiment—that is, simultaneous transmissions between two spatially distant sites in the ocean—conducted north of Hawaii in 1987 also demonstrated that differential travel times computed from reciprocal acoustic transmissions can be inverted to obtain ocean currents. In these experiments, three moored tomography instruments formed a triangle roughly 1,000 kilometers on each side. Tidal currents computed from acoustic transmissions agreed well with values derived from a numerical model and from current meter data.

Data storage, which was a limiting factor in early receivers, was subsequently handled by high-capacity, small hard disks. Mooring with satellite telemetry links was developed by Woods Hole Oceanographic Institution to provide near-real-time tomography data transmission to shore. For shorter-range experiments in the open ocean, single hydrophone instruments that transmit less intense signals at higher frequency (centered at 400 Hz) became available commercially.

For ocean tomography, the 1990s were a decade of learning and development. The primary focus had been on demonstrating that ocean acoustic tomography really works, that it can be used to map the mesoscale sound-speed and water current fields with the desired accuracy and precision, and that it is an efficient measurement tool. Moreover, it has been shown that acoustic transmissions can be used for integrating measurements. A great deal of effort has gone into technology development, refinement of techniques, and exploration of experimental limits. A steady progression of field experiments validated most of the assumptions that are basic to the method, and a rapidly advancing technology development program provided the necessary instrumentation. Inversion models and methods resulted in efficient techniques for extracting maximum resolution sound-speed maps and current fields.

Open ocean acoustic tomographic programs have been conducted at a variety of institutions, starting with MIT, Scripps Institute of Oceanography, the University of Michigan, and Woods Hole Oceanographic Institution. These organizations have been joined by others, including the University of Miami, the University of California at Santa Cruz, the University of Washington, the Naval Research Laboratory, the Naval Postgraduate School, NOAA laboratories, IFREMER in France, JAMSTEC in Japan, the University of Kiel in Germany, and several other agencies.

Reciprocal transmissions permit measurement of water currents. Measuring ocean current with the aid of reciprocal acoustic transmissions relies on the principle that the *difference* in travel time between signals propagating in opposite directions is proportional to the average along-track component of water current velocity. The spatial distribution of transmitter-receiver pairs (transceivers) in the X-Y plane determines the horizontal resolution. Resolution in the vertical (i.e., the Z-axis) arises naturally as a consequence of the ocean's vertical sound-speed profile, which causes multipath propagation. Longer-range tomographic transmissions have hinted at the possibility of measuring ocean basin-scale variability.

Technology had been the primary factor limiting the application of ocean acoustic tomography. First, a tomographic system requires devices capable of emitting and receiving acoustic pulses that are narrow enough to resolve separate multipath arrivals; second, they must be sufficiently above the background noise for precise arrival time estimation; third, acoustic pulses must be transmitted and received with coordinated time bases. Furthermore, unless the instruments are fixed rigidly in place, provision must be made to account for travel time changes that result from instrument motion, so as not to confuse them with changes due to variations in the ocean sound-speed field. Ideally, there should be means for telemetering arrival time data to shore for inversion. In practical terms, these requirements translate into pulses of several milliseconds' duration, timed to within about 1 millisecond/year, at the requisite sound pressure levels. Instrument motion must be monitored to within about 1 meter. A major part of tomography programs has been to develop equipment that meets these specifications.

Technology development resulted in low-frequency, wideband transmitting and receiving devices having the required millisecond timing accuracy; the development of new navigation techniques for precise positioning at sea; and the development of wide time-bandwidth signal-processing schemes for fixed and moving tomographic sensors. Intense research in the field of inverse theory resulted in development of techniques for extracting maximum resolution sound-speed maps from tomographic data. Acoustic tomography experiments in the Atlantic and Pacific oceans and the Greenland Sea demonstrated the capability of acoustic tomography methods to map mesoscale sound-speed variability and to measure ocean currents. Thus, OAT proved to be a powerful tool to measure mesoscale phenomena in the ocean. OAT has special advantages for capturing snapshots of oceanic sound speed and current velocity fields by measuring the travel time of sound (Munk and Wunsch, 1979; Munk et al., 1995).

The initial decades of OAT experiments were largely confined to the open seas. However, OAT grew at a rather fast pace from its early infant stages to adulthood—so much so that the technique, with appropriate improvements, began to be used for water current measurements from straits, inland seas, and rivers. Probably the first reported tomographic experiment in a strait was carried out by Elisseeff et al. (1999) in the Haro Strait. They assimilated the acoustic tomography data and point measurements from their field experiments in the Haro Strait into an ocean model.

Most of the semi-enclosed coastal seas facing industrial areas and urban regions are damaged by various environmental problems such as water pollution and red tides. Environmental management and protection require monitoring of water and material circulation inside the semi-enclosed coastal sea and water exchange to the offshore sea. However, the well-designed measurement of water circulation that covers the entire region of the coastal sea is quite difficult to perform in the coastal sea because of strong fishing activity and heavy shipping traffic. Coastal acoustic tomography (CAT) has thus been proposed as an innovative oceanographic technology that can yield snapshots of coastal sea circulation and relax the observational limitations of conventional methods (Zheng et al., 1998; Park and Kaneko, 2000; Yamaoka et al., 2002; Yamaguchi et al., 2005; Kaneko et al., 2005; Lin et al., 2005). It should be noted that the technology and science of deep-sea acoustic tomography, initiated from the United States, are accumulated in the CAT (Munk et al., 1995).

Taking cues from the results of OAT studies in the open oceans and straits, the application of this technology began slowly expanding to the arena of the coastal water bodies as well. Application of OAT techniques to the coastal seas has been found to be a very attractive theme. Japanese researchers have made excellent progress in the development of CAT techniques. The Hiroshima University acoustic tomography group's continued efforts since the 1990s has resulted in considerable progress in CAT technology for remote measurement of coastal current velocity fields (Zheng et al., 1997, 1998; Park and Kaneko, 2000, 2001; Yamaoka et al., 2002).

A small number of experiments were carried out in the coastal seas in the 1990s for remote measurements of temperature (Chiu et al., 1994) and current field (Zheng et al., 1997, 1998). During these two experiments, which were performed using a pair of acoustic stations, attention was focused on the vertical distribution of temperature and current. Subsequently, for estimation of horizontal distribution, a tomography experiment was carried out using four moored acoustic stations (Elisseeff et al., 1999). This experiment was aimed at estimating the horizontal structure of current and temperature, not by tomography data alone but by their assimilation into an ocean model. However, for quite some time there have been no attempts to perform the coastal tomography experiment where the observation domain was surrounded by multiple acoustic stations.

There were several reasons for focusing attention on CAT research. For example, monitoring water current fields in the coastal seas can produce basic information to help predict disasters caused by oil spill, red tide, water pollution, and so on. Although point measurements of water currents with the aid of Eulerian current meters and vertical profile measurements using acoustic Doppler current profilers (ADPs) possess the ability to measure flow fields from coastal water bodies, horizontally integrated measurements require the deployment of a sufficiently large number of such devices distributed inside the observation region. Apart from the financial burden imposed by the deployment of a large network of current measuring devices, such deployments are sometimes inhibited by heavy ship traffic and fishing activities. Furthermore, current meters deployed inside the observation region are difficult to moor or fix on the bottom under strong tidal currents. In principle, difficulties in monitoring the structure of coastal currents may be drastically resolved by the judicious application of CAT technology in which velocity fields are measured by multiple acoustic stations arrayed in the periphery of the observation region, away from navigation channels and regions of vigorous fishing activities.

Whereas mapping of coastal surface currents can be performed by HF Doppler radar systems, as indicated earlier, the acoustic tomography measures depth-averaged currents with future extension to the vertical profile measurement of currents. There are regions where logistic constraints prevent deployments of HF Doppler radar systems. For example, in the Seto-Inland Sea region in Japan, because of the development of residential and industrial areas it is often difficult to find sufficient shore space for locating the array of antennae needed by some of the HF Doppler radar systems. (Note that CODAR is a comparatively compact HF Doppler radar system devoid of arrays.) In contrast, CAT, operated by multiple sets of compact mooring stations and placed near the shore, can be a practically feasible system with more flexibility and potential ability than HF Doppler radar. In the Neko-Seto

Channel, the mooring observation has been strictly prohibited by the Japan Maritime Safety Agency, except for the near-shore region, because of the risk of shipping accidents.

Practical applications of CAT technology proved to be numerous. For example, the rapid processes of growth, transition, and decay of the tidal vortices were first measured using this technology (see Yamoaka, et al., 2002). It is hoped that, in the near future, the tomography system may make further progress with new instrumentation to measure the temporal and spatial variability of flow patterns to aid navigational safety in coastal water bodies and to understand phenomena such as strong tidal mixing and dissipation in logistically difficult coastal and estuarine regions and around islands without disturbing marine traffic. When this happens, appropriate tidal models will become more useful for operational oceanography. At that stage, real-time data telemetry via satellite or cellular modems will become all the more useful for predicting water current variability in combination with the ocean model. Perhaps long-term operation at shorter intervals can be carried out by putting solar panels on a surface buoy.

Application of acoustic tomography crossed the boundaries of water flow measurements in the open ocean, straits, and coastal water bodies and spilled over to flow and discharge measurements in estuaries and rivers using an advanced in-water acoustic remote sensing technology known as river acoustic tomography (RAT). For example, a RAT system that utilizes a GPS clock and 10th order M-sequence modulation was developed by Kawanisi et al. (2009) and applied to a shallow tidal river with a complex flow field. The RAT system, composed of a couple of transducers that are installed diagonally across the tidal channel, was able to measure the cross-sectional mean velocity in the channel. Advanced signal-processing technology used here yielded a sufficiently high signal-to-noise ratio owing to the 10th order M-sequence modulation. Thus, it was found that the RAT system works well even throughout flood events in which turbidity and acoustic noise are very high. In addition to measuring water discharge, mean water temperature and salinity could also be deduced from processing the sound-speed data collected by the system. Consequently, the RAT, operated at the shallow tidal channel with large changes of water depth and salinity, successfully measured the cross-sectional mean velocity over a long duration.

The water discharge deduced from the RAT system was compared with that measured by ADP. The agreement between RAT and ADP on water discharge was satisfactory. In addition, the mean temperature/salinity obtained from RAT fulfilled an acceptable compliance with CTD data. Thus, the RAT system is found to be a promising technology for continuous measurement of water discharge and mean temperature/salinity at estuaries. It is surprising that RAT technology could be successfully used for water current measurements, even from the highly dreaded tidal-bore-ravaged Qiantang River in China. Based on the success of this experiment in 2009, it has been suggested that the RAT method provides a prosperous way for continuous long-term monitoring of river discharge in large tidal-bore-infested rivers with heavy shipping traffic, such as the Qiantang River.

2.2.3. Measurements Based on Motion of Drifting Subsurface Floats

Apart from the GEK and acoustic tomography methods, subsurface drogues have also been tried for current measurement, initially in the mixed layer and subsequently in the abyssal depths. Freely drifting drogues, constructed of two mutually orthogonal PVC sheets, weighted to assure vertical attitude, and suspended from a float, have been used to indicate the trajectory of subsurface currents at specified depths. Color-coded flags on buoyant poles attached to the floats identified individual drogues set at different depths for optical tracking. Deployment consisted simply of dropping the drogues into the ambient current off the stern of a boat, which was used as the tracking control station. Precision theodolites were employed to track drogues (Murray, 1975).

The early major investigations into subsurface current measurements included the experiments of Stommel (1949) and Swallow (1955). The revolution in oceanic subsurface and abyssal current measurements began after John Swallow returned to Cambridge University after a wartime break, maintaining radar systems for the Royal Navy. Gould (2005) has given an absorbing account of John Swallow's pioneering initiatives in the development of a branch of subsurface current measurement technology. The prelude to Swallow's invention has been described thus: In the summer of 1954, John Swallow, a 30-year-old Cambridge Ph.D. student, made his first visit to the U.K. National Institute of Oceanography (NIO). The visit was to discuss with NIO oceanographers the possibility of making direct measurements of the vertical profile of water currents in the deep ocean by tracking a slowly sinking acoustic source and hence to derive the current profile.

Following the visit, Swallow accepted an invitation to join the staff of NIO. He left his initial interest in profiler development and, subsequently, his untiring experimentation with developing neutrally buoyant floats for Lagrangian measurements of deep ocean currents (which later came to be known as the "Swallow float," after his name) began at a time in the 1950s when little was known about the circulation of the deep ocean from direct measurements. Swallow's efforts focused on developing floats that would remain neutrally buoyant at an approximately constant specified depth (in practice, at a level experiencing constant water pressure) so that in the presence of water motion at that depth, the float will freely drift with the water motion over the specified isobaric surface (i.e., depth of constant water pressure). Tracking the float (i.e., determining the geographical position of the float) at frequent time intervals (e.g., by tracking it by ship-borne hydrophones or through acoustic receivers moored in the Sound Fixing and Ranging [SOFAR] channel) would then yield a Lagrangian description of the water motion at that depth layer.

Swallow's work at Cambridge had made him familiar with the compressibility of materials and of seawater. He had experience of the measurement of acoustic travel times and knew about the difficulty of making deep-sea pressure seals. This experience led him to consider trying to stabilize a float at some depth level within the ocean so that while it freely drifts with the ocean current at that depth, the neutrally buoyant float could be tracked acoustically and its drift integrated over an extended period. Construction of the first neutrally buoyant floats started at the beginning of 1955. Materials and money were in short supply, and so the dictum "necessity is the mother of invention" became truly applicable. Aluminum had the correct mechanical properties in terms of strength and density; the most readily available source of aluminum tubing was the scaffolding used in the construction industry. However, standard tubing had too great a wall thickness, so it had to be thinned by immersing the tubes in a bath of caustic soda. Six meters of tubing were needed to provide sufficient neutral buoyancy at the intended depth, and for ease of handling this was cut into two 3-m lengths laid side by side.

According to Gould (2005), over the next few years Swallow made further exploratory measurements in the Atlantic, gaining confidence in float ballasting, improving tracking techniques, and using floats to depths as great as 2,900 m but with tracking still lasting no more than two and half days. Subsurface current measurements were made in April and May 1956 west of Gibraltar and in the Norwegian Sea in October and November 1956. Apart from acquiring new knowledge of the variability of currents at depth and the comparison of these measurements with geostrophic shear calculations, Swallow was surprised to find that a float close to the Mediterranean water core did not move westward, as it was expected to. Gould (2005) further states that Swallow and Henry Stommel had by then started to correspond. They met for the first time in 1955 when John Swallow went to New England for a meeting to discuss radioactive waste disposal and was able to visit Woods Hole Oceanographic Institution (WHOI). Swallow's long-term collaborations with U.S. researchers, including Stommel, led to major advances in the study of deep-ocean dynamics.

The Swallow floats (see Sections 6.3 and 6.4) provided a Lagrangian view of the ocean interior and thus started the mesoscale revolution. Indeed, Swallow floats are given credit for revealing the existence of some exciting oceanic subsurface current paths, such as the strong countercurrents under the Gulf Stream. Although several differing designs of subsurface floats (drifters) emerged in the subsequent period, they were all some form of improvements of the Swallow floats, such as those listening to moored acoustic sources making use of SOFAR channels (see Section 6.5) and horizontally displaced and vertically cycling types that transmit the recorded data via satellite systems such as ARGOS (see Sections 6.6 and 6.7).

2.2.4. Measurements from Fixed Locations at Predetermined Depths

Although the rather crude Lagrangian methods employed in the olden times of ocean current measurements provided a rough indication of the trajectories of surface currents, no information was available on the temporal variability of currents at a given location of interest (i.e., Eulerian measurements). In addition, currents at depths below the sea surface needed to be known for several operational applications. These requirements led to the invention of devices known as *current meters*. Primitive methods of Eulerian-style ocean current measurements relied primarily on purely mechanical devices and sensors. Measurements of currents using such devices and sensors were based on the drag or physical rotation experienced by the sensors in response to the force exerted on them by the moving water. Some of these devices used in the early stages of oceanographic studies are no longer in use today. However, in view of their historical importance in the evolution of ocean current measurement technologies, some aspects of such measurements are briefly mentioned here, with the hope of kindling appreciation in the minds of the next-generation oceanographic researchers and academicians as to the difficulties with which current measurements were made in the past.

