Historical Developments of Current, Wave, and Turbulence Measurements Including those by MAVS

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***Abstract*-Personal knowledge of the author stretches from the Geodyne 850 current meter, predecessor of the VACM in 1969 to his own development of MAVS and its recent innovations. Housings, recording media, velocity sensors, and compasses have changed most noticeably. Applications of current measurements are next most striking about the developments in our field over the last 40 years. Where and how current meters are deployed have migrated from ship lowered or fixed moorings to bottom tripods, profilers on a mooring, and even to shore-based HF Radar antennas. Present developments address power to operate autonomous instrumentation, data communication in real time, and novel adaptations of current measurement techniques to non-traditional current measurement problems like horizontal profiles, turbulent mixing, and wave monitoring. New applications will be presented at this workshop, with perhaps greater emphasis than new developments in sensing.**

I. INTRODUCTION

Several decades ago, Bill Schmitz of Woods Hole Oceanographic Institution defined the central question of Physical Oceanography to be, "Where does the water go?" The ocean conveyor belt through the major ocean basins affects global climate yet is potentially sensitive to perturbations in surface heating or freshening that can inhibit deep convection, including variations that presumably have occurred through geologic history. The argument for studying oceanic plumbing is that to understand the earth, this large-scale fluid-dynamic process must be characterized. When questioned about the role of estuarine or coastal processes or sea-floor turbulence or even salt fingering, Bill said that these processes were merely noise on the important drivers of global convection.

Since this was a reasoned though not unanimous position of one of the major physical oceanography groups in the world, it deserved respect and the attempt to answer the question was supported for several decades by the Office of Naval Research and later by the National Science Foundation through the WHOI Buoy Group and its leadership, the variously appointed "Gang of Four". In 1969, when I arrived at WHOI, in what was then the Ocean Engineering Department, the Vector Averaging Current Meter was being developed in my lab, Doug Webb's Electronics Group. I observed Jim McCullough discussing how to remove the aliasing of the infrequently read vane in the Savonius rotor and vane current meter that was the standard of that time, the Geodyne 850, by taking a vector reading of direction every time the rotor detected that the fluid had advanced a short distance. These vectors were to be accumulated in a north and east register and the totals of these registers were to be recorded every 15 minutes or some other nominal interval. This was the Vector Averaging Current Meter [1], the VACM, which became a standard for deep-sea current measurements for almost four decades. I watched Dick Koehler convert Jim's ideas into digital circuits, struggle with magnetically damped (rather than fluid damped) compasses, and participate in Winfield Hill's development of a new tape recorder [2], and I vowed to myself that I would never get involved with current measurements. A decade later I said that measuring current wasn't too bad but I would never get involved in turbulence measurements and a decade after that I determined that I would avoid at all costs measuring waves. But fluid moves, that is what distinguishes fluid from solid, and it moves as current, the DC part, as waves, the AC part, and as turbulence, the chaotic part. And measuring fluid motion is the subject of this workshop and my exposure to this activity is the subject of my paper.

II. CURRENT METERS

A. Current Meter Housings

Housing design is one of the most striking changes from the 40 kg aluminum cylinders of the early instruments to the 4 kg titanium cases of some of the recent instruments. While this purely mechanical part of a current meter seems relatively unimportant, in fact, it drove the mooring design, the floatation required for the mooring line, the size of the deployment team to handle the moorings, and the size of ship and equipment on the ship. It even demanded establishment of Buoy Engineering, represented at WHOI by Bob Walden's Buoy Engineering Lab in the Ocean Engineering Department, mostly collaborating with the Buoy Group in Physical Oceanography but under Bob's successor, Henri Berteaux, sometimes in competition.

Moorings, as illustrated in Fig. 1, consist of an anchor at the bottom, a mooring line to a buoy at the top, and instruments strung along the line. In 1969, there were few acoustic command releases and surface buoys were the norm, possible to find with radio direction finders homing on their short-wave marine band radio transmitters, and then recoverable by hauling the buoy on deck followed by the mooring line with the current meters in line. But the mooring line was heavy, 3/16” steel wire rope, and the tension increased with distance off the bottom. This was and still is compensated for by flotation at intervals along the mooring line.

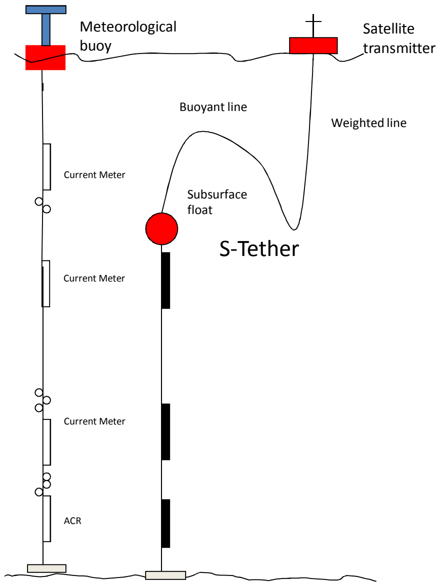

Fig. 1. Deep-sea mooring supporting heavy-case current meters requires glass ball buoyancy distributed along its length. A surface buoy is required for meteorological observations and for telemetry of data in real time. Sub-surface buoyancy is less stressful on a mooring and the S-Tether is one way to retain surface telemetry without a large surface buoy.

