Foreword

In this volume, Antony Joseph has comprehensively examined the history and practice of current measurements, including the mean current, wavelike motions, and turbulent velocities that constitute flow in the ocean. This text should be interesting to all oceanographers who have a need to understand ocean currents, flow in waves, and the measurement of turbulence. Joseph's treatment is accessible to anyone with a scientific or engineering background, but it will be especially useful to one who needs to know exactly what a prospective technology might deliver. If you want to know where the water goes, how it goes, or how to measure how fast it goes, this book will help you. It covers the field comprehensively from about 1910 to about 2010, with ample references to original work in nearly every case. As such it can serve as a reference as well as a tutorial.

Flow of water and its measurement are ancient and honorable concepts with which to be concerned. I myself built a boat with a sail as a child and thus became concerned with fluid flow and behavior of water as it supported the boat but also resisted the lateral force of the wind on the sail. Current was not at the forefront of my thinking until another homebuilt sailboat took a companion and me through Barnegat Inlet in New Jersey and current prevented us from landing on the shore until we had passed through to the bay inside. Lift and drag on the sail and hull presented aspects of fluids that interested me. But it was my introduction to oceanography after graduate work in upper atmospheric physics that again took me back to water and its movement. In fact, the movement was mixing, flow at the millimeter scale and molecular diffusion of heat and salt responsible for *salt fingers*, a process that permits stable stratification of the ocean with warm water above cooler water to lower its center of gravity through the differential diffusivity of heat and salt. The term *current* would hardly describe the centimeter-scale flow of cells of warm, salty water descending adjacent to cooler, ascending columns of fresher water. My shadowgraph images showed the region above the narrow horizontal fingering-interface to exhibit turbulent plumes of fresher water above and saltier water beneath. And it was this turbulent flow requiring measurement that brought me into the world of current measurement in 1973.

Flow consists of current, waves, and turbulence. Though my own odyssey started with attempts to measure turbulence, I subsequently directed my efforts to measurement of current and eventually to waves. Turbulence is zero-mean and dissipative, at least in boundary layers. Physical oceanographers may dismiss it as not really contributing to the global circulation budget, but it is responsible for all of the mixing, except for salt fingers, at the final diffusive scale. Waves are also zero-mean (except for a small Stokes drift contribution to current), but they transport energy and carry stress from wind at the wave-generating region to erosive processes and possibly destruction of property at great distances. What is left over when these zero-mean processes are subtracted or averaged is current, and current carries heat and material great distances, dispersing across ocean basins what may have been mixed by turbulent diffusion upstream.

As Antony Joseph explores topics in this volume, I too have touched on some and can report on them from my own experience. As I sought a technical solution to a measurement problem that was impeding understanding of an oceanographic process, I tried many of the solutions that the author explains and, as he has done, I found some less suitable for my purposes than those I finally selected. I have probably learned the most from blind alleys or solutions that didn't work, and my experiences may be instructive to others. So, in the spirit that these experiences may be useful, I will describe my career in current measurement.

In the laboratory where I was a postdoctoral investigator at the Woods Hole Oceanographic Institution (WHOI), there was a project to develop a new version of the Savonius rotor and vane internally recording moored current meter that became the VACM, for vector averaging current meter. It used digital electronics, the new RCA CMOS circuits, with a custom lookup table to accumulate each eighth turn of the rotor into north and east registers from the sine and cosine of the difference in angle between the vane and the internal compass. Watching this and the difficulties with bearings, magnetic damping of the compass, calibrations in a tow tank, and development of a suitable tape recorder for the data, I vowed that I would never become involved in the measurement of current, although I appreciated the instruction in digital electronics the exposure afforded me.