2.2.4.1. Suspended Drag

The simplest current meter is a *drag*, described in the literature as the *Chesapeake Bay Institute drag*, consisting of two crossed rectangular plates weighted and suspended by a thin wire (Pickard and Emery, 1982). When the drag is immersed, the force exerted by the water current (proportional to the square of the current speed) pulls the wire to an angle from the vertical. The current speed is computed using a formula relating the size of the drag, its weight in water, and the angle of the wire from the vertical. This wire angle is measured to determine the current. The device is simple and quick to use from an anchored ship. It is, however, limited to depths of a few tens of meters because the current drag on the wire increases with length and complicates the interpretation of the wire angle at greater lengths. Furthermore, the drag method is useful only for short-term *in situ* measurements of currents, not for continuous long-term measurements.

2.2.4.2. Propeller Revolution Registration by Mechanical Counters

Perhaps the most widely used current meter for some time in the past was the *Ekman current meter*. This device consisted of a propeller mounted within a frame, a vane that oriented the instrument so that the propeller faced the current, and a magnetic compass for sensing the orientation of the propeller relative to Earth's magnetic north and, therefore, the direction of flow. The instrument, attached to the end of a wire, was lowered to the desired depth. A metal weight (messenger) dropped down along the wire disengaged a lever to free the propeller to rotate with a speed directly proportional to the water current. A second messenger, dropped after a known interval of time, arrested the rotations of the propeller. The number of revolutions made by the propeller during the measurement interval was recorded by a mechanical counter. The water current speed could then be related to the number of revolutions per minute.

The current direction was recorded by an ingenious method of dropping minutely sized metal balls through a set of tubes into the indentations of a disk, at intervals, along a magnetic compass into one of 36 compartments with 10° sectors and graduated in degrees relative to Earth's magnetic north. The compass box was rigidly connected to the vane of the current meter, but its magnets could adjust themselves along the local magnetic meridian. The graduated sector of the compartment into which the ball dropped indicated the direction of flow at the moment the ball fell. The design of the current meter permitted one ball to drop for each 33 revolutions of the propeller. The average direction of water current during one single observation was obtained by computing the weighted mean according to the distribution of the balls.

A major disadvantage of the Ekman current meter was that it had to be lowered and raised for each measurement—a tedious job, often performed from small boats such as country crafts in hostile marine conditions. This drawback has been circumvented, to some extent, in the Ekman repeating current meter and the Carruthers residual current meter. However, these were also purely mechanical in design and direct reading in style and therefore unsuitable for deployments in continuous, long-term current-monitoring projects. These current meters have been used successfully by biologists in bays and near-shore waters to determine the current flow in relation to fish migration and marine life dispersal.

Recordings of current measurements were purely mechanical in nature. In such current meters, raised numbers indicating mechanically derived current speed and direction measurements were recorded by application of pressure on strips of tinfoil advanced by mechanical clockwork, or markings representing the data were recorded by a fine stylus on a paper chart run by mechanical clockwork. Two other instruments designed much later for current measurements are the Schaufelrad (paddlewheel) current meter, as reported on by Boehnecke (1949), and the Roberts radio current meter (Roberts, 1950). These were also mechanical instruments.

The Schaufelrad (paddlewheel) current meter is a self-contained, continuous recording instrument. The current meter is moored into position with an anchor and held off the bottom with a buoy. The buoy also aids in the recovery of the instrument. The size of the current meter, 170 cm long and 58 cm wide, makes it impossible to be deployed closer than 100 cm to the bottom. In this current meter, a paddlewheel mounted at the head of a bomb-shaped shell is turned by the prevailing currents. An intermittent light source records on a photographic film strip the turns of the paddlewheel and the direction as indicated by a compass. After the desired period of operation, up to four weeks, the current meter is raised and the film strip removed and developed. The traces of light are scaled to determine the water current's speed and direction adjacent to the current meter during the period of immersion.

Later current meters recorded speed and direction measurements on chronographs, magnetic tapes, and photographic plates. Modern versions of current meters record data in semiconductor recording media. Data acquisition techniques as well as recording and retrieval formats gradually improved with advances in technology. Modern recording current meters permit direct transfer of the recorded time-series vector-averaged current measurements to a computing device. This permits rapid analysis and documentation of results in the desired format. Ocean current measurement technologies have undergone rapid evolution both in terms of modernizing the basic sensors and adapting to the fast-changing hardware and embedded-software technologies incorporated in data acquisition and data recording/displaying devices. It is only recently that oceanographers have been able to make the continuous, long-term recordings required for achieving a realistic picture of ocean currents and to apply theories that take reasonable account of both winds and density gradients.

2.2.4.3. Unidirectional Impeller Current Meters

Probably the first electronic counterpart to the purely mechanical current meter was a modification of the Ekman current meter, popularly known as the *Roberts radio current meter* (*Manual of Current Observations*, revised (1950) edition; supplement to C&GS special publication No. 215, November 1961). The Roberts radio current meter consists of three parts: the meter, the buoy, and the transmitter. In this current meter a rotating impeller, which is actuated by the current, is connected through a magnetic drive to an enclosed interior mechanism that opens and closes an electric circuit by means of two contacting devices. One lever mounted on the compass is always oriented toward Earth's magnetic north. The other lever, fixed to the meter, is always oriented in the direction of the water current flow. A post, carried on a gear, revolves past the switch-actuating levers and causes the lever mounted on the compass shaft to close its switch contacts once for each revolution of the gear (five revolutions of the impeller). Each contact produces a radio signal. The frequency (i.e., number of cycles per second) of these signals is determined by the velocity of the impeller and therefore can be translated into the water current velocity through the use of a dedicated rating table. In the Roberts meter, a speed signal derived from an impeller and a direction signal derived from a magnetic compass as described are electrically transmitted (telegraphed) to the surface and recorded on a shipboard deck unit. The Roberts current meter was an important step in the direction of current meter design—in fact, a forerunner of the modern electronic current meters incorporating mechanical sensors.

In 1958 the Roberts radio current meter was modified by the addition of larger impellers and tailfins made out of 1/16" fiberglass. Known as the Model 1V low-velocity meter (Figure 2.8), to distinguish it from the older conventional Model III high-velocity meter, it had been modified to enable accurate measurement of current velocities as low as 0.1 knot (i.e., 5 cm/s).

In operation, a maximum of three current meters can be suspended below a buoy (of ship-like design) anchored at a particular station (Figure 2.9). A sequence switch, carried in the buoy, selects in proper order one current meter at a time. The buoy, which houses a radio transmitter, also houses batteries that supply power to the current meter. An antenna mounted on the buoy is used for transmission of the acquired data as a radio signal. At a radio receiving station, either ashore or afloat, the signals are received, amplified, and recorded by means of a chronograph. Observers tune the individual radio buoy frequencies, record the signals, scale the tape, and tabulate the values for each current station. Amplitude modulation (AM) radio gear has been used in the transmission of current signals from the buoy to the receiving station since the system was first developed. In 1958 frequency modulation (FM) radio gear was introduced to obtain separate velocity and direction radio signals, which are recorded by a three-stylus chronograph.

A disadvantage of this type of current meter is that the rolling of the ship (from where measurements are made) or the up-and-down movement of the mooring line (on which the current meter is mounted) may cause the impeller to turn and cause inaccuracies in the speed measurement. A hollow cylinder mounted around the impeller minimizes this effect. This is, in fact, implemented in the Toho Dentan direct-reading current meter (Figure 2.10). In the Toho Dentan current meter, the impeller diameter is 10 cm, and its time constant is 2 seconds. The current speed is continuously recorded on an analog tape recorder. The tape is subsequently processed on a signal analyzer.

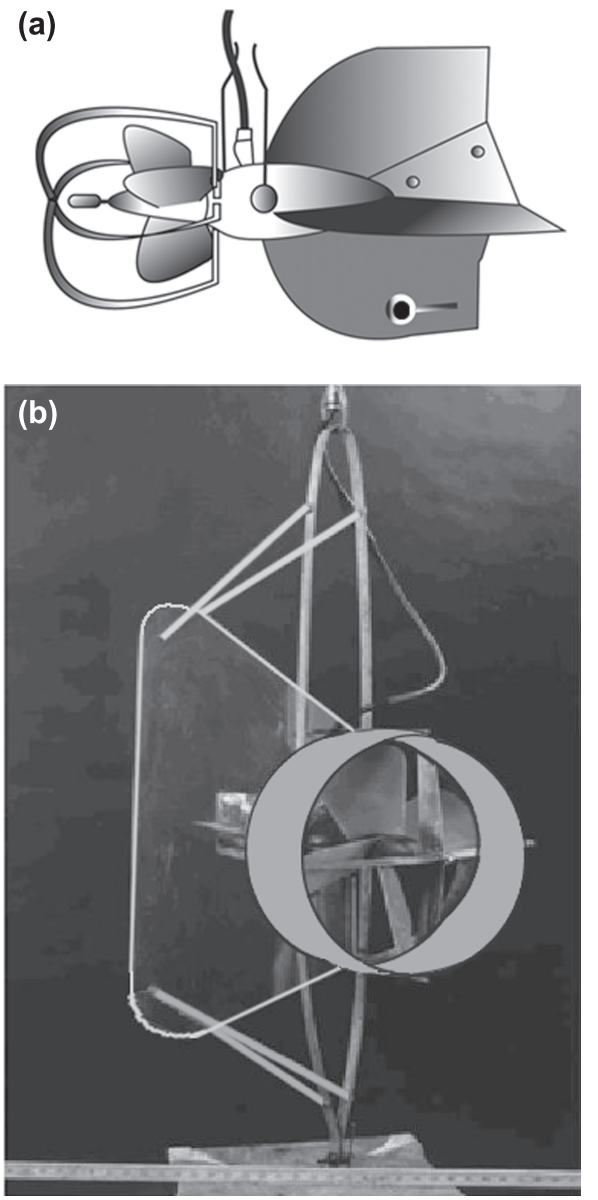


FIGURE 2.8 Model IV Roberts radio current meter: (a) side view; (b) front view. *(Source: NOAA Central Library and National Climate Data Center (NCDC), www.reference@nodc.noaa.gov.)*

2.2.4.4. Savonius Rotor Current Meters

Although the history of ocean current measurements is long, the advent of modern current meter development dates to the 1960s and early 1970s. A well-known current meter that, so to say, ruled the realm of Eulerian-style ocean current

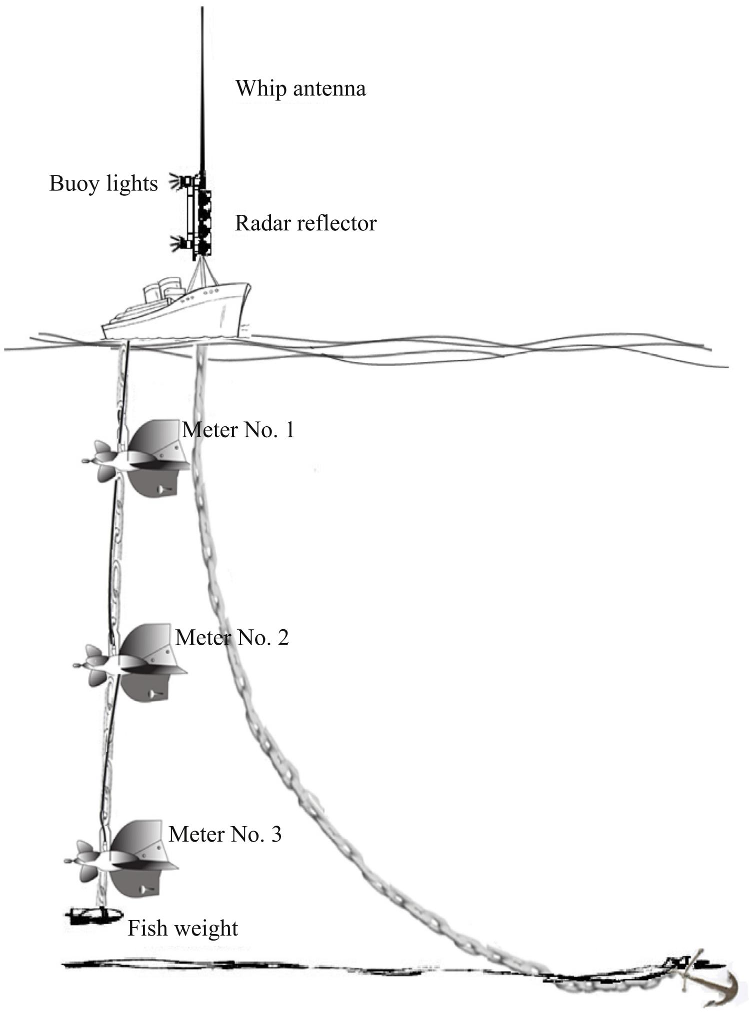


FIGURE 2.9 Multisuspension of Roberts radio current meters and data transmission from radio buoy. *(Source: NOAA Central Library and National Climate Data Center (NCDC), www.reference@nodc.noaa.gov.)*

measurements for some decades after the 1960s is the Savonius rotor current meter, popularly known as the *Aanderaa current meter* (see Chapter 8 for details). It is worthwhile to ponder the birth of this current meter and the success stories that followed. In 1960, the Christian Michelson Institute (CMI) was awarded the contract from the North Atlantic Treaty Organization (NATO) Subcommittee on Oceanographic Research to develop a recording oceanographic current meter. The project coordinator was Helmer Dahl, although the daily management of the project was handled by Ivar Aanderaa. After the project's end in 1966, Ivar Aanderaa left CMI and founded Aanderaa Instruments A/S on the basis of this current meter. The company still exists in Bergen, Norway, as well as in the United States and Japan. The Aanderaa current meter has been the single most popular oceanographic current meter worldwide for decades.

The story of the success of Aanderaa current meter is simply the keen interest Ivar Aanderaa showed in the field performance of this current meter. Several problems were observed in the initial years of Aanderaa current meter deployments. These included errors in the measured flow direction at large depths and over-speed registration when currents were weak. Such problems, reported by researchers and published in oceanographic journals, were taken seriously by Aanderaa, and corrective measures were implemented as early as possible. These measures included changing the material of the pressure housing and redesigning the basic sensor. My own personal interaction with Aanderaa in 1995 at his laboratory in Bergen on the latter issue was awe inspiring. The foundation of Aanderaa Instruments is a very early example of a commercial spin-off from the oceanographic research activity at CMI.

A highlight in the history of the Aanderaa current meter is the successful recovery, in the Weddell Sea (Antarctica), of one of the first units manufactured by Aanderaa Instruments. The instrument was deployed in 1968 and successfully

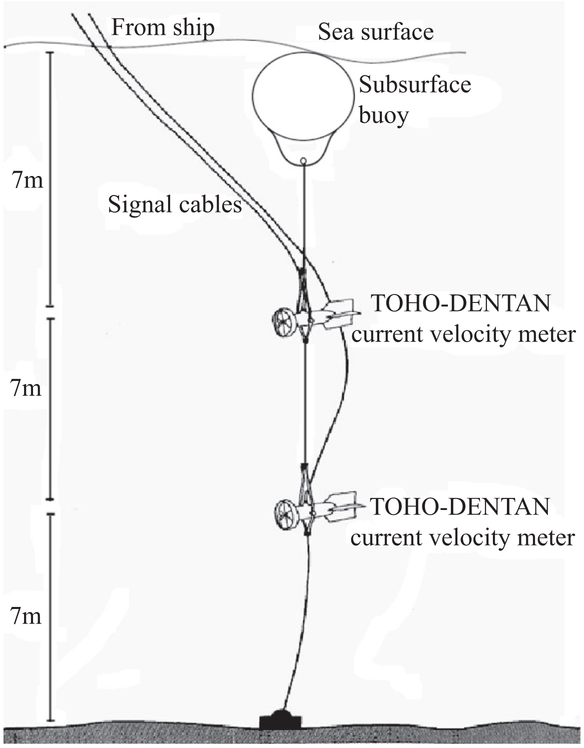


FIGURE 2.10 Toho Dentan direct reading current meter, in which a hollow cylinder mounted round the impeller minimizes inaccuracies in the speed measurement arising from turning of the impeller in response to the rolling of the ship (from where measurements are made) or the up-and-down movement of the mooring line (on which the current meter is mounted). *(Source: Veth and Zimmerman, 1981. © American Meteorological Society. Reprinted with permission.)*

recovered five years later, in 1973. This was the first long-term current meter data series ever to be collected from Antarctica. By January 1982, this company had built 7,000 instruments for recording ocean currents all over the world, and to commemorate this joyous occasion Mr. Aanderaa printed an exact copy of the first edition of the book *The Physical Geography of the Sea*, by M. F. Maury, an early pioneer who laid the foundation for modern oceanography by carrying out accurate observations of phenomena at sea during his many voyages. By recording his findings in his book, Maury created what became the first textbook on oceanography.