Hollow glass balls, 17in diameter providing 50-lb buoyancy each but also weighing 50 lb in air, are encased in plastic hard hats and bolted in groups to lengths of chain placed in line in the mooring, generally near a current meter, to float the mooring line and current meter beneath them. During recovery, each shot of chain with buoyancy must be stopped off and the buoyancy removed, then the current meter removed, and then the mooring line reconnected to the already recovered mooring line and the haul back continued. Before the development of the acoustic command release and its incorporation in the WHOI standard subsurface mooring, the anchor was also brought to the surface and its recovery was a dangerous thing. On at least one mooring cruise that I participated in as an observer, the anchor was jettisoned after the bottom current meter had been taken off to reduce that risk. Fig. 2 shows a deck filled with baskets of glass ball buoyancy for the moorings that are to be set.

The most damaging thing about the surface buoy, however, was its failure rate. Wear and corrosion at the top shackle was eventually discovered to be the weak link and a bushed universal joint replaced this former heavy duty shackle with great improvement from a life of three months to a life of several years. The surface buoy became essential for near-surface current and for meteorological measurements but until those became a requirement, acoustic command releases with subsurface buoys solved the problem of wave-induced wear and mooring life was extended to a year or 18 months.

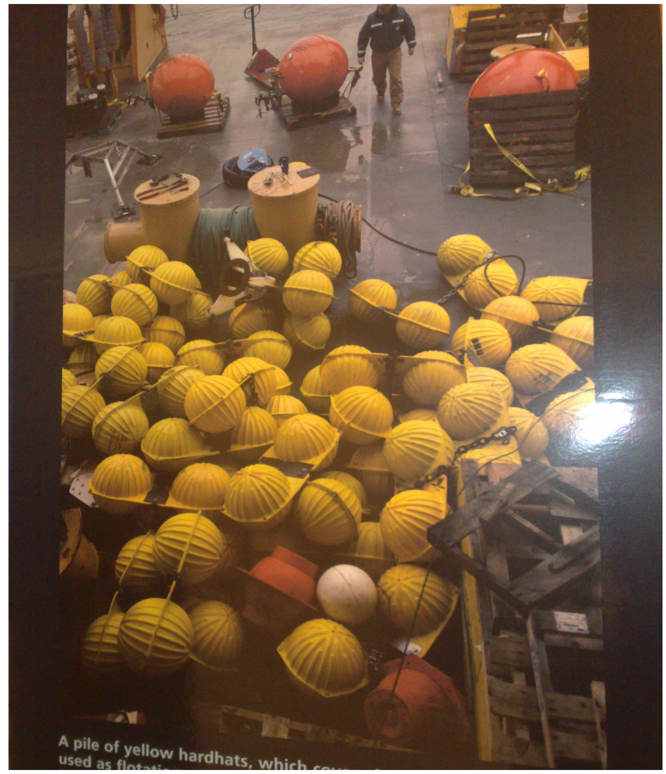

Fig. 2. The deck of this ship has piles of glass buoyancy balls required for heavy deep-sea moorings. Large deployment crews are required to handle these heavy mooring components.

The heavy housings as originally designed were able to encase long electronics racks for sets of cards supporting temperature and other measurements and there was room for a large alkaline battery to keep it powered for a year or longer. Fig. 3 shows a current meter of my own design in the same architecture as used in the VACM (Dick Koehler’s legacy of Elco 35-pin gold plated connectors on D-shaped boards) this time for BASS, the Benthic Acoustic Stress Sensor I used for benthic studies in the 1980s and 1990s [3].

Environmental testing of each instrument in a cold room reduced the failure rate of the VACM to a low level although there were bearing failures, fishing line tangles with the rotor or vane, compass bearing failures inside, and in one high-current deployment in the Agulhas current, Strouhal vibrations shook the components off the boards and the screws out of the electronics racks so that at recovery everything was found in a jumble at the bottom of the housings. In the end, however, it was the obsolescence of parts that made continuance of the VACM a problem, while other sensors and developments have surpassed many though not all of the VACM qualities.

The Aanderaa current meter housing was not as heavy as the Geodyne 850 or the VACM housing. The RCM 5 [4] was a very popular current meter and was sold in numbers unsurpassed by any single design until decades later. They were not in use at WHOI, however, and I didn't see them in my own early days nor did I learn how they were deployed. I suspect that moorings with Aanderaa current meters were not as heavy and didn't require as much buoyancy and were thus less reliant on a large buoy operations group to support them.

Fig. 3. BASS electronics rack based upon the electronics chassis design of Dick Koehler as introduced for the VACM with D-shaped circuit boards and the Elco 35 gold-plated contact connector. The VACM magnetically damped compass is the cylinder near the bottom. This BASS has an early microprocessor-based controller with a ribbon-connector bus giving it the designation of Smart BASS.