Not long after, I needed to measure the flow in the mixed layers adjacent to the fingering interface that I was obtaining in shadowgraph images, but clearly the Savonius rotor wasn't going to do it. A small and very sensitive flow meter was required, and in my thinking I considered laser Doppler, electromagnetic, drag-force spheres, heated thermistor, heated thin films, and acoustic differential travel-time methods. Fortuitously, a visitor from Norway traded me his design for an acoustic travel-time velocimeter for my help in duplicating the Neil Brown CTD that I was building to obtain temperature and salinity measurements on my salt-finger detector microstructure probe. Trygve Gytre was providing his acoustic shear probe to Thomas Rossby, who in turn needed the CTD, and we all benefited by the cooperative sharing of technology. Although the salt-finger detector, an optical system with film recording, was lost at sea soon after discovering salt fingers in the Mediterranean Outflow, the shear probe illustrated nicely the critical shear at density interfaces associated with Richardson-number instabilities that were potentially causing mixing through rolls on the sheared interface.

Having listened to seminars from physical oceanographers visiting WHOI and hearing their difficulties with mixing problems from a turbulence perspective, I vowed to perhaps measure current but never turbulence. Yet not long after that a student, John Tochko, asked me if my shear probe might be used to measure deep-sea currents and Reynolds stress. Reynolds stress, as Joseph explains in his boundary layer chapter, is the turbulent exchange of momentum from a flow above the bottom with the slower-moving fluid closer to the boundary. Small-scale, rapid, and sensitive 3D velocity measurements would be needed. I thought we might manage to do that with the acoustic velocity probe and by a serendipitous mistake, confusing fathoms with meters on the ship's echo sounder, managed to put the shear probe on the bottom and make such a current measurement. Reynolds stress awaited John Tochko's three-dimensional revision of the shear probe into BASS, the benthic acoustic stress sensor.

Antony Joseph describes nicely the benthic boundary layer investigations that were undertaken in the 1980s. I will summarize my own contributions here. My instrument, BASS, was a tower of six 3D velocimeters covering the benthic boundary layer from 35 cm to 5 m above the bottom with a logarithmic spacing. Indeed, over flat topography at 4,800 m depth on the lower rise off New England, the Reynolds stress was uniform over several meters most of the time, a true inertial sublayer without acceleration. The benthic storms that suspended sediment as thickly as 100 m above the bottom as determined from transmissometers on moorings during the High Energy Benthic Boundary Layer Experiment (HEBBLE) occurred a dozen times a year, whereas high-stress episodes also occurred about 10 times a year, but not at the same times as the turbidity storms, causing me to think of the events observed at the HEBBLE site as principally advective, bringing material eroded from the bottom and suspended into the nepheloid layer through the agency of storms somewhere upstream. Having learned as much as we could from this single HEBBLE site, most of us moved on to other sediment transport or bedform studies, but I was convinced we needed to learn more about upstream processes.

The prospect of capturing the actual erosional event and understanding the forcing that increased shear stress above the limited shear strength of the sediment seemed to require fluid stress sensors that might be deployed in an array extending upstream as much as 100 km. With that diameter and with a sensor every 10 km, about 100 sensors would be required. This became an economic as well as a technical issue, since the unit cost per sensor had to be modest, comparable at least to the ship time cost of delivery over a 10-km interval between launches—say, an hour of ship time. The only way to reduce the cost was to automate the construction of the BASS type of sensor, and the National Science Foundation (NSF) awarded me a development grant for what became the modular acoustic velocity sensor (MAVS), a small and thus inexpensive but vector-resolving sensor, subsequently manufactured at first by General Oceanics and later by Nobska Development, Inc. As a sensor, the MAVS served an imagined need for adding current measurement capability to a bottom lander with its own power and data-logging capability, much like a SeaBird temperature or conductivity sensor. This presented a potential market that would support the mass production that could lower unit costs to the level that would permit me to study the origin of the benthic storms that eroded sediment to be later transported downstream. I had to learn things about business that were not in my scientific training, but I had learned much about current meters.

Almost no customer wanted a modular sensor, so a data logger and battery were immediately added to make MAVS a current meter. Shortly after adding the data logger, a compass and then a tilt meter were added so that MAVS became a self-contained current meter. Since that time, capability has been added to accommodate the needs of customers, whom I viewed as clients since this isn't a commodity but a custom instrument supporting the researcher's or monitor's specific needs. Precision temperature or temperature arrays, pressure, conductivity, optical transmission, fluorescence, pH, and other sensors have been added, making MAVS less a modular sensor than a complete benthic platform supporting other modular sensors. There have been times when my concept of measuring current almost seems to be an afterthought for my clients. But advances in capability for current measurement in MAVS have also continued. It is this progression in my own experience in current measurement and technology to fill a specific need that has interested me in Joseph's comprehensive consideration of the history of current measurement technology, including the development of understanding the current systems of the world. He also addresses the processes mediated by currents that affect the oceans and the techniques that have been applied to their understanding.