2.2.4.5. Ultrasonic Acoustic Methods

Although current meters incorporating mechanical sensors were widely used for Eulerian-style measurements of currents, they are incapable of measuring weak currents and turbulence. This led to the development of current meters incorporating nonmechanical sensors. Ultrasonic acoustic sensor is one among such nonmechanical sensors.

The principle used in the design of acoustic current meters is that differential travel times computed from reciprocal acoustic transmissions between two acoustic transceivers can be inverted to obtain water current speed parallel to the acoustic path (see Section 9.2 for details). Such measurements along two mutually orthogonal acoustic paths enable estimation of the water current velocity vector within the volume bounded by the four transceivers. In practice, the straight-line distance between a pair of transceivers in an acoustic current meter is about 15 cm.

An advantage of the acoustic travel time (ATT) difference method is that it permits simple multiplexing, which allows current measurements along many axes using one set of circuits. In some designs (e.g., Lester, 1961), "zero calibration" can be accomplished by reversing the direction of the acoustic path of one of the probes. With the signals in the same direction, the water path time delays of both signals are identical, and therefore the electrical delays of the system can be adjusted to "zero."

A disadvantage, arising from the small distance ($\sim$15 cm) between the two transceivers, is that it requires the arrival time differences of acoustic pulses to be measured with sufficient speed to resolve currents less than 1 cm/s. For a practical transducer pair of this dimension, the travel time difference will be 1.3 nanoseconds for current flow speed of 1 cm/s along the acoustic axis. Time resolution as short as this requires ultra-high-speed electronic circuitry. Nevertheless, flow resolution of 1 mm/s has been achieved in a commercial instrument using this principle (Simrad ultrasonic current meter [UCM] manual).

It has been shown theoretically (Gytre, 1976) that the differential travel time type current sensors exhibit ideal cosine response in the azimuth. That is, if the acoustic path between a given transceiver makes an angle θ with the flow direction, the transit time difference is proportional to $v \cos \theta$. To achieve the theoretically ideal response of the sensor, it is required to optimize its hydrodynamic performance at all current speeds and directions. Good design demands that the sensor not disturb the current flow that is being measured. To obtain a true estimate of the flow field, the dimensions of the transceivers should be minimal. Practical designs employ piezoelectric crystals of about 1 cm diameter mounted in metallic tubes. The distance between these two piezoelectric crystals in a transducer pair is typically 15 cm.

If an orthogonal two-axis sensor possessing ideal cosine response in the azimuth is rotated in a horizontal plane while being towed at various constant speeds, the V_x and V_y current signals should follow perfect sine and cosine responses, and the measured mean currents at different speeds would ideally appear as perfect concentric circles. Laboratory experiments have shown that the circles are slightly squared (Gytre, 1980), probably due to the effect of mirror holders of the current meter. In a recent design (Williams, 1985), the use of a folding mirror is avoided by supporting four pairs of acoustic transducers on two vertically separated rings. Each acoustic path is inclined 45° to the horizontal and spaced 90° in azimuth. Thus, disturbances to the flow within the measurement volume are minimal for near-horizontal flows. The horizontal and vertical responses have been reported to be cosine with a maximum error of 5% of the speed along either axis until the vertical angle caused the flow to come within 20° of an acoustic axis. Near-ideal responses could be achieved because of the small size of the transducers (approximately 1 cm^3) and their thin (0.3 cm diameter) supporting structures. Thus, the wakes from the structures are reasonably low, and these wakes cross the measurement path only over a small percentage of its length.

In an alternate design, two low-frequency signals are derived from the original high-frequency signals (by a process known as *heterodyning*), which are transmitted between the two acoustic transceivers. The phase difference between these two low-frequency signals is then related to the speed of water current. This relation depends on the particular heterodyning technique used for deriving the two low-frequency signals.

In one method, reported by Lawson et al. (1976), ultrasonic signals of frequency f_1 are continuously transmitted from transducer-1 toward transducer-2 of a given pair, while similar signals of frequency f_2 are simultaneously sent from transducer-2 to transducer-1. Thus, each transducer simultaneously transmits one ultrasonic frequency and receives another frequency from the other transducer. Application of appropriate signal-handling and heterodyning (beating) techniques provides signals with a phase difference related to the acoustic path length, the square of the velocity of sound in water at rest, the transmission frequencies, and the component of the water current speed parallel to the acoustic path.

In a slightly different phase difference method (Robbins et al., 1981), continuous wave bursts of a single frequency are simultaneously transmitted by both the transducers of a given pair. Before the acoustic signals arrive, the transducers are simultaneously connected to the receiving circuits. The received bursts resynchronize "slave" oscillators, which maintain phase information between bursts. The continuous output of the slave oscillators is heterodyned with a local oscillator, resulting in low-frequency outputs. Phase difference between these low-frequency outputs is a linear function of the water current speed, *v*, governed by the relation:

$$\phi = \frac{2vl\omega}{c^2} \tag{2.1}$$

where ϕ is the phase difference, ω is the acoustic frequency in radians/sec, c is the local speed of sound in water at rest, and l is the transducer spacing.

An advantage of this method is that because the phase difference arising from the differential travel times is measured from low-frequency signals, timing requirements in the electronics circuitry are substantially less stringent than if performed at the acoustic frequency. In addition, because all the critical signal processing is implemented at the low-frequency beat signal, the circuitry is simplified. Furthermore, sensitivity and stability better than 1 cm/s become achievable at the low-frequency level because at a low frequency, it is not necessary to correct for changes in internal circuit delays due to temperature and other factors.

A disadvantage with this method, as with the travel time difference measuring method, is the dependence of the current speed measurements to the square of the velocity of sound in water—a parameter whose variability in different environments cannot be ignored.

Ocean current measurements using the travel time difference as well as the phase difference methods greatly depend on the sound velocity in seawater—a parameter that has large variability in space and time. A technique that has less dependence on the sound velocity in seawater is the swing-around method. A swing-around acoustic current meter consists essentially of two swing-around velocity-of-sound meters configured in such a way that the transmission paths in the water are side by side and of equal length and the directions of acoustic pulse travel are opposite in the two meters. The instrument is oriented by a large tailfin so that the directions of acoustic pulse travel are parallel to the current flow direction. This orientation ensures that the time of pulse travel is greater in one meter than in the other. One sensor measures the sum of the speeds of sound (in seawater) and the current flow; the other sensor measures the difference between the two speeds. The difference in swing-around frequencies of the two sensors is then proportional to the speed of the water current. It has been shown (Suellentrop et al., 1961) that the output frequency (f) of such a swing-around acoustic current meter is related to the speed (v) of the water current by the expression

$$f = \left(\frac{2v}{L}\right)\left(\frac{1-2tc}{L}\right) \tag{2.2}$$

where L is the separation between the transmitter and the receiver; c is the velocity of sound propagation in seawater at rest; and t is the time delay in the electronic circuitry of each sensor. For typical values of L = 0.15 m and t = 0.6 μs, the percentage error in f caused by a change in c is only 0.012 times the percentage change in c. This makes the error practically negligible.

An alternate swing-around method reported by Hardies (1975) provides an automatic correction for the variations of the speed of sound in water, without its separate measurement, by the use of an ingenious closed-loop technique. In this method, two swing-around loops are configured for the transducer pair such that they transmit in opposite directions along the same fluid path. Bursts of ultrasonic signals are first transmitted from transducer 1 to transducer 2. Reception of a leading edge at transducer 2 causes the transmission of a new burst of signals from transducer 1 to transducer 2, and a closed-loop A is established. After an initial displacement of a small time period, similar transmissions are initiated from transducer 2 to transducer 1, and another closed-loop, B, is established. Once started, these two loops continue to swing around, and the number of times the loops swing around during a fixed time period (T) is registered. After the elapse of time duration T, the swing-around loop is continued for an "additional" swing around. If there is a variation in c from a preset value, there occurs a corresponding variation in the duration of the swing-around loop such that the sound velocity term vanishes from the expression for the speed of current flow. Half the duration of the swing-around loop is equal to the magnitude of the speed of water current.

An advantage of this technique is that because the dependence of sound velocity on water current measurements is eliminated, it offers a promising solution to current measurements in estuaries and other water bodies where sound velocity may considerably vary in time and with depth.

A drawback of all types of ultrasonic acoustic current meters, however, is the response of acoustic signals to air bubbles in a wave field. Tiny, almost invisible air bubbles (micro bubbles) can have a resonance frequency the same as that of the acoustic signal in water. When this happens, the air bubble is a very strong scatterer and absorber of sound waves (Clay et al., 1977). Thus, aeration of water occurring in a wave field may limit the minimum depth at which ultrasonic acoustic sensors can operate successfully. In situations where these current meters are mounted on subsurface buoys or on bottom-mounted tripods, this drawback is not of any serious consequence. Because air bubbles are virtually absent in such areas, measurement errors will be minimal.

High accuracy current measurements are often needed by both the scientific and the commercial community. Acoustic current measurement technique employed by Falmouth Scientific Inc. (FSI) is based on measuring and comparing direct path acoustic phase shifts along multiple paths. Because the speed of sound in water is very large compared to the water current velocity in natural water bodies such as seas, inlets, rivers, and the like, historically it was very difficult to accurately measure the differential travel time of acoustic pulses propagated between pairs of acoustic transducers mounted at fixed, known locations in space. To circumvent this difficulty, FSI acoustic current meter (ACM) uses the *phase-difference* between upstream and downstream acoustic signals to accurately determine the water current speed.

FSI ACM has four "fingers" (Figure 2.11). Each finger houses two acoustic transceivers. The transceivers are used to create four acoustic paths. The flow velocity is measured by comparing phase shifts of sound pulses traveling along three of the four acoustic paths. One path that is contaminated by the wake from the center support strut is always disregarded (A. L. Kun and A. J. Fougere, Falmouth Scientific, Inc.).

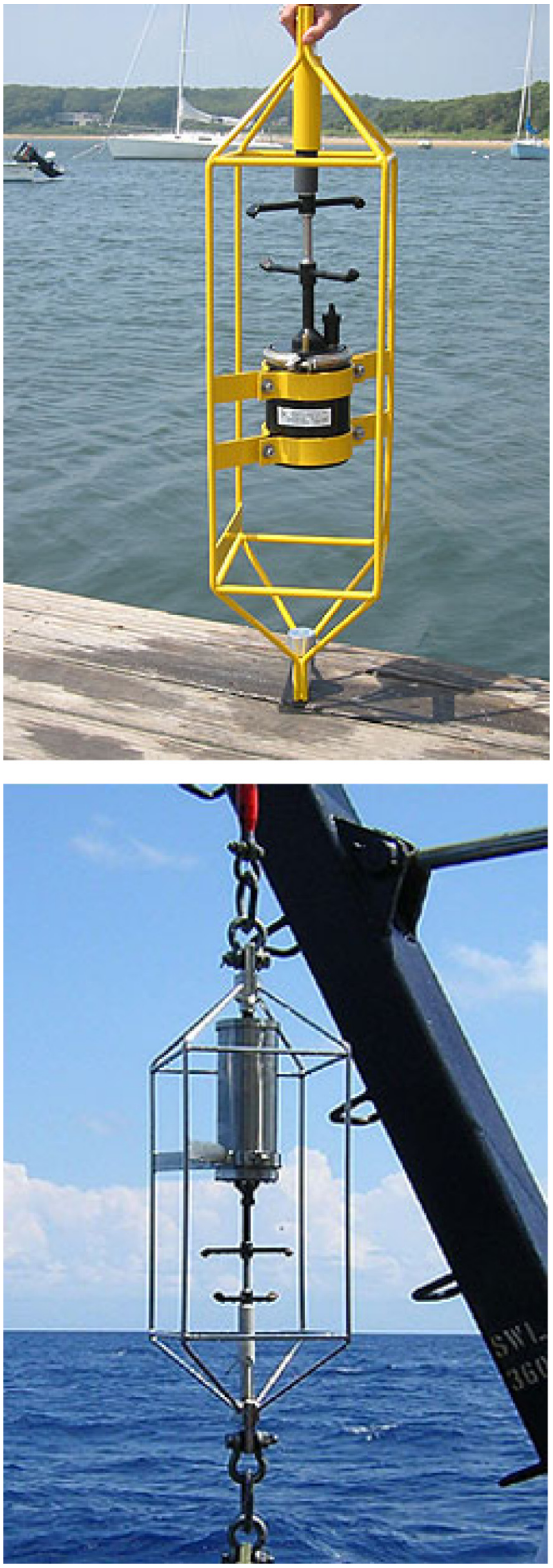


FIGURE 2.11 Falmouth Scientific, Inc. 3-D Acoustic Current Meter, incorporating acoustic phase-shift measurement principle, in protective frame. *(Courtesy of Falmouth Scientific Inc.; www.falmouth.com/sensors/currentmeters.html.)*

The acoustic current meter transmits a 1-MHz continuous wave signal for a period of 1 ms, first in one direction where the total phase shift including the receiver phase shift is measured, and then in the opposite direction where the total phase shift is measured again, using the same receiver. The current velocity is proportional to the difference in phase for the two directions. The advantage of measuring phase shift is that it can be accomplished with slower circuits than measuring time of travel. Slower circuits in turn require less power to operate.

The first acoustic current meter developed by FSI is the three-dimensional acoustic current meter (3D-ACM). The sample volume of the 3D-ACM is small; it is a sphere with a radius of roughly 13 cm. Individual measurements take a very short time (about 32 ms), and the single ping uncertainty is only 0.01 cm/s. The instrument includes a *3-axis* fluxgate compass, which measures the Earth's magnetic field, and a *2-axis* electrolytic tilt sensor, which measures the instrument's angle to the vertical. Using the internal compass and the tilt sensor it is possible to determine the heading of the instrument, and consequently estimate the water flow direction relative to the horizontal surface and magnetic north (in Earth-coordinates), without the need for specific orientation of the current meter during deployment. Vector averaging of the acoustic current sensor data also yields mean flow speed and direction.

In April 2012, FSI released a new generation ACM, the *ACM-PLUS* family, which allows the user to select between 2D and 3D measurement along with several other feature enhancements (*ACM-Plus* Compact, Vector Averaged Current Speed and Direction Meter User Manual, April 2012, P/N 8000-ACM-PLUS, Rev. 2). According to FSI, the ACM-PLUS uses the most accurate and stable current measurement techniques available today and is configured with features such as extended on-board data memory, fast download capability, high-accuracy real-time clock, and high speed data sampling. The unit's compact size and light weight make the ACM-PLUS well suited for multiple meter arrays. Windows-based software for meter setup, data collection and data visualization make the FSI ACM-PLUS very user-friendly. The ACM-PLUS is available in either shallow-water or deep-water housings. The device may also be equipped with an optional conductivity-temperature-depth (CTD) module and can be configured to log up to two analog inputs from external sensors (e.g., dissolved oxygen sensor, optical backscatter sensor, fluorometer, transmissometer).

2.2.4.6. Thermal Sensors for Measurements of Turbulent Motions

The requirement to measure microscale fluctuations in the oceanic velocity field and physical (laboratory) models and to investigate water current flows in areas that are difficult to access (e.g., rock crevices, micro-habitats) led to the development of thermal sensors such as thin films, thermistor probes, and temperature-sensitive quartz crystals. These sensors have no moving parts and are smaller than other water current-measuring sensors we have addressed so far.

Thermal sensors operate on the mechanism that the heat exchange between a heated solid body and the surrounding fluid medium is a function of the flow rate of the surrounding fluid. For use as water current meters, thermoresistive devices are electrically heated to a temperature higher than that of the surrounding water medium and are placed in the flow field.