B. Data Storage

Data storage has benefited most from parallel developments in the personal computer industry from the photographic recording of spots in the Geodyne 850 thru digital cassette tape to hard drive and now to Compact Flash memory in ever larger capacity. I never experienced the photographic recording but long after cassette tape recorders became common, David Nergaard at EG&G maintained the sole surviving reader for the remaining Geodyne 850 current meters with that recording modality. I was closely associated with the digital cassette tape development, however. Winfield Hill at Harvard University developed it for Jim Baker and it was selected for the VACM's recorder putting Hill into business as SeaData, Inc. and allowing for the first time, inexpensive bulk digital data recording in small size and very low power. Digital tape had a few other implementations but never achieved high reliability. Fig. 4 shows one of these cassette tape recorders mounted on my battery case endcap to capture serial current meter data sent from the BASS electronics of Fig. 3.

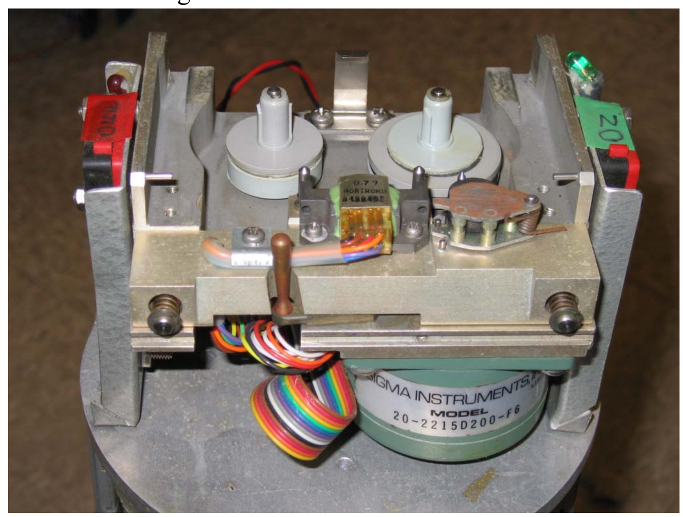

Figure 4. SeaData digital cassette tape recorder transport mounted on the endcap of the BASS battery/logger case. The four-track head and stepping motor drive allowed intermittant recording without power drain between records.

The SeaData digital cassette recorder used a four-track recording head with a stepping motor for the capstan that was locked in position when power was removed. It stepped ahead for each new record some 10 or 20 bit spaces with no magnetization in order to clear tape that might have relaxed since the previous record before starting a new record. NRZ (non-return to zero, a self-clocking single signal format) was used with a positive flux change to represent a one and a negative flux change to represent a zero. Digital words were moved from an external shift register into a buffer and characters of four bits at once were encoded in parallel to the four-track head. Eleven million bits could be recorded on a standard cassette tape although special digital cassette tapes (same density of bits) were used that had been pre-screened by the manufacturer through recording a pure tone and then verifying that there wasn't a single cycle missing in playback. Sadly, not every such certified cassette tape had been erased following this test and I was not the only user to find the inter-record gap undetectable. I took to erasing every cassette tape that I used on a bulk tape eraser but others told me I was certainly degrading the pristine quality of the certified tape by doing so. I even took a compact cassette tape eraser into the field and I sometimes recycled test tapes through it with surprising results since it simply set all the magnetic domains on the tape to one direction. This caused the first recorded phase transition of each record to vary from a positive transition to no transition depending on which half of the supply reel the piece of tape being recorded had occupied during the static tape erase. The result was that half the records could not be read, making the data spotty.

The big issue for me was the tape reader, a significantly more complex machine than the recorder. The transport was a standard four-track playback but the detector for the flux changes had to self synchronize as NRZ decoders do. A three-quarter-cell timing circuit was started on the first flux transition and then the sense of the next flux transition after three quarters of the full cell interval had passed was counted as a one for positive flux change and zero for negative flux change. Each track on the tape was detected separately since alignment between the recording head and the playback head could not be assured. A FIFO register aligned the bits from these four tracks so a serial output restored the order of the output to that of the original. Only one reader existed at the time I went to sea with the first internally recording CTD in 1972 and I was forced to fly blind, only able to tell that something had been recorded by playing the tape back upon a four-track stereo tape player.

Although my adaptation of the VACM cassette recorder was for a free vehicle CTD to supplement my optical salt finger detector, I was well positioned to employ it for my velocity sensor when that was needed and subsequently autonomous current measurements benefited from the SeaData recorders for almost two decades, becoming less free from errors as thinner tapes were used to extend the deployment duration. Faster recording for turbulence measurements required special stepping motors with a ramp-up circuit to get them up to speed. Ultimately I was limited to five fast recorders (5 Hz sampling of BASS measurements) owing to the retirement of a production worker at Sigma Instruments, the supplier of the stepping motors. Only he was able to deburr the rotors using walnut shells without rounding the corners and thus losing precise registration of each step as resulted from steel shot deburring, the technique his replacement insisted upon using.