Although the experiences leading to MAVS form a synopsis of my career in instrumentation, I watched and participated in experiments involving current measurement, drew conclusions, and learned lessons from my own and others' misadventures as well as successes. I will relate some of these and the lessons I learned.

Deep-sea current measurement is easy in contrast to shelf measurements in the presence of waves. But waves are flow and can be measured with current meters too. In the Coastal Ocean Dynamics Experiment (CODE), we discovered from BASS tripods and other measurements that at depths of 90 m on the California shelf, the ubiquitous 17 s Pacific swell was responsible for suspension and reworking of sea-floor sediment. It was the combination of waves and current that did the sediment transport at that depth.

At that depth waves were important, but in shallow water waves are much more important. Measurements with either three axes of current or two axes of current plus pressure can produce directional wave spectra plots that are informative for beach processes. Getting such data in real time may even help shorefront property owners make decisions about evacuation or armoring their beach. By running a cable ashore from a MAVS jetted into the bottom off a beach in Nantucket Island off Massachusetts, we were able to understand sand movement during a winter storm affecting a small community. Jetting provided a stable platform from which to make these measurements. Furthermore, providing a rigid support to make such measurements has been important and surprisingly difficult.

Directional wave spectra were reported in real time to coordinate construction operations at a ferry terminal in Martha's Vineyard near Woods Hole. Although the Nantucket measurements were made from MAVS on a jetted pipe, the MAVS at the ferry terminal in Martha's Vineyard was strapped to a piling on the pier. Divers had to move the attachment to a new piling as old pilings (one of which supported MAVS) were removed. Cabling to an Internet-connected computer on the dock allows construction crews and even ships' captains to assess wave conditions at the dock.

The design of the Martha's Vineyard ferry itself benefited from directional wave spectra, measured where the ferry to Martha's Vineyard turns on its run from Woods Hole, since there were no buoy observations in Vineyard Sound to inform naval architecture ferry design near the turning location. The directional wave spectra for this project were obtained from a small tripod with an internally logging MAVS weighted heavily to stay on the bottom. It was to have had support from an ADCP to extend the velocity profile to the surface that was mounted on one tripod foot, but this instrument had to be removed at the last minute, unbalancing the tripod, which rolled over shortly after launch. Such field experiences are instructive. It turned out that even after the tripod rolled over, good directional wave spectra were obtained, since the pressure sensor gave sufficient information to compute the spectrum from the vector velocities.

Obtaining wave measurements from a rigid mounting (even a rolled-over tripod) are easy compared to those beneath a surface buoy, yet that is where current meters are often mounted, either attached to the surface buoy or on the mooring line beneath the buoy. This totally violates the goal of a rigid mounting but nevertheless must be accommodated. Vector averaging flow measurements to obtain current is further complicated by the sensors that determine attitude, which are susceptible to errors from wave accelerations. Gimbaled magneto-inductive elements swing when subjected to wave accelerations, and strapped-down three-axis magneto-inductive sensors leveled by solid-state two-axis linear accelerometers for tilt sensing are also affected by wave accelerations. Most recently, inertial sensors combining three-axis rate gyros, three-axis magnetic sensing, and three-axis linear accelerometers have become available at a reasonable price. These can provide heading, pitch, and roll at a frequency of at least 5 Hz for rotating instrument frame current measurements into Earth frame coordinates. The remaining motion of the current meter that needs to be subtracted from the measured flow can be computed from the integral of linear acceleration, although this remains a research development problem.