Use of miniature metal-film probes for measurements of oceanic turbulence arises from their superior high-frequency response, fine spatial resolution, and high sensitivity. The thin-film probe consists of a thin metal coating such as platinum, with resistance of 5 to 20 Ohms, deposited on a substrate of high electrical and thermal insulating properties. A very thin layer of insulating coating, such as silicon dioxide or quartz, over the metallic film prevents its electrical shorting to the conductive saltwater yet provides good heat transfer. Platinum film is particularly suited to measurements of oceanic turbulence because it is chemically inert and offers low thermal time constants and nearly linear R-T (i.e., resistance versus temperature) characteristics. Experiments have shown (Brech et al., 1971) that the measurements tend to be unreliable when the angle of attack is near 90° to the axis of the probe, probably because of secondary flows caused by the probe. To make it insensitive to small variations in the direction of the current flows, the thin-film probes are usually provided with a conical shape. Additionally, this shape provides favorable hydrodynamic characteristics to the probe. The thin-film probe, as a result of its conical shape, is sensitive to the direction of flow velocity and exhibits a near-cosine response.

In operation, the thermal probe is usually connected in one of the arms of a DC bridge and used in a constant-temperature mode. The probe is electrically overheated, in the range of tens of degrees above the ambient temperature, and a feedback bridge maintains this constant temperature during the measurements. The bridge voltage required to maintain this constant temperature bears a relationship to the heat transfer from the probe and, therefore, to the velocity of the immediately surrounding flow field.

Although platinum thin-film probes have many ideal properties suitable for measurements of turbulence, their mechanical brittleness is a major hindering factor to its long-term use in the marine environment. They often develop pinhole leaks, and the insulating coating over the metallic thin-film flakes off (Irish and Nodland, 1978). Long-term accurate measurements of turbulent oceanic current velocity fluctuations are, therefore, difficult with these sensors. In fact, it has been observed (Dingwell and Weiskopf, 1981) that there is a strong correlation between the operating temperature and the probe's lifetime. The average operating lifetime of a thin-film probe is estimated to be approximately 200 hours.

The drawbacks of the thin-film probes necessitated the design and development of alternative thermoresistive elements such as thermistors for long-term measurements of the turbulent motions in the oceanic velocity field. As in the case of all thermal sensors addressed so far, the thermistor probe also operates on the mechanism that, when placed in a flow stream, the heated thermistor dissipates an amount of heat proportional to the flow. The amount of electrical power required to restore the lost heat is directly related to the flow speed. At low velocities the output of the thermistor-based water current meter is independent of the direction of flows, but above about 50 cm/s the thermistor probes are sensitive not only to the magnitude but also to the direction of flow (Barbera and Vogel, 1976). At high water current speeds the probes must, therefore, be oriented into the direction of the current flow.

Basically, there are two types of probe construction. In one construction the thermistor is directly heated. This construction is used where small size of the probe is an important requirement. With this construction, useful working ranges of 0.02–25 cm/s have been reported (Forstner and Rutzler, 1969). In the other construction, the thermistor is heated by a wire, which is wound over the thermistor. This construction is employed in situations where stronger currents are to be measured. Its useful working range is 1–100 cm/s. Probes of the second type have a much slower response than the directly heated types. The time constant is typically of the order of a few seconds. The essential criterion in any construction is that the thermistor be correctly mounted to achieve the best possible heat conduction to the flow medium. This is normally achieved by mounting it in a thin-walled, miniature silver cone filled with silicone grease for better heat conduction.

There are two classical bias conditions for heated thermistor probes used as flow meters—namely, constant current and constant temperature. The latter configuration is more suitable for compensation of the fluid temperature dependence (Catellani et al., 1982). One method used for compensation of the dependence on water temperature is the use of two thermistors (Forstner et al., 1969). In this, one thermistor is heated to approximately 5°C above the ambient temperature of the flow medium. The two thermistors are connected in the parallel arms of a Wheatstone bridge and the resistance changes in the thermistors are measured. The flow velocity is directly related to the differential temperature of the two thermistors. The usefulness of thermistor flow meters is limited to the measurement of currents and turbulences of low to medium speeds.

Heated temperature-sensitive quartz crystal-based sensors used for measurement of water current operates on the mechanism that, at low velocities, it is cooled by forced convection (Resch and Irish, 1972). A quartz crystal transducer utilizes two temperature-sensitive quartz crystals that are mounted in two separate pressure cases and maintained a small distance apart, having a common axis. One crystal is maintained at the temperature of the surrounding water; the other is electrically heated. The former measures the ambient temperature and the latter measures the increase above the ambient temperature. The difference in temperature is a function of the magnitude of the current flow. The transducer detects the currents perpendicular to the common axis of the two sensors. It measures low speeds that the mechanical devices cannot. Because deep-sea currents are typically 0.1 to 10 cm/s, this sensor is particularly well suited for deep-sea current measurements. However, because the time constant of the quartz transducer is approximately 10 to 20 seconds, it is not suitable for measurements of turbulence.

2.2.4.7. Laser Doppler Sensor

The Doppler effect, which was discovered in 1842 by the Austrian scientist Christian Doppler, is an effect in physics according to which the frequency of any harmonic wave motion at a receiver differs from the frequency at its source whenever the receiver or the source or both are in motion relative to one another. Subsequently, this effect began to be used for diverse applications in different areas of practical interest. In the areas of oceanographic research and operational oceanography, the Doppler effect is extensively used for remote measurement of ocean currents.

Laser Doppler techniques were applied to fluid-flow measurements as early as 1964. However, its marine application began as late as 1980. The laser Doppler current meter (LDCM) operates on the mechanism that the waterborne suspended particles in a flow field, illuminated by a monochromatic light radiation, introduce frequency shifts in the scattered light radiation by virtue of the Doppler effect. The scattering particles are assumed to be passive tracers of the water velocity. The Doppler shift in frequency thus introduced is linearly related to the water flow velocity, given entirely by the system geometry. The Doppler frequency shift is measured from the heterodyned signal produced as a result of photo mixing the received scattered radiation with the direct radiation or with another scattered radiation.

Two types of laser Doppler systems are in common use: the forward-scatter system and the backward-scatter system. The forward-scatter system requires two watertight enclosures, one containing the source of the laser radiation and the other containing the receiver. These enclosures are to be maintained in strict optical alignment. Scattering of light from natural particles is much stronger in the forward direction. With strong forward-scattered optical signals, continuous as well as periodic samples of water flow velocities may be obtained. A disadvantage of the forward-scatter system is that the struts joining the laser source and the receiver could disturb the flow that is intended to be measured. The backscatter configuration permits a "monostatic" design (i.e., source and receiver at the same location), enabling flow measurements to be made remotely without disturbing the flow. A backscatter system would thus require only one enclosure but a more powerful laser. This is because the signal-to-noise ratio for a backscattering system is generally poorer than for the forward-scattering system.

In a forward-scatter system reported by Fowlis et al. (1974), the original laser beam is split into two parallel beams by a beam splitter. To detect the magnitude as well as the direction of flow, it is necessary to introduce a known frequency offset, say f_R, in one of the laser beams. One method employed to introduce such a shift in frequency is to rotate a radial diffraction grating in one of the beams. Based on the rate of rotation and the total number of lines on the grating, the frequency of the diffracted light is shifted by a constant multiple of the original frequency, depending on which diffraction order is observed.

Another method employed to generate a known frequency offset is the introduction of a Bragg cell into one of the two parallel beams. A lens then focuses the two parallel beams, one of original frequency and the other of an artificially introduced frequency offset, to a common point within the flow field. The point of intersection (known as the *crossover point*) of these two beams defines the location of the scattering volume. This location is the position of water flow measurement. This geometry produces interference fringes at the common volume of intersection of the two beams. The volume of intersection of the beams, often termed the *probe volume* or *fringe region*, is related to the spatial resolution. The particles in the flow field, passing through the crossover volume, scatter light from both the incident beams. When a single scattering particle passes through a sinusoidal optical interference pattern, the intensity of the scattered light varies sinusoidally in time with a frequency proportional to the velocity of the particle. When more than one particle passes the interference pattern at the same time, phase shifts will occur between scattered signals corresponding to each particle. When the signal is large, the multiparticle phase shifts are of no concern (Stachnik and Mayo, 1977). Because there is an angle between the two incident beams, the scattered light from each beam is shifted in frequency (Doppler shift) by a different amount. The two forward-scattered light beams are then directed to a second collecting lens, which focuses the scattered light onto a photo detector. This arrangement is known as the *dual-scatter* or *fringe system*. The light beams scattered by the waterborne particles are mixed (i.e., heterodyned) on a photo-detector surface, resulting in the generation of beat frequencies. Because the voltage output from the photo detector is the superposition of a large number of pulses scattered from particles of different sizes and spatial separation, this signal will have a randomly varying amplitude and a randomly fluctuating phase (Greated and Durrani, 1971), the front-end electronic circuitry separates out, usually by a "frequency-domain" method, the difference frequency ($f_R \pm f_D$), where f_D is the water flow-induced Doppler shift. The sign of f_D depends on the flow direction. In the dual-scatter geometry, the flow velocity is related to f_D by the formula

$$f_D = \frac{2\mu v \sin\theta}{\lambda} \tag{2.3}$$

where μ is the refractive index of the fluid, λ is the wavelength of the laser radiation in vacuum, θ is half the angle between the two converging incident beams, and v is the component of the flow perpendicular to the plane containing the optic axis and the two beams of the system. In practical designs (Fowlis et al., 1974), this angle is less than 6°. Note that if an additional frequency offset f_R were not introduced into one of the incident beams, it would have been impossible to determine the sign of f_D, and then the system would have been sensitive only to the flow speed and not its direction.

A single set of incident beams can sense only one component of the water flow. Rotation of the beam splitter by 90° about the optic axis, or having a second beam-splitter mounted with its optic axis parallel to the original system but rotated by 90° with respect to it, would make the combined system sensitive to the two mutually orthogonal flow components. The former method would involve temporal separation of the measurement of the two flow components, whereas the latter method would involve spatial separation. For most ocean flow measurements such minor separations would not contribute to any significant errors. Simultaneous measurements of the two orthogonal flow components at the same position in space would require a multicomponent laser Doppler system.

An ingenious approach employed by Agrawal and Belting (1988) to obtain two separate velocity components using a forward-scatter system is the use of three beams from a single laser, but with widely differing offsets (Figure 2.12). The photocurrent from the detector is then amplified and mixed with local oscillators, the frequencies of which are very near the laser offset frequencies and bandpass-filtered to separate the two velocity axes.

In the backscatter systems, laser beams of different frequency offsets derived from the same source are focused to the point of measurement through a glass window. The backscattered radiation from the crossover volume is then steered to a photo detector, followed by signal processing. An advantage of the backscattering system is that, by a process of optical zooming, water current velocity profiles can be remotely measured (Agrawal and Belting,

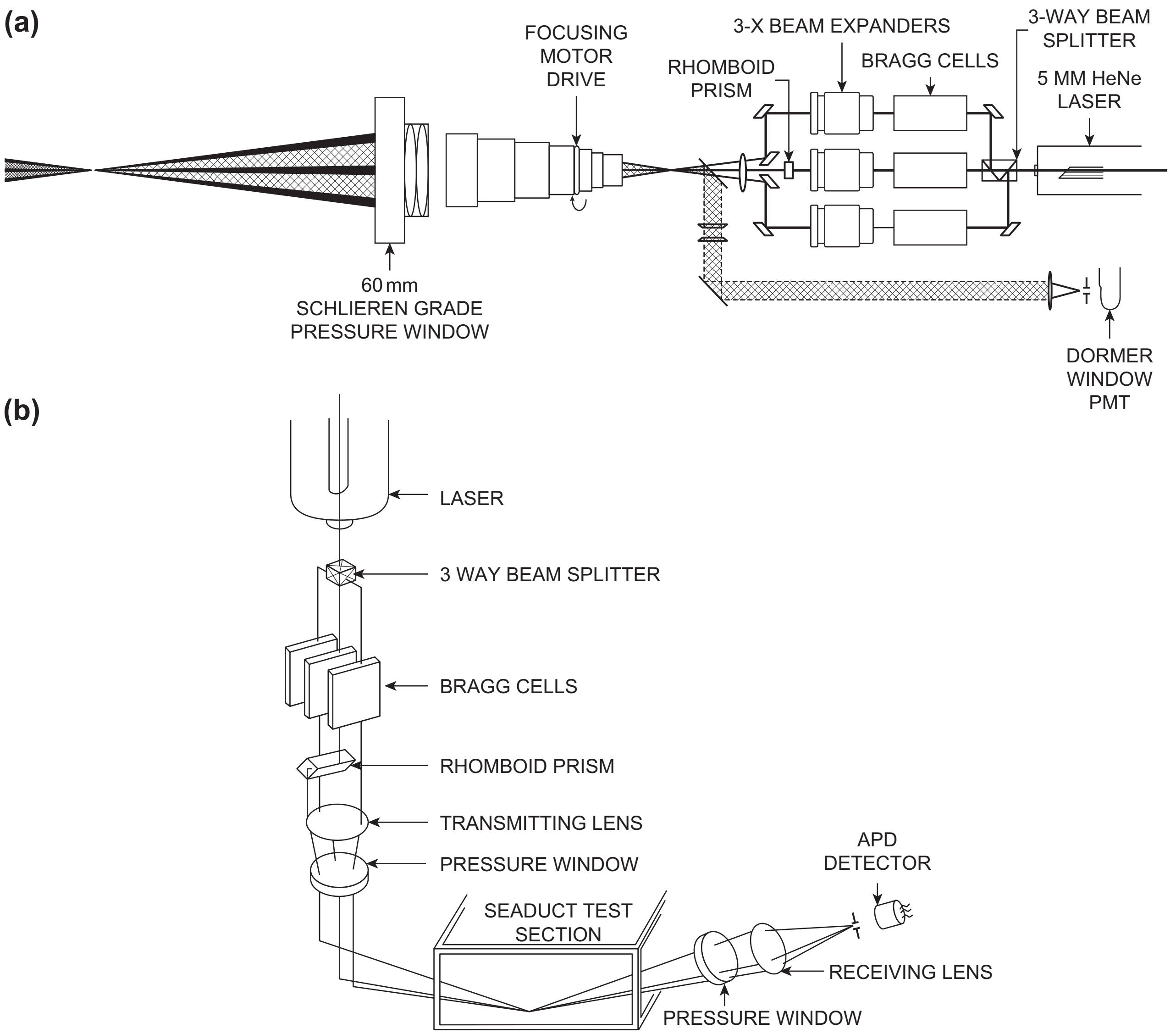


FIGURE 2.12 (a) Forward and (b) backward scatter system of Laser Doppler Velocimeter (LDV). *(Source: Agrawal and Belting, 1988.)*

1988). Optical zooming of the point of measurement along the optic axis is achieved by turning the incident beam-focusing lens with a stepping motor. This arrangement used in backscatter geometry produces range-dependent probe-volume geometry.

A noteworthy merit of laser Doppler velocimeters is that they can achieve extremely small sensing volumes (often less than one cubic millimeter) and can remotely (of the order of a meter) measure flow velocities without themselves disturbing the flow field. They also possess inherently fine accuracy and stability and do not require recalibration. They have extremely low flow speed thresholds and their responses are intrinsically linear. Flow speeds of 0.1 cm/s or less can be accurately measured. Their spatial and temporal resolutions are good and are capable of high sampling rates. The capability of the laser Doppler technique to detect slow flows suggests its suitability in the designs of vertical-flow-measuring current meters. These characteristics arise from the fact that the short wavelength of coherent laser radiation allows it to be focused to very small sensing volumes and the high frequency-stability of laser sources allow optically interfering beams to form stable interference patterns in space and in time (Stachnik, 1977).

A disadvantage of the LDCMs is that, although they have no moving parts external to them, many practical designs need to have internal moving parts. Rotations of the beam splitter and the radial grating, optical zooming, and so forth are some of the areas where the use of a motor becomes inevitable. Furthermore, a relatively high power is required to operate the laser, Bragg cell, photo multiplier, and the like. As a result of these logistic limitations, laser Doppler flow velocimeters are now being used only for specialized applications such as study of sediment transport in the deep sea and turbulent velocity fields closer to the sea bottom, where other types of current meters may not be suitable.