Limited digital storage capacity rapidly became a thing of the past when hard drives could be put inside current meter housings with the Onset Computer Tattletale 6 [5] and capacity of disk drives went from 20 MB to 120 MB to 200 MB, stressing the adaptation of PC driven disc developments for low power turn-on turn-off use (typical for laptops but then not yet standard). Before the really large disk drives became available, compact flash became available as the Onset Tattletale 8 with Persistor board and up to 2 GB compact flash [6]. This can store sufficient velocity data for any of the applications that I am aware of but I am sure that applications will arise that demand more. But it is one of the most gratifying developments in the technologies that have been current meter limiters in the past.

C. Sensors

1) Current Sensors

Current sensors have migrated from mechanical rotor and vanes or propellers to electromagnetic, acoustic Doppler, and acoustic travel-time, not to mention HF Radar for surface current measurement. This progression has been motivated by applications where the previous sensor had limitations. The Savonius rotor and vane drew negligible power and in moderate steady current, the rotations of the rotor varied linearly with speed of the flow and measuring the direction of the flow from a single sample of the vane at the end of the sampling interval was sufficient. But when the current was not steady, the sample of vane direction did not represent the average current accurately and thus vector averaging was needed in place of a single sample of direction per sample interval.

Near the ocean surface, waves create reversal of current direction over short periods and the vane in a VACM fails to follow these reversals at wave excursion lengths of half a meter or so, sometimes associating the current with a direction opposite to the true average current. In addition if the VACM is pumped vertically, the rotor spins even in absence of current. So to measure current accurately in this more demanding environment, Bob Weller with Russ Davis invented the Vector Measuring Current Meter consisting of orthogonal pairs of fan rotors [7]. These each have an excellent horizontal cosine response and resolve the instantaneous flow for every excursion of flow sufficient to rotate the fan rotor a fractional revolution. The VMCM is essentially the last mechanical sensor of current introduced to ocean measurements. Subsequent ocean flow sensors have been acoustic and electromagnetic.

Acoustic Doppler and acoustic travel-time sensors play a major role in current measurement today. More will be said in a subsequent section about these two acoustic techniques. Here it is sufficient to observe that they have no moving parts and to a greater or lesser degree make their measurements of fluid velocity some distance away from the structural support of the acoustic transducers and thus may be considered minimally invasive, measuring an undisturbed flow.

The Geomagnetic Electro-Kinetograph (GEK) [8] introduced in the 1950s by Bill von Arx and utilized in a dropsonde as Tom Sanford's electric field measuring instrument [9], has a long history. The earth's magnetic field induces an electric current in moving, conductive seawater such that the voltage between two electrodes moving with the water is related to the difference between the conductivity-weighted vertically-averaged fluid velocity and the velocity of the electrodes. The conductive part of the seafloor is included in this conductivity-weighted vertically-averaged velocity. Current meters have used the magneto-induction of electric current in a moving conductive fluid as well, the S4 current meter by InterOcean being the best known realization of this modality [10]. In this instrument, housed inside a plasticribbed sphere, coils generate a magnetic field, square wave chopped, from which electric fields are measured with pairs of electrodes on the skin of the sphere, detected synchronously with the chopped magnetic waveform. From each coil two components of flow can be measured so by using two coils, a full 3-D current vector can be determined. The S4 is a self contained, internally powered, and internally recording instrument.

2) Compasses

The compass has long been a limiting element in accurate current determination and the early bar-magnet driven Grey coded disc used in the VACM has been superseded by flux gate magnetometers and three-axis magneto-inductive sensors coupled with tilt sensors such as two-axis accelerometers. However, there are still limitations in azimuthal resolution especially at high magnetic latitudes. Inertial sensors can be coupled to magnetic sensors for a combination azimuthal sensor in which the low-frequency part is provided by a magnetic device and the high-frequency part comes from the inertial sensor [11]. Fig. 5 illustrates this. The efforts to improve the compass have been continuing for three decades so far. Ocean applications are not the only drivers of this effort.

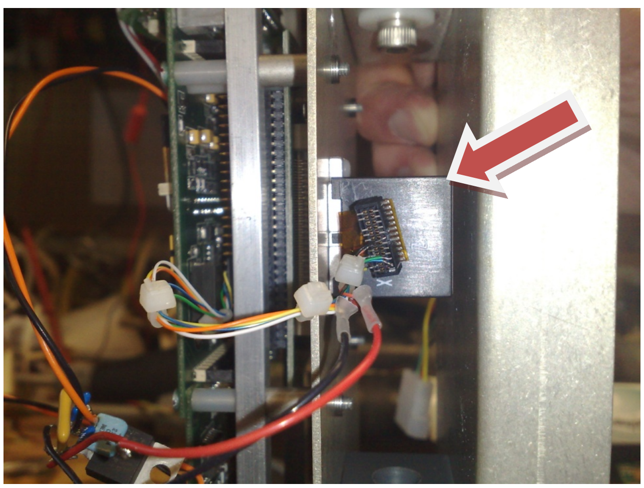

Fig. 5 The shiny black cube between the two chassis plates (arrow) is the rate gyro in the Ice Tethered Profiler wired to the TT8 µP of MAVS with the colored wires. This inertial sensor by Analog Devices adds high-frequency yaw back to the low-frequency measurement of heading by magneto-induction

D. Applications

Applications of current measurements have expanded from point measurements of subsurface currents in straits and long-term averages of currents in places like the Gulf Stream, to profiles of current by acoustic Doppler profilers in stratified or inhomogeneous flows. Deep deployments of current meters have been used to estimate bottom-water transport and sections of current along a parallel of latitude have been used to estimate meridional transport of heat. Turbulence sensors, a kind of small scale, sensitive current meter, have been used to measure bottom stress and sediment transport as well as to estimate turbulent mixing in the thermocline.