Here I want to interject a few words about the community of those of us who measure current, use measurements of current, manufacture current meters, and sell current meters or current measurements. Under sponsorship of the IEEE Oceanic Engineering Society (OES), a technology committee, originally named the Current Measurement Technology Committee, holds workshops about every four years. The value of our techniques for measurement of waves and turbulence caused us to rename ourselves the Current, Waves, and Turbulence Measurement Technology Committee, and CWTM workshops have been held most recently in Charleston, South Carolina, and Monterey, California, and will be held in 2015 in St. Petersburg, Florida. As Antony Joseph explains and describes in this volume, many techniques for observing water movement and waves and precisely measuring these and turbulence are presented and discussed at these workshops. At some workshops the problems with existing current meters were the theme, at others new technologies were stressed. Every year, and more recently twice every year, an Oceans conference is sponsored by the Marine Technology Society (MTS) and the OES, at which there is generally a session or two at which current measurement talks are presented. HF Radar, also described by Antony Joseph, is often presented at Oceans conferences, since it is considered part of ocean remote sensing as well as current, wave, and turbulence measurement, all of which are topics in Oceans conferences. Less is presented about physical oceanographic topics in currents at Oceanic Engineering events, as presented by Antony Joseph in his first chapter, yet it has been a principal driver of measurement of ocean currents and sensors. Though I have learned something from physical oceanographers at Oceans conferences, it is really at WHOI where I have learned the most about physical oceanography from talks and from cruises on which I have been present.

Western boundary currents like the Gulf Stream, Kuroshio, and Agulhas were first observed by ship drift but later by moorings, motivating the development of the VACM for capturing variability in the Gulf Stream. An interesting experience that this instrument endured in the Agulhas (I learned from talks) was the nearly total destruction of its electronics from Strouhal oscillation of the mooring cable in the very high-velocity Agulhas current. This experience motivated more secure construction of the chassis and even the circuit boards as well as some efforts to reduce the Strouhal excitation. I learned that one possible approach to reducing Strouhal oscillation could be to wrap lines around the current meter housings in a spiral to force detachment of the vortices at defined points along the housing and thus reduce the forcing. There was even some consideration given to use of faired mooring lines, including Science Applications International Corporation's Quiet Cable, which, though developed to support hydrophones, had a sharp extruded plastic shape along the cable. The total drag is purportedly reduced by suppression of the Strouhal oscillation. I found attractive the possibility that rather than building great strength into the moorings for current meters, a lightweight solution might achieve as much with a beer-can-sized current meter and 3,000 m of 100 Kg test-strength Quiet Cable.

The discovery of rings and eddies has been well described by Antony Joseph. I learned of rings shortly after my arrival at WHOI. On occasion, a warm ring from the Gulf Stream was observed at moorings north of the mean location of the Stream. The strong current dragged buoys under, moved anchors, and sometimes caused moorings to go missing. But there were important processes going on in these rings. Inertial and near-inertial oscillations in these rings had been estimated to increase internal shear sufficiently to cause shear instabilities and consequent mixing. WRINCLE, the Warm Ring Inertial Critical Layer Experiment of 1990, investigated these layers with XCTDs (expendable CTD probes), XBT (expendable bathy thermograph) drops, my RiNo (Richardson number) float, and numerous CTD lowerings to obtain density profiles and current shear at 700 m depth. RiNo was essentially a BASS tripod covering 5 m vertically without a weighted part that measured velocity at six locations and density at the ends to characterize Richardson number, a measure of resistance to shear instabilities. It was neutrally buoyant and acoustically commanded to occupy an intermediate depth (700 m in WRINCLE) until recalled for data recovery after a week. In the ring, it was tracked with a low-frequency beacon so that it could be found after this duration. I enjoyed my collaboration with Ray Schmitt and Eric Kunze in these measurements. Rings became recognized as important structures for bioproductivity as well as strong current anomalies in the western ocean regions.