2.2.4.8. Acoustic Doppler Current Meter

In the initial designs of Eulerian style acoustic Doppler current meters, a bistatic configuration (i.e., the transmitter and the receiver are located at different points) has been employed. These transducers were inclined to each other so that the volume of intersection of the transmitted and the received beams defined the scattering volume. Depending on the spatial separation and the angle between the transducers, the Doppler-shifted echoes were received from a reverberation volume located at a known distance from the transceivers (Koczy et al., 1962). An advantage of the acoustic Doppler measurement technique over conventional ocean current measuring devices was that the geometry could be set to receive the backscattered signals from a region sufficiently away from the body of the meter so that the velocity of flow could be nonintrusively detected from the undisturbed flow field. The basic accuracy of measurements is determined by the stability of transmission frequency, precision of mechanical alignment of the transducers, and knowledge of the ambient velocity of sound in water. The frequency used for transmission was in the range of 1−10 MHz.

In situations in which a vane oriented the instrument into the direction of the flow (Figure 2.13), only a single transceiver set has been used (Kronengold and Vlasak, 1965). In this current meter, a 10-MHz transmitter projected a narrow beam of acoustic energy into the seawater. A similar transducer, which is inclined to the transmitter, received the backscattered signal from a location 10 inches away, where the transmitter and the receiver beam pattern intersected, thus providing measurements from a 1 cm^3 volume in the flow field. Because a large vane fixed to the instrument oriented the transceivers into the flow, the current meter measured flows away from its wake field.

A geometry that does not require a vane to detect the direction of flow is the use of two pairs of transceivers. In a design developed by EDO Western Corporation, two sets of mutually orthogonal transceiver systems (i.e., transducers mounted 90° apart in the azimuth) transmitted narrow-beam, high-frequency continuous tones. Two other transducers below each transmitter received the backscattered signals from a region 0.5 to 1 meter ahead of the respective transmitter. The transmitting and the receiving narrow-beam patterns of each pair of the transceivers were inclined on a vertical plane at an angle to each other so that the "volume" of flow measurement was defined by the intersection of the transmitting and the receiving beams. An advantage of this system is that it can measure two orthogonal components of the flow field, which is assumed to be uniform in the vicinity of the instrument. Because two orthogonal components of the mean horizontal flow field are measured, there is no necessity for a direction-orienting tailfin. A disadvantage of this configuration, however, is that the common axis of each transceiver pair lies in the same horizontal plane, and there exists a probability for any one of the transceiver pairs to sense distorted flows from the wake field of the current meter.

The drawback associated with contamination of current measurements by water current flows from the wake field of the current meter was circumvented in later designs. In a bistatic Doppler sonar system of a tripod shape reported by Wiseman et al. (1972), an upward-looking transmitter positioned at the axis of symmetry of the sonar platform transmitted a narrow-beam ultrasonic sinusoidal signal (approximately 10 MHz). Three receiving transducers, located in a horizontal plane, were symmetrical about the transmitter. Each of these receiving transducers, making an angle of 45° to the transmitter beam, detected the backscattered acoustic waves. Because the sensing volume was located sufficiently above the instrument, the measurements were free of contamination from the disturbances due to the flow-induced wakes, irrespective of the direction of flow. Because the conventional north and east components of the flow field are derived from measurements at the same sensing volume, errors normally introduced in other configurations as a result of the assumption of the uniformity of the flow field over a sufficiently large area in the vicinity of the current meter are nonexistent. Additionally, this configuration permitted remote measurements of true vector averages of the three-dimensional velocity.

For the geometries mentioned, continuous transmission is possible because the transmitter and the receiver are separate. In principle, precision of the current flow velocity estimates is higher for continuous transmission than pulse transmission, but the range resolution is very poor (Pinkel, 1980). For an Eulerian-style current meter, poor range resolution is not a constraint because measurements are made from a given fixed range. A disadvantage with continuous transmission is electrical and acoustical crosstalk between the transmitter and the receiver. This problem can be reduced by ensuring that the receiving transducer does not lie in the path of the side lobes of the transmitter.

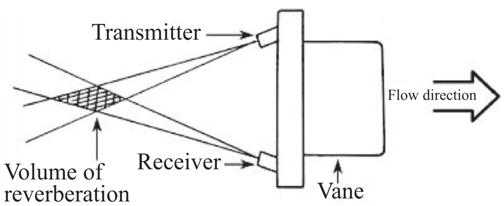


FIGURE 2.13 Schematic of an acoustic Doppler current meter where a vane oriented the instrument into the direction of the flow. *(Source: In part from Kronengold and Vlasak, 1965.)*

Another solution to this problem is the use of parametric transducers, which have suppressed side lobes and possess high directivity from a relatively small aperture (Konrad and Moffett, 1977). Insertion of an acoustically opaque medium between the transmitter and the receiver may be another method to prevent crosstalk between the transceivers.

In earlier designs, Doppler shift of the received signals was estimated using conventional electronic hardware-based frequency measurement methods such as detection of zero crossings of received pulse streams or using the frequency-locked-loop method. Although the Doppler method permits flow measurements in a nonintrusive manner, for a long time Doppler current meters suffered from severe signal dropout problems arising from the inadequacy of Doppler shift estimation techniques. As just mentioned, a common difficulty associated with most of the Doppler systems in the past was with regard to efficient extraction of the Doppler-shift information. Because the volume reverberation effect is statistical in nature with Gaussian distributions, extraction of Doppler-shift information using analytical methods introduced errors. However, these problems are now adequately handled using advanced signal-processing techniques, thereby enhancing the accuracy of measurements. Such modern acoustic Doppler current meters are now commercially available from Aanderaa Instruments.

2.3. SEAFLOOR BOUNDARY LAYER CURRENT MEASUREMENTS

Ocean currents and waves exert frictional forces on the seafloor by transport of momentum through a boundary layer. The flow in this region scales with the velocity shear, seafloor roughness, unsteadiness in the flow, and stratification of the fluid. It is turbulent, three-dimensional, and varies principally with distance above the seafloor (e.g., see Nowell, 1983; Grant and Madsen, 1986). Measurement of stress and turbulent-kinetic-energy (TKE) generation and dissipation in turbulent boundary layers is fundamental to understanding how the ocean works. Bottom boundary-layer stress is very important in sediment erosion, transport, and deposition. Understanding TKE production and dissipation is important in modeling the mixing of oxygen, heat, waste, and nutrients in the ocean. Precise vector flow measurements in the inner region of the bottom boundary layer are required to determine stress and to describe the momentum field during erosional and depositional periods. A vertically distributed array of current meters is necessary to estimate the stress profile to reveal the inner boundary layer structure. Because the water current measured by any sensor is a weighted average over its volume, miniature sensors are required to make observations of turbulent current fields closer to the deep seafloor, where the flow structure tends to be spatially inhomogeneous.

The water flow speed within the boundary layer, under certain conditions, increases logarithmically with distance from the bottom. The slope and intercept of the logarithmic profile provides two parameters, friction velocity and roughness length, which are needed to characterize the flow. More generally, the flow can be characterized by the turbulent kinetic energy and the Reynolds stress as a function of distance from the seafloor. *Reynolds stress* is the turbulent exchange of momentum in a frictional flow that carries stress from the interior flow to the boundary. It is determined by correlating the fluctuations in vertical velocity with the fluctuations in downstream velocity. It is the need to resolve small advected eddies contributing to the turbulent kinetic energy and the Reynolds stress that determines the sensor size and defines the sampling rate.

The mean velocity, $\overline{U}$, at 1 meter above the seafloor, is a valuable parameter because of its requirement in the computation of shear stress, τ, which is expressed as:

$$\tau = C_d \times \rho \times \overline{U}^2 \tag{2.4}$$

where C_d is a drag coefficient and ρ is the fluid density. The drag coefficient, when waves are not present, is typically between $2 - 4 * 10^{-3}$ (Sternberg, 1968). In a tidally driven shallow flow, ignoring wind stress, one expects the stress to vary linearly from the seafloor to zero at the top surface, as given by the expression (Thwaites and Williams, 2001):

$$\tau(z) = \tau_b\left(1 - \frac{z}{h}\right) \tag{2.5}$$

In this expression, $\tau(z)$ is the shear stress at a height z above the seafloor, τ_b is the seafloor shear stress, and h is the total water depth. The log-fit stress estimate is made by fitting mean velocities at the different sensor heights above the bottom to a logarithmic layer model, expressed as (Monin and Yaglom, 1971):

$$\frac{\overline{u}}{u_*} = \frac{1}{k}\ln\left(\frac{z-d}{h_o}\right) + B \tag{2.6}$$

In this expression, $\overline{u}$ is the mean velocity at height z; u_* is the friction velocity, defined as the square root of the shear stress divided by density; k is von Karman's constant, taken to be 0.4; d is a displacement height; h_o is the roughness scale, and B is an empirical function of the roughness Reynolds number. Log-fit stress estimates require that equilibrium exists and the boundary layer flow is fully developed over the sensors. The log-fit stress estimate further requires currents from at least three heights to compute the stress and displacement height.

To study seafloor boundary layer flows, vertical arrays of current meters have been used either as mean current sensors (Weatherly and Wimbush, 1980) or as stress sensors

(Heathershaw, 1979). For some measurements where the flow directions cannot be known in advance, the sensor must be omnidirectional and its supports must not shed appreciable wakes into the measurement volume (Wyngaard et al., 1982). At the same time, the velocity fluctuations responsible for the turbulence signal may be small, so the structure supporting the sensor must be stiff and not vibrate, lest it contaminate the measurements. A tripod-type platform provides such stiffness with minimum flow disturbance. Instrument pressure cases and buoyancy modules on the measurement platform are severe flow disturbers, but these can be confined to a certain height level where measurements can be sacrificed.

2.3.1. Mechanical Devices

Attempts to measure currents near the seafloor in the open ocean have employed variations of three basic techniques: (1) current meter lowered to the bottom with wire from a ship (Pratt, 1963); (2) current meter suspended from an anchored buoy (Richardson et al., 1963); and (3) current meter attached to submersible bodies (LaFond, 1962). Currents have also been inferred from bottom photographs of ripple marks on the bottom (Hurley and Fink, 1963).

Knauss (1965) described a device that, when launched, sinks to the bottom, remains there for a predetermined length of time, and then surfaces. The instrument system consists of five components: current meter, release mechanism, weights, floatation device, and the transmitter. In air, the system weighs ~217 kg. The current meter is a self-recording instrument, recording on photographic film. The release mechanism can be set to go off in any 20-minute interval up to 140 days. At a predetermined time, an explosive device releases the line attached to the anchor and the gear floats to the surface.

A purely mechanical current meter used exclusively for bottom-current measurements is the deflecting wand current meter (Niskin, 1965). This device operates on the principle that a positively buoyant wand tethered at one end will assume an angle of inclination and a direction that are functions of the water current speed and direction, respectively. To make seafloor current measurements, the device, with an anchored weight, is dropped down to descend to the seafloor, where it preserves a single recording of the current. Upon dissolution of a soluble link, the instrument is automatically released from the anchor to float to the sea surface, where it is recovered and its recording noted. If further measurements are desired, another soluble link is inserted, an anchor weight attached, and the operation is repeated. This current meter could record even abyssal currents.

Another purely mechanical device for measuring very weak currents near the seafloor and designed to mount on a tripod is the Nansen pendulum current meter. In this current meter, a light pendulum freely swung above a slightly concave disk, which was carried by a magnet and covered by graduated waxed paper. At short intervals of time, a clock-work lowered the pendulum and a fine stylus attached to its bottom marked the paper, indicating the speed and direction of the current.

Since the early 1970s, bottom boundary layer and sediment transport experiments have been conducted with rigid bottom-mounted frames, which are arrayed with a variety of instruments. Experiments have obtained mean water current flow velocity data with Savonius rotors (Sternberg et al., 1973; Butman and Folger, 1979; Weatherly and Wimbush, 1980). Although the rotors have low power requirements and are durable, their usefulness is limited by their inability to measure the smaller time and length scales of the fluctuating turbulence components.

Direct measurement of turbulent velocity fluctuations in sand-transporting flows were made with the rugged impellor clusters of Smith and McLean (1977). Three small ducted rotors allowed measurements of the three components of the velocity vector from which direct measures of the fluctuating Reynolds stress, $u'w'$ (where u' is the fluctuating part of the along current velocity and w' is the fluctuating part of the vertical velocity) and three-dimensional spectra could be obtained. Thus, no dependence on the velocity profile being logarithmic was required. However, these sensors had to be oriented into the flows and were thus unsuitable for long deployments in reversing flows.

2.3.2. Nonmechanical Devices

Nonmechanical sensors used for water current flow measurements close to the seafloor include electromagnetic (EM), acoustic travel time difference (ATT), acoustic Doppler (AD), laser Doppler (LD), thermistors, thin-film probes, and quartz crystals. In addition to the sensors just mentioned, photographic techniques have also been employed for detection of currents at the deep-sea boundary layer (Sternberg, 1969) and for measurement of currents at the tip of a core (Ewing et al., 1967). Heated thermistor probes have been successfully employed for studies of boundary layer turbulence at small heights above the deep ocean bottom (Chriss et al., 1982). Their main advantages are small size and sturdiness. Nevertheless, they are not intrinsically fast devices and have nonlinear R-T characteristics. Doppler current meters were also used for study of sediment transport in the deep sea and turbulent velocity fields closer to the seafloor, where conventional current meters may not be suitable.

Thorpe et al. (1973), Heathershaw (1979), and Swift et al. (1979) used two-axis electromagnetic current meters to measure Reynolds stress, but these instruments had to be oriented into the flow via a fin on the supporting frame. All of these instruments have difficulty measuring water current flows in which the mean velocities are low relative to the fluctuations occurring in boundary layers. Cacchione and Drake (1979) added four electromagnetic current meters in a vertical array to measure two dimensions of the turbulence velocity vector. The finer spatial resolution, absence of speed threshold, and omnidirectional response allowed average current profiles to be measured even under wave reversals on the shelf. Most of these instruments depend on the velocity profile technique to estimate stress, and this requires a logarithmic velocity profile over the vertical region covered by the sensors.

2.3.2.1. BASS and MAVS

Seafloor boundary layer current measurement technology saw great advances under the able laboratory and field work carried out by Sandy Williams and co-researchers at Woods Hole. He showed keen interest in this topic because optical microstructure observations in 1972 and 1973 showed close-spaced vertical bands on thermo-haline interfaces. These bands are the signature of salt fingers. But there were also jumbles of curved lines in other regions that he presumed were the shadowgraphs of a stirring event, mechanical folding, or rolling of an interface and the cascade to smaller scale of the turbulence, as is expected in 3-D turbulence. He wanted to see the velocity structure at these irregular shadowgraph images, but there were no current meters suitable for this task. Trygve Gytre from Bergen, Norway, was visiting Dr. Williams' lab at Woods Hole for several months, wanting to add the new Neil Brown CTD to an acoustic shear meter he had developed and that Dr. Williams was building for his own use, and they agreed to help each other—Dr. Williams to help Gytre with the CTD and Gytre to help Dr. Williams with the acoustic shear meter. This was in 1973.

The shear meter worked fine for the intended purposes and obtained an excellent shear profile. But a student of Williams, John Tochko, queried whether they could adapt the acoustic shear meter to benthic boundary layer studies where geologist Charley Hollister had seen photographic evidence that there was active sediment transport in the deep sea. For this purpose, the two horizontal acoustic paths of the shear meter had to be augmented with additional paths to obtain the vertical component of flow so that the Reynolds stress could be measured.

Because Reynolds stress is determined by correlating the fluctuations in vertical velocity with the fluctuations in downstream velocity, a 3-D current sensor was required. The acoustic shear meter had a sensitivity of 1 mm/s in velocity fluctuations, so it seemed to have the capability. And they built the first Benthic Acoustic Stress Sensor (BASS). The BASS is a novel deep-sea tripod-supported ATT current meter array instrument that was specifically designed to study bottom turbulence. The BASS was expected to meet the necessary performance criteria and at the same time be deployable in a wide range of oceanic and near-shore environments. The purpose of this vertical array of instruments was to measure acoustically the average water flow along each of four axes in 15 cm diameter volumes at six heights above the bottom (Williams and Tochko, 1977). This array was expected to avoid the problems of flow disturbance, flow alignment, limited sensitivity, and unknown measurement volume common to other boundary layer flow sensors.