My own search for internal mixing processes is what pushed me into the current measurement business. I had photographed salt fingers in the Mediterranean Outflow on an interface as reproduced in Fig. 6. On that interface, the 1-cm

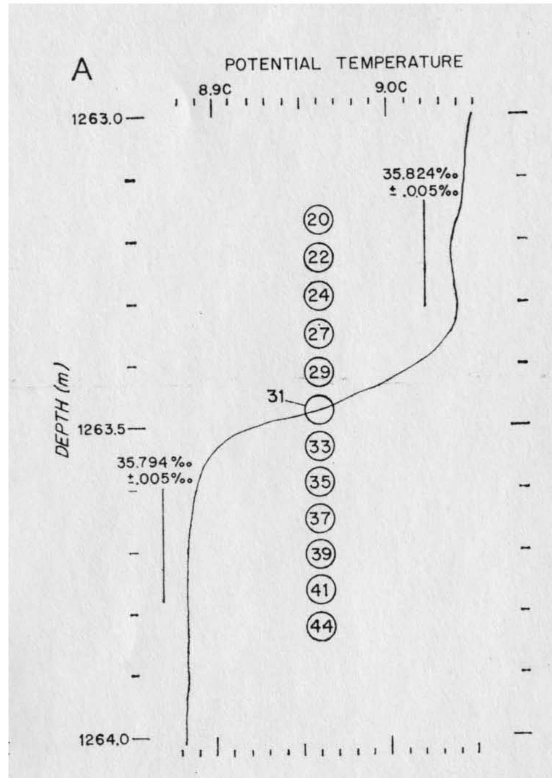

Fig. 6. At a 15-cm thick interface between two mixed layers differing in temperature by 150 millidegrees and salinity by 0.030‰ beneath the Mediterranean Outflow, shadowgraph images 29 to 33 revealed the vertical bands of salt fingers.

scale vertical columns exchange fluid across an interface between warm, salty water floating above cooler, fresher water, the rising fingers gaining heat faster than salt while the sinking fingers lose that heat without loss of salt to become heavy. However, not all shadowgraph photographs I obtained in the stratified regions of the ocean showed vertical bands. The conclusion I was forced to make is that velocity shear-induced mixing was competing with double-diffusive convection for mixing in part of the thermocline. The images from Fig. 7 show the range of structures revealed by the shadowgraphs.

While the CTD on the autonomous vehicle, Autoprobe, which carried the SCIMP, gave critical supporting measurements of salinity and temperature for associating the shadowgraph images with salt fingering, a velocity sensor was needed to relate the shear instability images with the shear. In fact the critical relationship between stratification and shear is the Richardson number. About the time that I borrowed Tryge Gytre's acoustic travel-time current meter for a shear probe as illustrated in the free sinking vehicle in Fig. 8, the Autoprobe carrying SCIMP was lost and I never obtained shear profiles made concurrently with shadowgraph images.

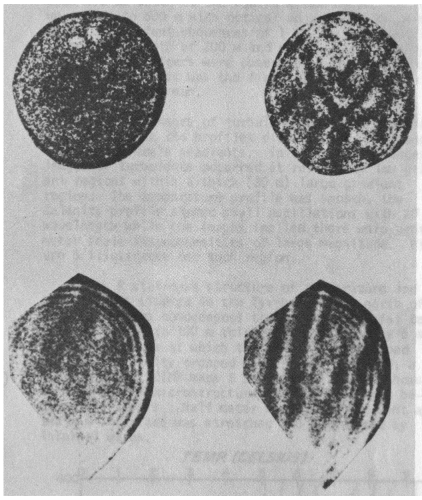

Fig. 7. Shadowgraph images from the Self Contained Imaging Micro-Profiler, SCIMP. Upper left is a blank from the shadowgraph used in Fig. 6. Lower left is from location 27, and lower right is from location 31 of Fig. 6 showing clearly the vertical bands of salt fingers. Upper right is a shadowgraph from an interface without this kind of stratification and shows optical structure without a vertical alignment. This is presumed to be a shear instability overturning event.