Diapycnal mixing, the turbulent or possibly diffusive mixing between water masses separated by a horizontal interface or gradient, called for both integrative measurements with tracer releases and subsequent sampling and direct measurements of shear velocity. The RiNo float mentioned with respect to the WRINCLE project was designed to measure shear over a 5-m vertical span and simultaneously measure the temperature gradient over that range and the density difference between the two ends. RiNo was neutrally buoyant and could be acoustically commanded to float stably at a selected depth for periods as long as a year (although 10 days was the longest deployment that was ever recovered). The ratio of the density gradient to the velocity gradient squared, the Richardson (Ri) number, is a measure of stability to overturning, where $Ri = 1/4$ is the critical value below which finite perturbations grow into overturning events that are moderately ($\sim$30%) efficient at mixing fluid. The expected scale of this mixing is order 1 m, and the intermittency even with $Ri = 1/4$ is low, perhaps 1–5% of the time. The RiNo float was deployed in WRINCLE and allowed to drift around the warm ring for about half a revolution of the ring and then recovered to obtain the data, later reported by Eric Kunze.

Two RiNo floats were deployed subsequently in the North Atlantic Tracer Release Experiment (NATRE) in 1991, west of the Cape Verde islands near Seiberling Seamount. Although one float was attached to a bobber float (a variable ballast CTD-measuring Swallow float, acoustically tracked through the SOFAR channel), this float became silent after seven months and was never recovered. The other was lost during ballasting operations, showing that not every technically challenging operation is successful. Observations with RiNo and from other probes capable of measuring Richardson number have shown that in regions where diapycnal mixing seems to be occurring, $Ri = 1/4$ is frequently observed and hovers near that value or slightly above much of the time. This gives the idea that much of the thermocline is marginally stable and susceptible to some trigger to cause active mixing, something as small as an internal wave superimposed on a steadier shear from inertial oscillations.

As a drifter near the surface, RiNo offered a glimpse of the forces affecting surface drifters since the velocity at depths spanning 5 m were logged as well as the surface float position being tracked. In an experiment Rocky Geyer performed in 1989 at WHOI, the behaviors of several surface drogues were compared to RiNo. Although it had been assumed that the surface layer in Buzzards Bay near Woods Hole was well mixed in a moderately high wind event in April, before surface heating was significant, RiNo showed a shear layer at several meters' depth that had a strong effect on the drogues, depending on the type of subsurface drag (rope or window shade) and the shape of the buoy (spherical, half sphere, or cylindrical) exposed to the wind. These instrumental validations were important since Lagrangian drift measurements have been used to discover currents acting over great distances in remote parts of the ocean. More can be read about these surface drift measurements in Antony Joseph's chapter on that topic.

In his chapter on Lagrangian-style subsurface current measurements through tracking of subsurface drifters, Joseph amply describes and explains the techniques used to study deep currents. Subsurface drifters are certainly better current-measuring probes than surface drifters and can even provide real-time tracks from SOFAR acoustic transmissions, as demonstrated by the floats employed by Douglas Webb and Thomas Rossby. If data in real time are not required, the SOFAR system that uses sound transmitted by the float and received at fixed deep listening stations can be inverted. This inverted RAFOS system developed by Rossby uses sound transmitted from moored sound sources to permit floats to listen and track themselves from the arrival times of the pulses from three or more beacons. Having done work with both Webb (I was assigned the job of repolling one of the original low-frequency SOFAR transducers) and Rossby (I participated in the cruise where his shear probe received its sea trial), I followed these developments with interest.

The arrival times logged over the deployment life of the float are relayed by satellite after several months of Swallow-float drifting when a recovery weight is dropped and the float surfaces to tell its story before becoming another dead floating glass object on the surface or sinking. I found this mode of recovering data from an instrument that might be expendable economically compelling, since ship time is so expensive. In fact, I attempted to use this strategy for an array of MAVS expendable benthic landers, XBLs, to study benthic weather. This proposal was not funded, however. There is a time to study benthic processes, and there is a time to focus on other scientific puzzles. The time to investigate benthic weather has passed.

The highly successful ARGO array (Argo is named for Jason's ship from Greek mythology) has floats that drift subsurface for about a week and then pump ballast to the surface and give a satellite fix and transmit temperature, and often salinity and pH or other measured properties, from its excursion to the surface before pumping ballast to return to the sampling layer. More than 3,000 of these floats in nearly every part of the world ocean now are providing a global picture of currents, eddies, gyres, and the water masses that are associated with these current structures. As Joseph tells in his discussion of subsurface floats, the time on the surface where the float is not at its target depth causes its drift to deviate from that desired and must be corrected with surface current estimates. The degree of autonomy in this program is most impressive and takes us to the new generation of ocean large-scale observations.