It is interesting to ponder the development cycle of BASS, in which teamwork was the key. Sandy Williams had electronic help from a Woods Hole engineer, Richard Koehler. He addressed the now-critical problem of zero point drift. Early in his experiments to improve the shear meter to BASS, he became tired of getting a 300-V shock when he inadvertently touched the part of the circuit with the high voltage. First he marked this part of the circuit with red and yellow striped tape, but next he revolted entirely against using high voltage and trying to excite a spike to achieve high-amplitude acoustic pulse transmission. Replacing the single switched voltage with a burst of low-voltage square waves tuned to the resonant frequency of the piezoceramic transducers produced the same steep voltage excursion at the receiver transducer as the single spike had in the shear meter. The steep slope was on the 14^{th} negative going zero crossing. Because the excitation waveform was a simple low-voltage square wave at 1.8 MHz, standard digital circuits could be used and the danger of shock was a thing of the past. Williams was satisfied that the added complexity was worth it. But drift of the "zero" was still present. The electronic drift was eliminated with further modifications in the circuitry. This was confirmed in tests done in a bucket of still water and later in cast gelatin without convection currents.

Williams was fortunate to have eager geologists wanting to know what the deep-sea currents might be, and a few fluid dynamics people also showed interest in examining whether a one-dimensional boundary layer model was appropriate for flow in the deep sea over simple flat topography. Because of this interest and a concern of U.S. Navy about acoustic detection of Soviet submarines, Williams received support from the National Science Foundation (NSF) for the first and Office of Naval Research (ONR) for the second concern, and he was able to continue design and testing and eventually deployed his BASS instrument (see Section 9.2 for details). About that time, a valuable colleague, William Grant, joined the Ocean Engineering Department at Woods Hole from MIT, where he had studied the problem of wave-current interaction. He wanted to get his hands on the BASS to test his models in the coastal zone. In the early history of the BASS, it suffered from "zero-point" uncertainty, and this needed to be solved. The issue was that the BASS transducers were connected to the housing with the electronics by 6-meter coaxial cables, and pressure caused the capacitance of the cables to change. With appropriate correction to this problem, the BASS turned out to be the gold standard for boundary layer current measurements against which other current meters might be compared.

On the continental shelf and in estuaries, the BASS must meet additional requirements. Here the logarithmic velocity profile method often fails because the wave boundary layer is a major influence, whereas at other times stratification or internal wave excitation is dominant. In these situations, the ability to measure turbulent kinetic energy at a series of sensor heights and to compare the stress estimates derived from them with the velocity profile is valuable. BASS is unique in permitting turbulent quantities to be measured in reversing flows of a wave field with low enough disturbance to estimate stress. Here, fast sampling (5 Hz) is necessary. The large datasets are accommodated in shallow deployments by telemetering the data by radio from a moored transmitter near the tripod.

BASS has been proven to be a valuable instrument for turbulent flow measurements. It has been used in near-shore studies of large swell and wind-wave-current interaction off the coast of California in the CODE experiment (Grant et al., 1984). Measurements of velocity profiles, turbulent energy, and velocity spectra resolving the inertial range and bottom wave influence were made. Adaptations to deploy the BASS for long-term boundary layer monitoring in the HEBBLE site enabled quantitative evaluation of the effect of benthic storms (Gross et al., 1986; Grant et al., 1985). These two- and six-month deployments allowed changes in bottom roughness over timescales of hours to weeks to be observed using logarithmic velocity profiles and direct measurements of Reynolds stress and kinetic energy. The BASS's unique ability to measure across timescales from half a second to several months with velocity resolution of 0.03 cm/s has made possible studies of the benthic boundary layer, which was unattainable by any other instrument in use.

It may be worthwhile to note that the ultimate success came after several difficulties suffered by the instrument designers and the technologists. According to Williams et al. (1987), transducer failures were common in the early days, sometimes affecting as many as half the acoustic axes. Initially the problems were broken wires, then intermittent connectors, misaligned transducers, and delaminated ceramic elements. These faults were eliminated by changing materials, changing construction techniques, modifying designs, and inspecting subassemblies in the molding process. In 1984 over 500,000 transducer hours were logged and there were no failures (Dunn, 1984). An additional 280,000 transducer hours were logged in 1985−86 on these same sensors, still with no failures. As of 1987, total immersion was over one year for 80 of these transducers.

The full value of ultrasonic acoustic current meters for measurements of weak currents and turbulence in the bottom boundary layer can be achieved only if flow obstruction by the body of the current meter is arrested. This is easier said than done. As we have seen already, in the history of acoustic current meter development much effort has indeed gone in this direction. Unfortunately, although the novel ATT current meter known as the BASS has been designed to achieve improved performance to meet the needs of near-bed benthic boundary layer studies, this device required the use of external electrical cables, which are thicker than the structure cage rods.

In continuation of intense efforts toward achieving better performance, Thwaites and Williams III (1996) started developing the derivative of the BASS, known as the Modular Acoustic Velocity Sensor (MAVS) to achieve better performance by removing some of the obstacles found in the BASS. Featured was a new sensor that had no exposed coaxial cables to compress and change the "zero point"; it also had faired rings supporting the acoustic transducers, to reduce the vertical cosine response error. This sensor is shown in Figure 2.14. (By chance, the sensor shown in this figure, a photograph taken on February 21, 2013, was coated with a silicone coating called ClearSignal and had spent six months about 1 meter beneath the surface in a local salt water pond over the summer. Organisms were easily washed off under the tap with mild rubbing between thumb and forefinger.) At the end of the MAVS development, it was offered to a company called General Oceanics for manufacture and marketing. The issues that arose during development were the shape of the sensor rings, their molding (injection molding of PVC and later ABS

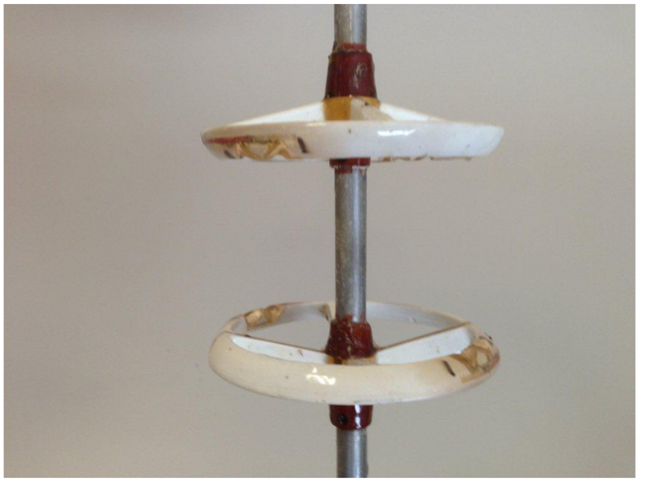


FIGURE 2.14 Modular Acoustic Velocity Sensor (MAVS) having faired rings to reduce the wake along the acoustic axes *(Source: By permission of Dr. Albert J. Williams 3rd.)*

FIGURE 2.15 MAVS marketed by Nobska Development, Inc. *(Source: Kobe Tutorial; MAVS Current Measurement, Nobska Development, Inc., Albert J. Williams 3rd, and Archie Todd Morrison III. By permission of Dr. Albert J. Williams 3rd.)*

plastic), the mounting and electrical wiring to the transducers, the overcoating and sealing of the transducers and wire, and finally the pressure compensation of the support tube with its pressure-resisting through-hull conductors. MAVS is also a three-axis ATT current meter that measures differential-acoustic-travel time in a small measurement volume. Each acoustic axis on MAVS is oblique, with the axes 45° to the plane of the rings and passing from one ring to the other. The paths are spaced 90° in azimuth around the rings, one path going obliquely up, the next obliquely down, the third obliquely up, and the fourth obliquely down. Manufacturing passed from General Oceanics to Nobska Development, Inc., and it went well. (A MAVS marketed by Nobska is shown in Figure 2.15.) MAVS was deployed at a 2,300-m depth at the Juan de Fuca hydrothermal vent field and successfully measured the flow characteristics there (a color picture of this deployment is available at WHOI archives). It is also deployed in shallow waters including coral reef sites. Figure 2.16 is the picture of MAVS mounted on a lander amidst the gorgeous coral reefs in the Florida Keys.

2.4. VERTICAL PROFILING OF HORIZONTAL CURRENTS

In the early years of oceanographic studies, linear arrays of multiple current meters deployed at different depths, using mooring lines, were used for measurements of vertical profiles of horizontal currents. However, such measurements became unfeasible for high-resolution measurements over large depths, primarily because of the prohibitively large expenditure involved in terms of current meter cost.

The just mentioned difficulty forced oceanographic technologists to develop alternative methods for such measurements. Taking a cue from the successful use of meteorological balloons for wind-profile measurements, oceanographers developed dropsondes for current profile measurements in the ocean. Freely falling dropsondes have been extensively used to determine vertical profiles of horizontal currents in the ocean. The basic concept underlying the dropsonde technique is that any submerged body will be accelerated by the horizontal drag forces arising from differences between the velocity of the local fluid and that of the body. If the equilibration to the flow is rapid enough, successive determinations of the position of the body can be used to estimate the velocity of the field. Accurate navigation is the key to the system. The technologies used in the early years for determination of vertical profiles of horizontal currents in the ocean were essentially variants of those used in meteorology for tracking meteorological balloons, which provided a large fraction of the basic wind profile data.

In oceanography, the technique of determination of vertical profiles of horizontal currents using freely falling/rising dropsondes was pioneered by Richardson and Schmitz (1965) in the Florida Straits. They used Decca

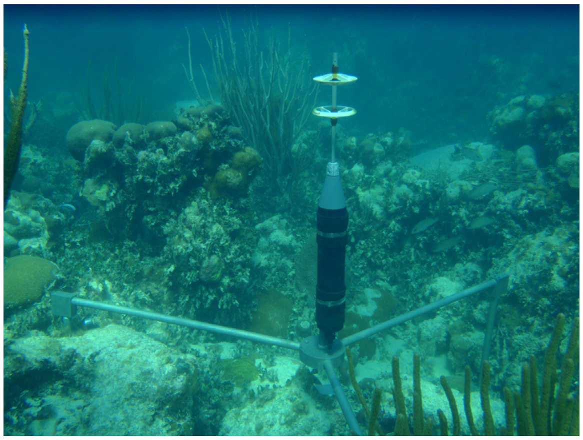


FIGURE 2.16 Picture of MAVS current meter mounted on a lander amidst the gorgeous coral reefs on a Florida Key. The picture is taken by an Olympus Digital Camera and creation date is 3/5/2012 *(Source: Courtesy of Prof. Wade R. McGillis.)*

Hi-Fix navigation with land-based stations. The limited range of Hi-Fix navigation and insufficient accuracy of the Loran-C or Omega navigation have restricted the Richardson-Schmitz technique to coastal situations. Largely because of such limitations, a few researchers were motivated to use acoustic navigation techniques to track freely falling or rising probes. Rossby (1974) and Rossby and Sanford (1976) developed acoustic dropsondes using underwater acoustic technique. Both instruments are based on pulsed navigation, in which the travel time is determined between a fixed transmitter-receiver (transceiver) and the freely falling instrument (see Chapter 10 for details). Subsequently, other techniques such as continuous wave phase tracking (Spindel et al., 1976) and correlation sonar became available. These more advanced technologies could provide more accurate navigation and could be utilized for dropsonde systems.

The marvelous success achieved over the years in the development of various kinds of ADPs brought about a drastic change in the history of current profile measurements from diverse types of ocean water bodies (see Chapter 11 for details). The most important feature of the ADP is its ability to measure current profiles, which are divided into uniform segments called *depth cells* or *bins*. ADPs significantly altered the face of current profile measurements, since a single instrument is now available to remotely profile the speed and direction of water currents throughout the water column (horizontal or vertical), as opposed to capturing only an isolated point measurement.

In essence, a single ADP can now acquire water current measurements that are obtainable from a full string of single-point current meters. Bottom-mounted ADPs as part of "light" or "heavy" trawl-resistant deployment configurations are suitable for measurements of currents in the coastal regions of vigorous fishing activity, where conventional current meter moorings have difficulty surviving. ADPs have been designed for deployments on stationary platforms (e.g., offshore structures and moorings) and mobile platforms (e.g., ships) of various kinds, merging trends in the field of sensor and platform development. It has been found that lowered ADCPs (L-ADCPs) can be used as deep as 5,000 m, to make vertical profile measurements at very low marginal cost in conjunction with CTD profiles, and can provide scientifically useful measurements of currents such as inertial oscillations and the equatorial deep jets with vertical wavelengths less than about 1,000 m.

In the early 1980s, RD Instruments (RDI) commercialized the ADCP for remotely measuring 3-D water current vectors throughout the water column. Subsequently, several other agencies began to manufacture ADPs, each manufacturer vying to outshine the other in terms of miniaturization, improved quality of data, user-friendly features, and so on. With the passage of time, ADPs began to be deployed by several users across the world. The present scenario is that in coastal and continental shelf waters, the ADPs have largely replaced mooring strings of current meters; moving boat measurement of river discharge using the ADP is replacing the traditional method; and using ADPs from coastal crafts has provided a previously unavailable survey capability for measuring circulation patterns in inshore and coastal waters.

Closer examination of high-resolution, high-frequency ADP current measurements in wave-laden waters led to new discoveries. It was noticed that current profile measurements from ADPs deployed in shallow wave-laden waters or located closer to the surface (e.g., on an offshore pier) in deep waters differed in some ways from conventional measurements. To those pessimistic users who are wedded to the old technologies, who lacked acumen, and who have no nose for exploring the unknown, the observed peculiarities in ADP measurements would have been "instrument noise" or a result of "deployment error." There have been instances in which voluminous high-resolution shallow-water ADP measurements have been thrown to the winds, blaming them as having been contaminated by "instrument noise"! However, to those erudite technologists and devoted researchers who have a nose for mining the hidden treasures from the deep, the "noise" was indeed an invaluable signal.

Research initiated in the 1980s (e.g., Krogstad et al., 1988; Terray et al., 1990) and bin-wise and beam-wise analysis of ADP current measurements from flow-cum-wave tank upward-looking deployments by Appell et al. (1991) as well as continuation of research beyond the 1990s (e.g., Herbers et al., 1991; Zedel, 1994; Visbeck and Fischer, 1995; Terray et al., 1999; Pedersen and Lohrmann, 2004) showed that clearly, sea surface wave orbital velocities were also being measured, and the shallow-water ADP measurements are indeed a combination of currents, wave orbital velocities, and

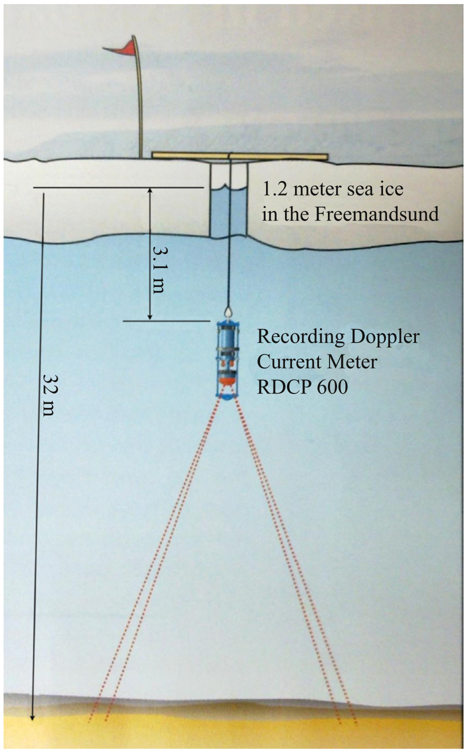


FIGURE 2.17 Current profile measurements below polar ice sheets using an ADCP. *(Source: Aanderaa News Letter, B137, pp- 1–4, May 2004).*

turbulence. This realization ultimately culminated in the invention of the now-famous seminal piece of oceanographic remote-sensing device known as the directional wave-measuring ADP. Thus, apart from the well-established capability of ADPs for remote measurement of horizontal and vertical water current profiles, they can also be used for measuring sea surface wave height and direction from a single upward-looking multibeam ADP package deployed in shallow depths relative to the sea surface. With inclusion of the additional capability of ADPs for directional surface wave measurements since the late 1990s, the survey capability of ADPs has been doubled. Consequently, ADPs can now be used to measure both directional wave spectra and current profiles at the same time. The abilities to sample the flow field without disturbing it and, most important, to simultaneously measure the three components of the fluid velocity are important features of the multitransceiver acoustic Doppler current meters. Figure 2.17 demonstrates the capability of ADP to make current profile measurements below polar ice sheets.