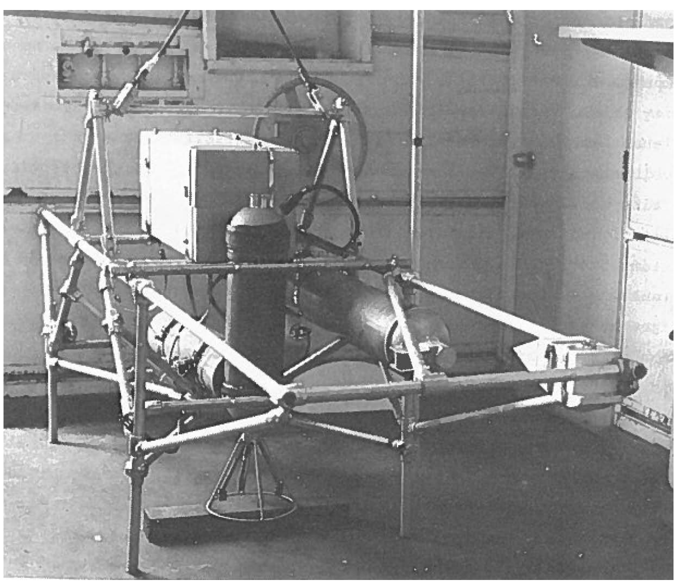

Fig. 8. The vertical shear meter with CTD and variable buoyancy was tracked and controlled acoustically from the support vessel. The velocity sensor is the object sticking down from the vertical cylindrical housing. It has two horizontal acoustic axes, undisturbed when the vehicle is slowly sinking. Syntactic foam buoyancy at the top and on the corner trimmed the vehicle. The CTD with its internal SeaData logger is on the right. The two bladders containing methanol and sodium dichromate brine with pumps for buoyancy control are in the cylinder on the left.

Fig. 9 illustrates the profile of velocity shear from the shear meter along with the density (computed from conductivity and temperature) and temperature indicating shear at the density interface as anticipated. But for purposes of this paper, the acoustic differential travel-time current meter became the Benthic Acoustic Stress Sensor, BASS [3] and with the encouragement of my student, John Tochko, the arrangement of the acoustic paths was varied from purely horizontal as the most effective for a free-sinking shear meter, to oblique for primarily horizontal boundary-layer flow.

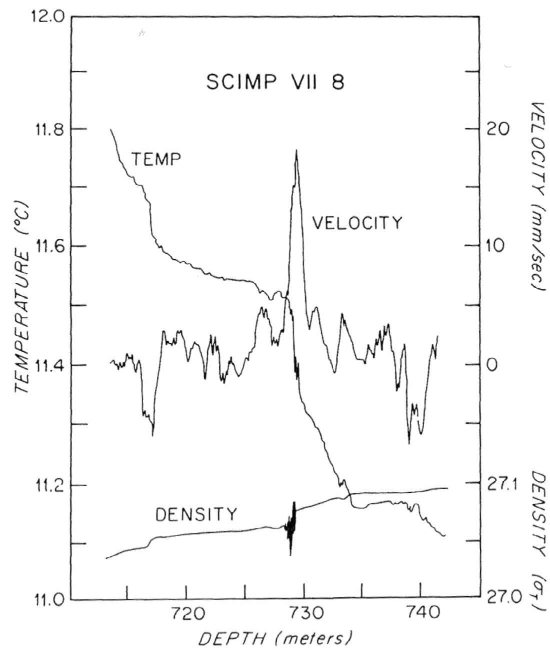

Fig. 9. The measured velocity peaks at 20mm/s on the thermal and density interface as the shear meter sinks through it.

The original arrangement of transducers on chemical ring stands evolved to the sensor cage of Fig. 10 supporting four pairs of transducers opposed on vertically-separated horizontal rings. These cages are or were bolted together with spacer cages to make a tower 5-7m tall and supported by a bottom landing tripod 6-8m tall. The six to eight sensor cages have a logarithmic spacing from the bottom to cover the anticipated turbulent benthic boundary layer. Deployed in groups of as many as four tripods during HEBBLE on the Nova Scotia lower rise [12], the uniformity of the constant stress layer was demonstrated and coincidentally, benthic storms at 4800m depth were discovered, with high turbidity events lasting several weeks about 15 times a year. The origin of these storms has never been demonstrated and they would probably require a benthic weather array of bottom-mounted current and turbidity sensors, just to map out the origin of the turbidity with the subsequent deposition of the suspended sediment and the decay of the turbidity downstream [13].