In considering large-scale ocean currents, nothing is as large scale as the tides, and these are important even on the seafloor, where they can give benthic larvae a ride to a new home. By chance I had two roles to play in such tidal flow measurements at the Endeavor site of the Juan de Fuca hydrothermal vent. Twenty MAVS current meters, some with temperature arrays to monitor flow and thermal gradient in the bottom meter, were deployed for a year by the University of Washington, and then several years later WHOI deployed three MAVS instruments to measure tidal flow. This was at a site called Easter Island and determined that heat apparently modulated by the tide was in fact only advected by the tide from steady flow through the diffuse vents there. Tidal flow, rectified along the axis of the valley, is capable of dispersing larvae and may therefore be the mechanism for colonization of new vents. This is another example of the utility of current measurements in inaccessible regions. But this had not been my first exposure to a hydrothermal vent.

In 1979 Fred Grassle at WHOI invited me to bring my prototype BASS acoustic velocity sensor on a dive by the deep submersible, Alvin, to the newly discovered hydrothermal vent, Garden of Eden near the Galapagos, where a previous attempt to measure flow with a propeller had suffered from crab infestation. With low velocities and probability of fouling by crabs, the BASS current probe measured a vertical flow of 12 cm/s and a temperature anomaly of about 8°C above ambient temperature.

At the surface, Lagrangian trajectories of drifters tracked by Argos satellite (Argos is Advanced Research and Global Observation Satellite) and processed by CLS Service Argos have given us low-cost information about eddies and gyres and, almost as an afterthought, data from the transmitters on the surface. The identification number that permits several or many PTTs (the surface transmitters) to be distinguished from one another also allows data to be transmitted about temperature, conductivity, acoustic arrival time delays, and recent profiles of these quantities so that the ARGO floats spending most of their time submerged can send not only position but profile data to the user. As Joseph explains, the certainty of a single Argos transmission being received and then captured without error is low so that repeated transmissions are required to ensure essentially total data transfer. The RAFOS floats that remain submerged for periods as long as half a year and then surface to transmit all the acoustic arrival times of beacon transmission during their submerged deployment continue to transmit the full data log for several weeks until their battery is exhausted, with about 80% of the log eventually recovered, much of it in duplicate. This capability has opened up a great window on ocean-scale processes. Service Argos also offers a relocation service for instruments that have popped to the surface unexpectedly. I have subscribed to this service, but the few times when it might have allowed me to recover a lost instrument, it has not worked, probably because there is a low probability of detecting a transmission when it first occurs. However, its utility for recovering data from an expendable instrument is excellent.

As Joseph describes, many different techniques have been used to measure current and, more particularly, turbulent flow in a boundary layer. My own contribution to this technology has been acoustic travel-time techniques (ATT), but my admiration for Doppler techniques is great; I particularly envy their freedom from flow distortion by structure of the sensor. Certain problems in making measurements from a moving surface buoy plague both techniques: motion of the current sensor. As mentioned previously, this affects both knowledge of in which direction the measurement of flow velocity has been made and the uncertainty of the velocity of the sensor itself. The new attitude sensors that have become available are inexpensive in power, volume, and cost and will be utilized in the next generation of current meters mounted on mooring or surface buoys exposed to surface waves. As configured, the inertial measurement units (IMUs) are capable of removing the rotations of the current meter housings, whereas the attitude and heading reference sensor (AHRS) units can permit direct rotations of instrument frame velocity measurements to Earth frame coordinate velocities. The second problem, determining current meter velocities in waves, remains unsolved, although using linear accelerations is clearly a path to its solution.