REFERENCES

Agrawal, Y.C., Belting, C.J., 1988. Laser velocimetry for benthic sediment transport. Deep-Sea Research 35 (6), 1047–1067.

Appell, G.F., Bass, P.D., Metcalf, M.A., 1991. Acoustic Doppler Current Profiler performance in near surface and bottom boundaries. IEEE J. Ocean Eng. 16 (4), 390–396.

Barbera, M.L., Vogel, S., 1976. An inexpensive thermistor flow meter for aquatic biology. Limnology & Oceanography 21, 750–756.

Bjorkstedt, E., Roughgarden, J., 1997. Larval transport and coastal upwelling: An application of HF radar in ecological research. Oceanography 10, 64–67.

Boehnecke, G., 1949. German oceanographic work, *Transactions*. American Geophysical Union 29 (1), 59–68.

Brech, R., Bellhouse, B.J., Bellhouse, F.H., 1971. A directionally sensitive thin film velocity probe. J. Phys. E: Scientific Instrumen. 4, 464–465.

Broche, P., Crochet, J.C., de Maistre, J.C., Forget, P., 1987. VHF radar for ocean surface current and sea state remote sensing. Radio Sci. 22, 69–75.

Butman, B., Folger, D.W., 1979. An instrument system for long-term sediment transport studies on the continental shelf. J. Geophys. Res. 84, 1215–1220.

Cacchione, D.A., Drake, D.E., 1979. A new instrument to investigate sediment dynamics on continental shelves. Mar. Geol. 30, 299–312.

Catellani, A., Stacchicitti, R., Taroni, A., Canali, C., 1982. Performance and temperature stability of an air mass flow meter based on a self-heated thermistor. Sensors and Actuators 3 (1), 23–30.

Chew, F., Berberian, G.A., 1970. Some measurements of current by shallow drogues in the Florida current. Limnol. Oceanogr 15, 88–99.

Chiu, C.S., Miller, J.H., Lynch, J.F., 1994. Inverse technique for coastal acoustic tomography. In: Lee, D., Schultz, M.H. (Eds.), Theoretical and Computational Acoustics. World Scientific, 2, Singapore, pp. 917–931.

Chriss, T.M., Caldwell, D.R., 1982. Evidence for the influence of form drag on bottom boundary layer flow. J. Geophys. Res. 87, 4148–4154.

Clay, C.S., Medwin, H., 1977. Acoustical oceanography: Principles and applications. Wiley-Interscience.

Cochin, V., Mariette, V., Broche, P., Garello, R., 2006. Tidal current measurements using VHF radar and ADCP in the Normand Breton Gulf: Comparison of observations and numerical model. IEEE J. Ocean. Eng. 31 (4), 885–893.

Crombie, D.D., 1955. Doppler spectrum of sea echo at 13.56 Mc/s. Nature 175 (4459), 681–682.

Crombie, D.D., 1972. Resonant backscatter from the sea and its application to physical oceanography. Proc. IEEE Oceans '72 Conference, 172–179.

Dingwell, R.E., Weiskopf, F.B., 1981. A hot film anemometer for ocean turbulence measurements. Proc. Oceans '81 Conferene. 1, 468–472.

Dornhelm, R.B., 1977. Current measurements offshore Humboldt bay, California for proposed ocean outfall. Proc. Oceans '77 Conference. pp. 46C-1 to 46C-7.

Duchossois, G., Martin, P., 1995. ERS-1 and ERS-2 Tandem Operations. ESA Bull. 83, 54–60.

Duncan, C.P., 1965. Disadvantages of the Olson drift card and description of a newly designed card. J. Marine Res. 23 (3), 233–236.

Duncan, C.P., Schadlow, S.G., 1981. World surface currents from ships' drift observations. International Hydrographic Review LVIII, 101–111.

Dunn, C.V.R., 1984. A miniature urethane-molded acoustic transducer. Woods Hole Oceanogr. Inst. Tech. Rep. WHOI-84-30.

Dushaw, B.D., et al., 2009. A decade of acoustic thermometry in the North Pacific Ocean. J. Geophys. Res. 114, C07021.

Elisseeff, P., Schmidt, H., Johnson, M., Herold, D., Chapman, N.R., McDonald, M.M., 1999. Acoustic tomography of a coastal front in Haro Strait, British Columbia. J. Acoust. Soc. Amer. 106, 169–184.

Ewing, M., Hayes, D.E., Thorndike, E.M., 1967. Corehead camera for measurement of currents and core orientation. Deep-Sea Research 14, 233−253.

Ferretti, A., Prati, C., Rocca, F., 1999. Permanent scatterers in SAR interferometry. In: International GeoScience and Remote Sensing Symposium. Germany, Hamburg, 28 June−2 July, 19991−3.

Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Trans. GeoSci. Remote Sensing 38 (5), 2202−2212.

Ferretti, A., Prati, C., Rocca, F., 2001. Permanent scatterers in SAR interferometry. IEEE Trans. GeoSci. Remote Sensing 39 (1), 8−20.

Flynn, T.L., Cook, D.C., 1978. Charting of outer continental shelf surface currents by aerial tracking of tracers. Proc. Oceans '78 IEEE Conference, 315−320.

Forstner, H., Rutzler, K., 1969. Two temperature-compensated thermistor current meters for use in marine ecology. Journal of Marine Research 27 (2), 263−271.

Fowlis, W.W., Thompson, J.D., Terry, W.E., 1974. A laser-Doppler velocimeter with ocean applications,. J. Marine Res. 32 (1), 93−102.

Gabriel, A.K., Goldstein, R.M., Zebaker, H.A., 1989. Mapping small elevation changes over large areas: differential radar interferometry. J. Geophys. Res. 94 (B7), 83−91.

Gonsalves, W.D., Brainard II, E.C., 1981. Geomagnetic Electrokinetograph (GEK): A technological advancement in long-term continuous monitoring of fluid flow velocity. Proc. Oceans '81 Conference 1, 233−238.

Gould, W.J., 2005. From Swallow floats to Argo: The development of neutrally buoyant floats. Deep-Sea Res. II 52, 529−543.

Graber, H.C., Limouzy-Paris, C.B., 1997. Transport patterns of tropical reef fish larvae by spin-off eddies in the Straits of Florida. Oceanography 10, 68−71.

Graham, L.C., 1974. Synthetic interferometer radar for topographic mapping. Proc. IEEE 62 (6), 763−768.

Grant, W.D., Williams III, A.J., Glenn, S.M., 1984. Bottom stress estimates and their prediction on the northern California Continental Shelf during CODE-I: the importance of wave-current interaction. J. Phys. Oceanogr. 14, 506−527.

Grant, W.D., Williams III, A.J., Gross, T.F., 1985. A description of the bottom boundary layer at the HEBBLE site: low-frequency forcing, bottom stress and temperature structure. Mar. Geol. 66, 219−241.

Grant, W.D., Madsen, O.S., 1986. The continental-shelf bottom boundary layer. Ann. Rev. Fluid Mech. 18, 265−305.

Greated, C., Durrani, T.S., 1971. Signal analysis for laser velocimeter measurements. J. Phys.E: Instrum. 4, 24−26.

Gross, T.F., Williams III, A.J., Grant, W.D., 1986. Long-term in situ calculations of kinetic energy and Reynolds stress in a deep-sea boundary layer. J. Geophys. Res. 91, 8461−8469.

Gurgel, K.W., Antonischki, G., Essen, H.H., Schlick, T., 1999. Wellen radar (WERA), a new ground-wave based HF radar for ocean remote sensing. Coastal Eng. 37 (3-4), 219−234.

Gurgel, K.W., Essen, H.H., Schirmer, F., 1986. CODAR in Germany: A status report valid November 1985. IEEE J. Ocean. Eng. 11 (2), 251−257.

Gytre, T., 1976. The use of a high sensitivity ultrasonic current meter in an oceanographic data acquisition system. The Radio and Electronic Engineer 46 (12), 617−623.

Gytre, T., 1980. Acoustic travel time current meters. In: Dobson, F., Hasse, L., Davis, R. (Eds.), Air-sea interaction; Instruments and methods, pp. 155−170.

Hardies, C.E., 1975. An advanced two-axis acoustic current meter. Proc. Offshore Technology Conference, II, 465−476.

Hasselmann, K., 1971. Determination of ocean wave spectra from Doppler radio return from the sea surface. Nature Physical Science 229, 16−17.

Heathershaw, A.D., 1979. The turbulent structure of the bottom boundary layer in a tidal channel. Geophys. J.R. Astron. Soc. 58, 395−430.

Herbers, T.H.C., Lowe, R.L., Guza, R.T., 1991. Field verification of acoustic Doppler surface gravity wave measurements. J. Geophys. Res. 96 (9), 17023−17035.

Heron, M.L., Dexter, P.E., McGann, B.T., 1985. Parameters of the air-sea interface by high-frequency ground-wave HF Doppler radar. Aust. J. Mar. Freshwater Res. 36, 655−670.

Heron, M.L., Helzel, T., Prytz, A., Kniephoff, M., Skirving, W.J., 2005. PortMap: A VHF ocean surface radar for high spatial resolution. Proc. IEEE OCEANS—Europe 1, 511−515.

Hickey, K., Khan, R.H., Walsh, J., 1995. Parametric estimation of ocean surface currents with HF radar. IEEE J. Ocean. Eng. 20 (2), 139−144.

Huang, W., Wu, S., Gill, E., Wen, B., Hou, J., 2002. HF radar wave and wind measurement over the Eastern China Sea. IEEE Trans. Geosci. Remote Sens. 40 (9), 1950−1955.

Hurley, R.J., Fink, L.K., 1963. Ripple marks show that countercurrent exists in Florida Straits. Science 139 (3555), 603−605.

Inman, D., Tait, R., Nordstrom, C., 1971. Mixing in the surf zone. J. Geophys. Res. 76, 3493−3514.

Irish, J.D., Nodland, W.E., 1978. Evaluation of metal film temperature and velocity sensors and the stability of a self-propelled research vehicle for making measurements of ocean turbulence. Proc. Oceans '78 Conference, 180−187.

Johannessen, J.A., Kudryavtsev, V., Akimov, D., Eldevik, T., Winther, N., Chapron, B., 2005. On radar imaging of current features: 2. Mesoscale eddy and current front detection. J. Geophys. Res. 110, C07017.

Johannessen, J.A., Kudryavtsev, V., Akimov, D., Eldevik, T., Winther, N., Chapron, B., 2005. On radar imaging of current features: 2. Mesoscale eddy and current front detection. J. Geophys. Res. 110, C07017.

Joseph, A., 2000. Applications of Doppler effect in navigation and oceanography. In: Encyclopedia of Microcomputers, vol. 25. Marcel Dekker, New York, NY, USA, 17−45.

Kaneko, A., Yamaguchi, K., Yamamoto, T., Gohda, N., Zheng, H., 2005. A coastal acoustic tomography experiment in Tokyo Bay. Acta Oceanologica Sinica 24 (1), 86−94.

Kawanisi, K., Watanabe, S., Kaneko, A., Abe, T., 2009. River acoustic tomography for continuous measurement of water discharge. 3rd International Conference and Exhibition on Underwater Acoustic Measurements: Technologies & Results, 613−620.

Knauss, J.A., 1965. A technique for measuring deep ocean currents close to the bottom with an unattached current meter, and some preliminary results,. J. Marine Res. 23 (3), 237−245.

Koczy, F.F., Kronengold, M., Loewenstein, J.M., 1962. A Doppler current meter. In: Marine Sciences Instrumentation, 2. Proc. Symposium on transducers for oceanic research, pp. 127−134.

Konrad, W.L., Moffett, M.B., 1977. Specialized drive waveforms for the parametric acoustic source. Proc. MTS-IEEE Oceans '77 Conference. pp. 10B-1 to 10B-4.

Krogstad, H.E., Gordon, R.L., Miller, M.C., 1988. High resolution directional wave spectra from horizontally mounted Acoustic Doppler Current Meters. J. Atmos. Oceanic. Technol. 5, 340−352.

Kronengold, M., Vlasak, W., 1965. A Doppler current meter. In: Marine Sciences Instrumentation, 3. Proc. Third National Marine Sciences Symposium, pp. 237–250.

LaFond, E.C., 1962. Deep current measurements with the bathyscaphe Trieste. Deep-Sea Res. 9 (2), 115–116.

Lawson Jr., K.D., Brown, N.L., Johnson, D.H., Mattey, R.A., 1976. A three-axis acoustic current meter for small scale turbulence. Instrument Society of America. pp. 501–508.

Legeckis, R., 1987. Satellite observations of a western boundary current in the Bay of Bengal. J. Geophys. Res. 92 (C1 2), 12974–12978.

Lester, R.A., 1961. High-accuracy, self-calibrating acoustic flow meters. In: Gaul, R.D., Ketchum, D.D., Shaw, T.T., Snodgrass, J.M. (Eds.), Marine Sciences Instrumentation, 1, pp. 200–204.

Lin, J., Kaneko, A., Gohda, N., Yamaguchi, K., 2005. Accurate imaging and prediction of Kanmon Strait tidal current structures by the coastal acoustic tomography data. Geophy. Res. Lett. 32, L14607.

Lobel, P.S., 2011. Transport of reef lizardfish larvae by an ocean eddy in Hawaiian waters. Dynamics of Atmospheres and Oceans 52, 11977 vol. 25, 130.

Lobel, P.S., Robinson, A.R., 1986. Transport and entrapment of fish larvae by ocean mesoscale eddies and currents in Hawaiian waters. Deep-Sea Res. 33, 483–500.

Lobel, P.S., Robinson, A.R., 1988. Larval fishes and zooplankton in a cyclonic eddy in Hawaiian waters. J. Plank. Res. 10 (6), 1209–1223.

Mangelsdorf Jr., P.C., 1961. The world's longest salt bridge. In: Gaul, R.D., Ketchum, D.D., Shaw, T.T., Snodgrass, J.M. (Eds.), Marine Sciences Instrumentation, Vol. 1. A publication of Instrument Society of America, pp. 173–l85.

Massonnet, D., et al., 1993. The displacement field of the Landers Earthquake mapped by radar interferometry. Nature 364, 138–142.

Maury, M.F., 1855. The physical geography of the sea. Harper & Brothers, New York, NY, USA.

Merritt, S.R., Pattullo, J.G., Wyatt, B., 1969. Subsurface currents off the Oregon coast as measured by parachute drogues. Deep-Sea Res. 16, 449–461.

Monin, A.S., Yaglom, A.M., 1971. Statistical Fluid Mechanics. MIT Press, Cambridge, MA, USA. pp. 257–364.

Munk, W.H., Wunsch, C.A., 1979. Ocean acoustic tomography: A scheme for large scale monitoring. Deep-Sea Res. 123–161.

Munk, W., Baggeroer, A., 1994. The Heard Island Papers: A contribution to global acoustics. J. Acoustical Soc. of America 96 (4), 2327–2329.

Munk, W., Worcestor, P.F., Wunsch, C., 1995. Ocean acoustic tomography. Cambridge University Press, Cambridge, U.K. pp. 433–433.

Murray, S.P., 1975. Trajectories and speeds of wind-driven currents near the coast. J. Phys. Oceanogr. 5, 347–360.

Niskin, S.J., 1965. A low-cost bottom current velocity and direction recorder. Marine Sciences Instrumentation 3, 123–131.

Nowell, A.R.M., 1983. The benthic boundary layer and sediment transport. Rev. Geophys. Space Phys. 21, 1181–1192.

Offner, F.F., 1967. Electrodes. In: Electronics for biologists. McGraw-Hill, pp. 141–147.

Olson, F.C.W., 1951. A plastic envelope substitute for drift bottles,. J. Marine Res. 10 (2), 190–193.

Park, J.-H., Kaneko, A., 2000. Assimilation of coastal acoustic tomography data into a brotropic ocean model. Geophys. Res. Lett. 27 (20), 3373–3376.

Park, J.-H., Kaneko, A., 2001. Computer simulation of the coastal acoustic tomography by a two-dimensional vortex model. J. Oceangr. 57, 593–602.

Pedersen, T., Lohrmann, A., 2004. Possibilities and limitations of acoustic surface tracking. Proc. Oceans, 2004, Kobe, Japan.