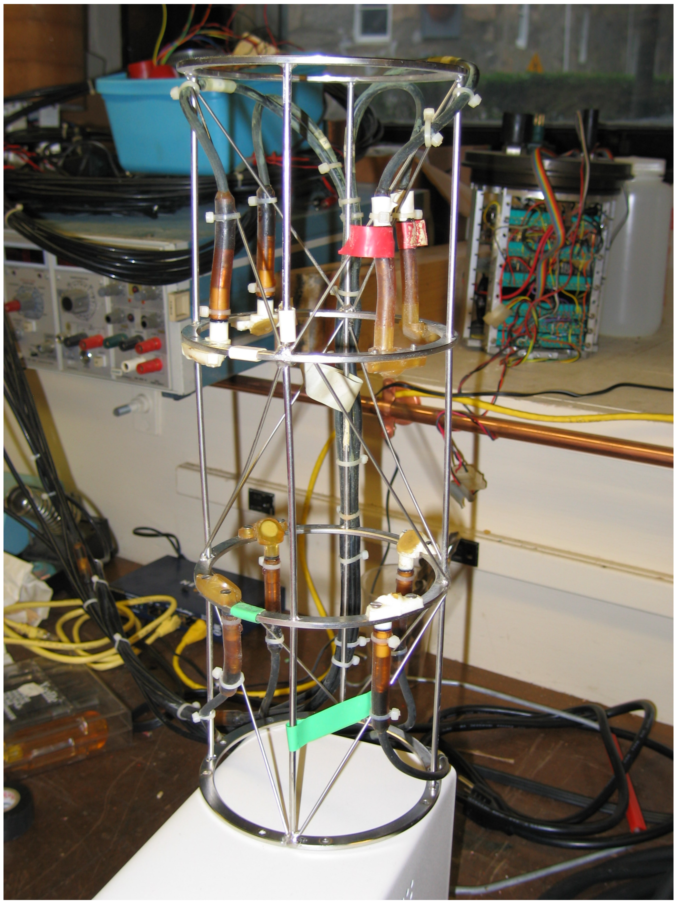

Fig. 10. The acoustic sensor cage for BASS (Benthic Acoustic Stress Sensor) supported eight piezoceramic transducers spaced 90° in azimuth and defining paths 45° in elevation. Coaxial cable connected the transducers to the electronics so that up to eight cages (with spacers) could be stacked to obtain a vector velocity profile over as much as 7 meters. Logarithmic velocities across the benthic boundary layer in the deep sea were observed with uniform Reynolds stress over the lower 3 meters, typically.

E. Acoustic Doppler Developments

In 1981, near the beginning of CODE, the Coastal Ocean Dynamics Experiment [14], Neal Pettigrew and Jim Irish placed an order for an upward looking acoustic Doppler current profiler, an instrument that had barely been thought possible as an autonomous, self-powered, and internally-recording sensor. From this was born RDI and the ADCP, an instrument that was to revolutionize coastal current measurement and eventually deep sea current measurement as well. Doppler measurements of velocity had been used in the shipboard mounted Amatek Straza speed log and adapted by Eli Katz to a towed body for sub-surface measurements of velocity. But to be a profiler was an important step and from this beginning has arisen an industry of Doppler current meters and current profilers represented by RDI (now Teledyne RDI [15]), SonTek (now YSI SonTek [16]), Nortek [17], Aanderaa [18] and others.

All of these Doppler instruments depend upon scattering of the transmitted sound from particles or other acoustic inhomogeneities in the water. The frequency shift from motion of the scatterers is tracked, in the case of a profiler, for individual bins sorted by delay from the transmitted burst and thus range from the transmitter, and the component of velocity along the acoustic beam, or for bistatic systems, along the angle bisector between the transmitted and received beams, is logged. In addition to the frequency shift, correlation index, acoustic backscatter signal strength, and quality index derived by comparison of redundant measurements such as the vertical component from two sets of oblique pairs, are also logged.

Applications for acoustic Doppler profilers include horizontal sections of current across rivers and harbors where access to locations of interest to pilots or estuarine scientists may be denied by surface ship traffic. Acoustic Doppler Current Profilers (ADCPs as RDI terms them) are mounted on AUVs, looking down for bottom tracking to get absolute vehicle velocity and up to get velocity profiles to the surface or to also get vehicle tracking under ice. Range of ADPs is related to frequency such that 300 kHz may be good for a range of 300m while 1.2MHz is limited to perhaps 60m, depending on the abundance of scatterers. Turbulence measurements are also possible with ADPs if the range is limited by high frequency and the sample rate is sufficiently high. For turbulence, frequently a bistatic arrangement is preferred, where the transmitting beam intersects a receiving beam to define a small intersection volume, and from this volume the received signal is continuous so the sample rate is not limited by burst frequency [19].

F. Acoustic Travel-Time Sensors

Acoustic differential travel-time sensors have been the other acoustic current measurement technique, not dependent upon scatterers and thus able to work equally well in absolutely clear water (as is found in the mid-water, well below the surface and in central-basin surface water far from shore) and in turbid or bubbly water up to fluid mud. The difference in the time taken for oppositely directed acoustic bursts to cross the measurement volume is linearly proportional to the integral of flow component along the acoustic axis. BASS, and its successor, MAVS [20], are such sensors. Another has been FSI's ACM line [21].

These instruments obtain an average velocity of fluid along an acoustic path between two transducers, like those illustrated in Fig. 10, and therefore must minimize flow distortion near the transducer supports. The excellent horizontal cosine response of the BASS sensor (Fig. 10) comes at a cost in vertical cosine response [22]. To improve vertical cosine response, MAVS has faired support rings reducing worst case vertical cosine response to 25% velocity defect for end on flow [23]. When used on a moored profiler, there may be better geometries knowing the flow will be in the forward half space only. This will be a future design target for the moored profiler MAVS [24].