Measurements of current from moving vehicles are becoming more important, with gliders and AUVs observing water properties and flow. Ships have long obtained current measurements with ADCPs and can remove the ship motion with GPS measurements of ship velocities in deep water and with bottom-tracked Doppler-shifted returns in shallow water. But when the vehicle is submerged as a glider or AUV, the GPS signal is not available and in deep water a bottom-tracked Doppler signal is not available either. A Doppler profile of velocity beneath a descending vehicle has been used to extend surface measurements of velocity where GPS is available to greater depths by a bootstrap extension downward. This remains a problem, however, and measurements of velocity on a submerged moving vehicle are still tricky. Of course, the AUV doing a survey may have navigational transponders on the bottom that give precise AUV velocities from which profiles with an ADCP can be extended. One of the more difficult AUV navigational tasks is from the underside of ice, where "bottom tracking" with an upward-looking ADCP might be hoped to provide precise AUV velocities, but the ice is not as reliable a backscatter target as seafloor generally is. And whenever the reference surface is very rough, as the underside of ice may be, and hydrothermal vent chimneys are the bottom track, it is difficult to maintain. My own experiences with these problems are hearsay from my colleagues at WHOI and the National Oceanography Center (NOC) in Southampton, where the navigation problems are taken very seriously and the current profiles are almost an afterthought.

There are practical issues with current meters, such as power, sensitivity, sampling rate, calibration, linearity, and freedom from flow disturbance. The last is partly dependent on the measurement technique so that, for example, a Doppler sensor is less influenced by the structure of the sensor than a mechanical or acoustic travel-time sensor. But even when the distortion of flow by the structure of the sensor is accounted for in the design of the structure, there is often an issue of bio-fouling, and that is quite serious and difficult to prevent. My own earlier applications of the BASS current measurements were in deep water, and bio-fouling was not experienced. But in shelf depths there were barnacle infestations that didn't affect the acoustic sound transmission but surely had some effect on the flow around the transducer supports. This condition became more severe in the near-surface region where sunlight permitted seaweed to grow as well as tunicates, so that in several months there was sufficient material growing on the transducer supports to obstruct the flow through the sensor. The acoustic signal was not affected unless seaweed with flotation bladders obstructed the acoustic path. Tri-butyl tin antifouling worked to some extent, and Desitin (zinc oxide) cream also delayed the accumulation of bio-fouling, but the solution was only found in 2010 with a silicone coating, two sources being ClearSignal and PropSpeed. These coatings did not kill organisms but rather prevented them from attaching to the substrate tightly, and the organisms washed off or could be removed with a light rubbing.

Power limits deployments with stored energy (batteries), so it is desirable to keep the power consumption low. Mechanical sensors like the Aanderaa RCM4 and the VACM derive the power for the sensor of fluid movement from the flow itself, and these have lower power consumption than Doppler or ATT sensors. But even in active flow sensors, the acoustic power is often less responsible for the power budget than the digital processor controlling the process. When I encountered the problem with deployment time limitations in MAVS from microprocessor power consumption, the short-term remedy was to switch to a controller that could be put into low-power sleep between measurement bursts and where the clock frequency of the microprocessor could be reduced between samples within a burst. This extended the available deployment duration from two weeks to a year or more. Recent applications are now cable-supported for observatories, which reduces the demand somewhat for low power. But other techniques to reduce power, if the need is great enough, have not yet been explored. BASS, for example, used the COSMAC microprocessor as a controller with significantly lower power than modern microprocessors, but this system did not offer the user the friendliness we now expect of current meters.

Sensitivity is rarely a serious limit except for turbulence studies or critical deep-sea flows where the flow is very slow and there is little turbulence to overcome hysteresis or *sticktion* in the sensor. But some of these conditions do require such sensitivity. In mechanical sensors there is residual bearing friction so that no motion occurs with flows below some threshold near 2 cm/s, depending on design and condition. Since direction of this unresolved flow is sometimes more important than the actual volume of transport, it is argued that applying this sticktion velocity threshold for no motion to the vane-indicated direction of flow still yields valuable information. Something similar can occur with acoustic Doppler sensors as well, particularly in very clear (no acoustic scatterers) water. The Doppler signal may be so weak that it cannot be distinguished from the side lobe scatter from mooring hardware, and this zero Doppler-shifted signal might be interpreted as no motion and accounted for in some way that is not representative of the actual flow. ATT sensors do not have hysteresis or sticktion issues since they respond linearly right through zero flow, but the determination of the zero-flow reading is a calibration requirement in the absence of this distinctive reading.