Pickard, G.L., Emery, W.J., 1982. Instruments and Methods. In: Descriptive physical oceanography: An introduction, 77, vol. 25. Pergamon Press, 124.

Pinkel, R., 1980. Acoustic Doppler techniques. In: Dobson, F., Hasse, L., Davis, R. (Eds.), Air-sea interaction: Instruments and methods, pp. 171–199.

Prandle, D., Loch, S.G., Player, R.J., 1993. Tidal flow through the Straits of Dover. J. Phys. Oceanogr. 23 (1), 23–37.

Pratt, R.M., 1963. Bottom currents on the Blake Plateau. Deep-Sea Res. 10, 245–249.

Resch, F.J., Irish, J.D., l972. Quartz crystals as multipurpose oceanographic sensors — II speed. Deep-Sea Research 19, 171–178.

Richardson, W.D., Stimson, P.B., Wilkins, C.H., 1963. Current measurements from moored buoys. Deep-Sea Res. 10, 369–388.

Richardson, W.S., Schmitz Jr., W.J., 1965. A technique for the direct measurement of transport with application to the Straits of Florida,. J. Marine Res. 16, 172–185.

Richardson, W.S., White Jr., H.J., Nemeth, L., 1972. A technique for the direct measurement of ocean current from aircraft. J. Marine Res. 30 (1), 259–268.

Richman, D., 1971. Three-dimensional azimuth-correcting mapping radar. United Technologies Corporation, USA.

Robbins, R.J., Morrison, G.K., 1981. Acoustic direct reading current meter. Proc. IEEE Oceans '81 Conference, 506–511.

Roberts, E.B., 1950. Roberts radio current meter mod. II operating manual. U.S. Coast and Geodetic Survey, Revised.

Robinson, I.S., 1985. Satellite Oceanography, An introduction for oceanographers and remote sensing scientists. Ellis Horwood Limited (a division of Wiley).

Rossby, H.T., 1974. Studies of the vertical structure of horizontal currents near Bermuda. J. Geophys. Res. 79, 1781–1791.

Rossby, H.T., Sanford, T.B., 1976. A study of velocity profiles through the main thermocline. J. Phys. Oceanogr. 6, 766–774.

Shay, L.K., Lentz, S.J., Graber, H.C., Haus, B.K., 1998. Current structure variations detected by high-frequency radar and vector-measuring current meters. J. Atmos. Oceanic Technol. 15, 237–256.

Shearman, E.D., Moorhead, M.D., 1988. PISCES: A coastal ground-wave radar for current, wind and wave mapping to 200 km ranges. Proc. Int. Geosci. Remote Sens. Symp. (IGARSS), 773–776.

Smith, J.D., McLean, S.R., 1977. Spatially averaged flow over a wavy surface. J. Geophys. Res. 82, 1735–1746.

Smith, R.C., Brown, O.B., Hoge, F.E., Baker, K.S., Evanas, R.H., Swift, R.N., Esaias, W.E., 1987. Multiplatform sampling (ship, aircraft, and satellite) of a Gulf Stream warm core ring. Applied Optics 26 (11), 2068–2081.

Spiesberger, J.L., Metzger, K., 1991. Basin-scale tomography: A new tool for studying weather and climate. J. Geophys. Res. 96, 4869–4889.

Spindel, R.C., Porter, R.P., Marquet, W.M., Durham, J.L., 1976. A high resolution pulse 2— Doppler underwater acoustic navigation system. IEEE J. Ocean Eng. 1, 6–13.

Stachnik, W.J., Mayo Jr., W.T., 1977. Optical velocimeters for use in sea water. Proc. Oceans '77 Conference. pp. 18A-1 to 18A-5.

Stander, G.H., Shannon, L.V., Campbell, J.A., 1969. Average velocities of some ocean currents as deduced from the recovery of plastic drift cards. J. Marine Res. 27 (3), 293–300.

Sternberg, R.W., 1968. Friction factors in tidal channels with differing bed roughness. Mar. Geology 6, 243–260.

Sternberg, R.W., 1969. Camera and dye-pulser system to measure bottom boundary-layer flow in the deep sea. Deep-Sea Research 16, 549–554.

Sternberg, R.W., Morrison, D.R., Trimble, J.A., 1973. An instrument system to measure near bottom conditions on the continental shelf. Mar. Geol. 15, 181–189.

Stommel, H., 1949. Horizontal diffusion due to oceanic turbulence. J. Mar. Res. 8, 199–225.

Suellentrop, F.J., Brown, A.E., Rule, E., 1961. An acoustic ocean-current meter. Marine Sciences Instrumentation 1, 190–204.

Sverdrup, H.U., Johnson, M.W., Fleming, R.H., 1942. The oceans: Their physics, chemistry, and general biology. Prentice Hall, New York, NY, USA.

Swallow, J.C., 1955. A neutral-buoyancy float for measuring deep current,. Deep-Sea Res. 3 (1), 74–81.

Swift, M.R., Reichard, R., Celikkol, B., 1979. Stress and tidal current in a well-mixed estuary. J. Hydraul. Div. Am. Soc. Civ. Eng. 105, 785–799.

Takeoka, H., Tanaka, Y., Ohno, Y., Hisaki, Y., Nadai, A., Kuroiwa, H., 1995. Observation of the Kyucho in the Bungo Channel by HF radar. J. Oceanogr. 51 (6), 699–711.

Teague, C.C., Vesecky, J.F., Hallock, Z.R., 2001. A comparison of multifrequency HF radar and ADCP measurements of near-surface currents during COPE-3. IEEE J. Ocean. Eng. 26 (3), 399–405.

Terray, E.A., Brumley, B.H., Strong, B., 1999. Measuring waves and currents with an upward-looking ADCP. In: Proc. IEEE Sixth Working Conference on Current Measurement. Institute of Electrical and Electronic Engineers, pp. 66–71.

Terray, E.A., Krogstad, H.E., Cabrera, R., Gordon, R.L., Lohrmann, A., 1990. Measuring wave direction using upward-looking Doppler sonar. In: Appell, G.F., Curtin, T.B. (Eds.), Proc. of the IEEE 4th Working Conf. on Current Measurement. IEEE Press (IEEE Catalog No. 90CH2861-3), New York, NY, USA, pp. 252–257.

The ATOC Consortium, August 28, 1998. Ocean climate change: Comparison of acoustic tomography, satellite altimetry, and modeling. Science Magazine, 1327–1332.

Thorpe, S.A., Collins, E.P., Gaunt, D.I., 1973. An electromagnetic current meter for measuring turbulent flow near the ocean floor. Deep-Sea Research 20, 933–938.

Thwaites, F.T., Williams 3rd, A.J., 1996. Development of a modular acoustic velocity sensor. Proc. Oceans '96, 607–612.

Thwaites, F.T., Williams III, A.J., 2001. BASS measurements of currents, waves, stress, and turbulence in the North Sea bottom-boundary layer. IEEE J. Oceanic Eng. 26 (2), 161–170.

Veth, C., Zimmerman, J.T.F., 1981. Observations of quasi-two-dimensional turbulence in tidal currents. J. Physical Oceanogr. 11, 1425–1430.

Visbeck, M., Fischer, J., 1995. Sea surface conditions remotely sensed by upward-looking ADCPs. J. Atmos. and Oceanic Technol. 12, 141–149.

von Arx, W.S., 1950. An electromagnetic method for measuring the velocities of ocean currents from a ship under way, Papers in Physical Oceanography and Meteorology. Massachusetts Institute of Technology and Woods Hole Oceanographic Institute 3 (3).

Weatherly, G.L., Wimbush, M., 1980. Near bottom speed and temperature observations on the Blake-Bahama Outer Ridge. J. Geophys. Res. 85, 3971–3981.

Williams III, A.J., 1985. BASS, an acoustic current meter array for benthic flow-field measurements. Marine Geology 66, 345–355.

Williams III, A.J., Tochko, J.S., 1977. An acoustic sensor of velocity or benthic boundary layer studies. In: Nihoul, J.C.J. (Ed.), Bottom turbulence. Elsevier Oceanography Series, 19, pp. 83–98. Amsterdam, the Netherlands.

Williams III, A.J., Tochko, J.S., Koehler, R.L., Grant, W.D., Gross, T.F., Dunn, C.V.R., 1987. Measurement of turbulence in the oceanic bottom boundary layer with an acoustic current meter array. J. Atmos. Oceanic Technol. 4, 312–327.

WisemanCrossby Jr., R.M., Pritchard, D.W., 1972. A three-dimensional current meter for estuarine applications,. J. Marine Res. 30 (1), 153–158.

Wyatt, B., Burt, W.V., Pattullo, J.G., 1972. Surface currents off Oregon as determined from drift bottle returns. J. Phys. Oceanogr. 2, 286–293.

Wyngaard, J.C., Businger, J.A., Kaimal, J.C., Larsen, S.E., 1982. Comments on 'A reevaluation of the Kansas mast influence on measurements of stress and cup anemometer overspeeding,'. Bound. Layer Meteor. 22, 245–250.

Yamaguchi, K., Lin, J., Kaneko, A., Yamamoto, T., Gohda, N., 2005. A continuous mapping of tidal current structures in the Kanmon Strait. J. Oceanogr. 61, 283–294.

Yamaoka, H., Kaneko, A., Park, J.-H., Zheng, H., Gohda, N., Takano, T., Zhu, X.-H., Takasugi, Y., 2002. Coastal acoustic tomography system and its field application. IEEE J. Ocean. Eng. 27 (2), 283–295.

Yamoaka, H., Kaneko, A., Park, Jae-Hun, Zheng, H., Gohda, N., Takano, T., Zhu, Xiao-Hua, Takasugi, Y., 2002. Coastal acoustic tomography system and its field application. IEEE J. Oceanic Eng. 27 (2), 283–295.

Zebker, H., Werner, C., Rosen, P., Hensley, S., 1994. Accuracy of topographic maps derived from ERS-1 interferometric radar. IEEE Trans. Geosci. Remote Sens. 32, 823–836.

Zedel, L., 1994. Deep ocean wave measurements using a vertically oriented sonar. J. Atmos. and Oceanic Technol. 11 (1), 182–191.

Zheng, H., Yamaoka, H., Gohda, N., Noguchi, H., Kaneko, A., 1998. Design of the acoustic tomography system for velocity measurement with an application to the coastal sea. J. Acoust. Soc. Jpn. (E) 19, 199–210.

Zheng, H., Gohda, N., Noguchi, H., Ito, T., Yamaoka, H., Tamura, T., Takasugi, Y., Kaneko, A., 1997. Reciprocal sound transmission experiment for current measurement in the Seto Inland Sea, Japan. J. Oceanogr. 53, 117–127.

BIBLIOGRAPHY

Breivik, Ø, Ø. Sætra, 2001. Real-time assimilation of HF radar currents into a coastal oceanmodel. J. Mar. Syst. 28, 161–182.

Cornuelle, B., Wunsch, C., Behringer, D., Birdsall, T., Brown, M., Heinmiller, R., Knox, R., Metzger, K., Munk, W., Spiesberger, J., Spindel, R., Webb, D., Worcester, P., 1985. Tomographic maps of the ocean mesoscale; Part I: Pure acoustics. J. Phys. Oceanogr. 15, 133–152.

Davis, R.E., 1985. Drifter observation of coastal surface currents during CODE: The statistical and dynamical views. J. Geophys. Res. 90, 4756–4772.

Dever, E.P., Hendershott, M.C., Winant, C.D., 1998. Statistical aspects of surface drifter observations of circulation in the Santa Barbara Channel. J. Geophys. Res. 103, 24781–24797.

Gill, A., 1982. Atmosphere-ocean dynamics. Academic Press, New York, NY, USA, 662−662.

Gould, W.J., 2001. Direct measurement of subsurface ocean currents: a success story. In: Deacon, M., Rice, T., Summerhayes, C. (Eds.), Understanding the ocean. UCL Press, pp. 193−211.

Howarth, 1999. Wave measurements with an ADCP. IEEE 1999, 41−44.

Howe, B.M., Mercer, J.A., Spindel, R.C., Worcester, P.F., 1989. Accurate positioning for moving ship tomography. Proc. Oceans'89, Seattle, WA, USA, 880−886.

Krause, G., 1986. *In situ* instruments and measuring techniques. In: Sündermann, J. (Ed.), Landolt−Bornstein Numerical Data and Functional Relationships in Science and Technology, n.s. Group V, vol. 3a. Oceanography, Springer-Verlag, Berlin, Germany, pp. 134−232.

Lane, A., 1997. Currents and SPM measurements, Holderness, East Coast, England, November−December 1993, October 1994−February 1995, and October 1995−January 1996. Proudman Oceanographic Laboratory Report No. 45.

Lane, A., Prandle, D., Harrison, A.J., Jones, P.D., Jarvis, C.J., 1997. Measuring fluxes in tidal estuaries: sensitivity to instrumentation and associated data analyses. Estuarine Coastal and Shelf Sci. 45, 433−451.

Lewis, J.K., Shulman, I., Blumberg, A.F., 1998. Assimilation of Doppler radar current data into numerical ocean models. Cont. Shelf Res. 18 (5), 541−559.

Longuet-Higgins, M.S., Stem, M.E., Stommel, H., 1954. The electrical field induced by ocean currents and waves, with application to the method of towed electrodes,. Papers in Physical Oceanography and Meteorology 13, 1−37.

Medwin, H., 1975. Speed of sound in water: A simple equation for realistic parameters. J. Acoust. Soc. Amer. 58, 1318−1319.

Oke, P.R., Allen, J.S., Miller, R.N., Egbert, G.D., Kosro, P.M., 2002. Assimilation of surface velocity data into a primitive equation coastal ocean model. J. Geophys. Res. 107 (C9), 3122.

Paduan, J., Niiler, P., 1993. Structure of velocity and temperature in the northeast Pacific as measured with Lagrangian drifters in fall 1987. J. Phys. Oceanogr. 23, 585−600.

Schmidt, W.E., Woodward, B.T., Millikan, K.S., Guza, R.T., 2003. A GPS-tracked surf zone drifter. J. Atmos. Ocean. Technol. 20, 1069−1075.

Smith, S.R., Jacobs, G.A., 2005. Seasonal circulation fields in the northern Gulf of Mexico calculated by assimilating current meter, shipboard ADCP, and drifter data simultaneously with the shallow water equations. Cont. Shelf Res. 25 (2), 157−183.

Spiesberger, J.L., Spindel, R.C., Metzger, K., 1980. Stability and identification of ocean acoustic muItipath. J. Acous. Soc. Am. 67, 2011−2017.

Spindel, R.C., Worcester, P.F., 1991. Ocean acoustic tomography: A decade of development. Sea Technol. 32 (7), 47−52.

Spydell, M., Feddersen, F., Guza, R.T., Schmidt, W.E., 2007. Observing surf-zone dispersion with drifters. J. Phys. Oceanogr. 37, 2920−2939.

Stommel, H., 1954. Exploratory measurements of electrical potential differences between widely spaced points in the North Atlantic Ocean, Archiv fur Meteorologie. Geophysik und Bioklimatologie, A 7, 292−304.

Stommel, H., von Arx, W.S., Parson, D., Richardson, W.S., 1953. Rapid aerial survey of the Gulf Stream with camera and radiation thermometer. Science 117, 639−640.

Sundermeyer, M.A., Price, J.F., 1998. Lateral mixing and the North Atlantic tracer release experiment: observations and numerical simulations of Lagrangian particles and a passive tracer. J. Geophys. Res. 103 (C10), 21481−21497.

Swallow, J.C., 1954. Seismic investigations at sea. Ph.D. thesis. University of Cambridge, Cambridge, U.K.

Vachon, W.A., 1977. Current measurement by Lagrangian drifting buoys—Problems and potential. Proc. Oceans '77. pp. 46B-1 to 46B-7.

Williams III, A.J., Terray, E.A., 2000. Measurement of directional wave spectrum with a Modular Acoustic Velocity Sensor. Oceans 2000, 1175−1180.

Zhang, C., Zhu, X.-H., Kaneko, A., Wu, Q., Fan, X., Li, B., Liao, G., Zhang, T., 2010. Reciprocal sound transmission experiments for current measurement in a tidal river, 2010 IEEE.

Zhurbas, V., Oh, I.S., 2003. Lateral diffusivity and Lagrangian scales in the Pacific Ocean as derived from drifter data. J. Geophys. Res. 108, 3141.