Calibration, linearity, and sampling rate are important considerations for any current meter. Calibration might mean electronic calibration against some standard. For the Savonius rotor and vane instruments, this means readout of turns of the rotor and angle of the vane. For an ATT instrument, it means readout versus nanosecond delay in a simulated acoustic path. For each of these, the model of behavior indicates that these calibrations are a good representation of the linearity of the instrument and the limitations of hysteresis, drift, and noise of the measurement. But a secondary calibration is necessary for each technology, at least every time a major change is made, and that is a tow through still water and other actual fluid calibrations. These will include the effects of flow disturbance and vortex shedding by the structures so that readout can be related to tow speed. To obtain more comprehensive calibration confidence, there should be variation in angle of the sensor during the tow, variations in towing speed, addition of oscillatory motion during the tow, and such possible effective environmental conditions as temperature, salinity, bubbles, small-scale turbulence, and depth or pressure.

Sample rate limits how high a frequency of flow variability one can accurately capture. To first approximation, this is the number of independent samples per unit of time. In some instruments, a single measurement taken at each sample interval is sufficient as an independent sample, whereas in other instruments the measurement rate may be much greater than the sample rate, and the measurements are averaged to obtain a lower noise sample at the sample rate. Acoustic Doppler current meters generally make many measurements or pings for each recorded sample, since the noise in a single ping is fairly large, but measurement frequency is limited only by the effective range, which in turn is a function of the acoustic frequency. By contrast, the ATT instruments achieve a lower noise from a single ping, so that is the sample rate limit. High sample rates use more power but permit tracking flow variations at a higher frequency.

These practical concerns for current meters affect what problems can be addressed. Turbulence requires high sampling rate and may require high sensitivity. Creeping flow in the deep sea requires sensitivity and linearity near zero velocity; all require calibration.

Current measurement technology develops at the intersection of oceanographic problems and technological capabilities in society at large. Modern HF radars, acoustic Doppler current meters and profilers, satellite altimeters, and SAR systems all depend on electronic and cybernetic innovations. Even such basic capabilities as titanium and ceramic materials for housings were not available formerly. Meanwhile, the demand for more detailed information about high-frequency variability at finer vertical separations has driven the need for profilers and real-time cabling of sensors to the user. Antony Joseph has assembled a comprehensive and scholarly story of the technologies and their applications in this volume, and I congratulate him.

A final thought in such a volume is, what is next in current measurements? The author has restricted himself to what has been done and reported, but I feel freer to project to what might be done. The surprises from communications, electronics, remote sensing, and data handling will continue to influence current measurement technology. As significant will be the influence of problems ready for observations to illuminate. Global circulation changes in response to global climate change are at the forefront. Diffusive mixing, interleaving of water masses, dispersion in horizontal flows, and surface forcing by heating, evaporation, wind stress, and freshwater runoff are all drivers and need technology to measure and track them. The scales are small for mixing processes and large for dispersive processes, whereas the circulation scales are global and require extension of the ARGO array to very high latitudes. Gliders and other autonomous vehicles, including the Waveglider for near-surface surveys, will become more important since they provide a multiplier in human effort and investment. But they stress data handling, as do the observatories where data continues to pour in in ever-increasing streams. Processes at the boundaries are still among the most important—not just the air-sea surface but the bottom (especially at vents) and the shore. These regions are all more difficult to measure than the interior and will require new technologies such as vorticity sensors and flux probes for heat, salt, CO_2, and nutrients. Biological observations in concert with physical measurements are critical for understanding many of the most important interactions, and each practitioner, both biologist and physical oceanographer, will need to ask for help from the other. The task in the broadest sense is to understand the Earth, at least the ocean part of the Earth and its atmosphere, sea floor, shores, and the water budget that results from storms, insolation, evaporation, and precipitation. Finally, the past is a key to the future, and understanding periods of freezing and heating in the geological record, paleooceanography, may enable us better to anticipate the future.

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