G. *Wave Measurements and Observations*

Current meters with pressure sensors, or as three-axis velocity sensors, have been applied to the measurement of surface waves. In CODE, BASS was subject to wave influence and in fact the major stress on the bottom in 90m depth at the edge of the continental shelf resulted from 17-second waves. But to measure the waves required more effort. The Modular Acoustic Velocity Sensor, MAVS (derived from BASS), made by my company, Nobska Development [25], was adapted to the wave measuring task. A program MWAVES [26], referred the MAV-measured wave velocity near the bottom back to the surface. In the case of pressure, relating the surface elevation amplitude as a function of frequency to the pressure fluctuation was relatively easy. In the case of the velocity, it was somewhat more complex. In practice either pressure or three components of velocity can be used to obtain directional wave spectra. Doppler measurements can also obtain directional wave spectra and Nortek uses a vertically directed beam to get the surface elevation without having to deconvolve the velocity or pressure measured at depth back to the surface to couple with the horizontal components in making this determination [27].

H. *Remote Sensing of Surface Current*

HF Radar has been used to map surface currents in 2-D using backscattered radio energy from waves. The benefit of mapping surface current in real time from harbors, estuaries, or coastal regions has been appreciated by coastal states, which are now deploying them for continuous coverage in some countries, the U.S. in particular. Two main types of antennas have been used, a phased array from multiple antennas along a shoreline [28] and a directional antenna from a single location [29]. Two or more directions of view are needed to obtain a vector map of surface current and sight lines that do not cross the sample area at a significant angle do not yield as much resolution and accuracy for the components normal to the sight lines as those that have sight lines that cross more nearly at right angles.

Bragg scattering of the radio waves by surface gravity waves with a wavelength half that of the radio wave provides the scattering that gives the Doppler frequency shift that is measured. Since this defines the wavelength sensed, and since the dispersion relation for gravity waves is known, the speed of the scattering wave can be predicted. This means that the Doppler shift is also predictable but deviations from that prediction in the measured shift must be due to motion of the water upon which the wave is propagating. This becomes the velocity component for that direction and range that is used in the mapping.

Where the water shoals, the deep-water dispersion relation is modified by a shoaling wave relation and that reduction in Doppler shift is a measure of the depth of the water as well as the surface current. By using two radio wavelengths, the different shoaling contribution to the Doppler shift can be separated from the surface current contribution to the Doppler shift difference (the same for both wavelengths) and thus current and depth can be recovered.

HF Radar isn't the only remote sensing of surface current that has been employed. Microwave radar has also been employed for mapping surface current where the Doppler shift of scatterers moving on the water surface, foam, capillary waves, debris etc. are tracked as in conventional polar range display but with Doppler shift for velocity along the illuminating direction. These have been deployed from a moving ship where different view angles result from the ship displacement as it moves along its track.

Wave characteristics are also recovered from Radar measurements but this is not a direct fluid velocity measurement and will be left to the specialists in that subject to report.

I. *Present and Future Applications*

A single-point current sensor (MAVS [20]) has been incorporated in the design of an extremely sensitive experiment to measure very low-frequency ambient acoustic noise near and under the seafloor. This measurement attempts to extend the low-frequency limit of the Wenz ambient noise diagram [30] below the self-noise limits of the hydrophones upon which Wenz based his universal model. Flow noise is almost certainly part of the limit to these measurements so determination of the fluid motion near the seafloor can reveal times when flow noise should be absent.

Current measurements are useful for assessing the promise of tidal and streaming current energy production. The strength of the Gulf Stream off Fort Lauderdale has been tracked for a year or more and found to vary by more than a factor of two, an important baseline for design of a power turbine array [31]. Tidal energy has been tapped at a few places in the world but again, current measurements should preceded design of such a power production installation.

The application of current measurement for monitoring of loop current and delivering of warnings in the Gulf of Mexico is now required by MMS and has been valuable to the offshore oil production industry [28]. Ecological studies in coastal areas and estuarine monitoring have depended in part on good current measurements. These and new applications are one of the most encouraging developments in current, wave, and turbulence measurements.

J. *Present and Future Developments*

Present developments concerning electrical power to support current measurements are worth examining. In early instruments, the power to make the measure was mechanical only and thus drawn from the flow itself. The only electrical power required was for recording the measurements. Then came CMOS digital electronics and the power consumed by these circuits was minimal. But when analog measurements were added, power became a concern. The big issue with power arose with microprocessors, particularly high speed, and capable systems using compiled high level programs. But these power requirements were small compared to the power budget for telemetry of data. Power sources were alkaline batteries, briefly mercury and other higher capacity batteries, and finally lithium batteries of various chemistries. Cable-supplied current meters in observatories make this concern largely vanish. But for autonomous installations there is room for consideration of a return to extracting energy for current measurement mechanically again, from a charger nearby. The benefit is extended deployment duration. Clearly there is energy where flow is significant but some of the longest duration deployments have been in regions where the mean flow is very small and an electrical generator is unlikely to be able to help. This presents a research challenge.

It is useful to consider the range that current measurements have evolved to cover. Single point sensors have been connected together in a mooring to make an extended short vertical array. Moving the measurement volume without replicating the sensor itself has been a benefit for us with profilers both acoustic and mechanical. The mechanical profiler also allows CTD measurements to be made along the profile as well as current and possibly turbulence. The benefits of the ADCP and other acoustic Doppler profilers have been already noted.

2-D arrays of current meters have rarely been deployed but have been proposed, I am particularly sensitive to my own hope, so far unfulfilled, to deploy a Benthic Weather Array of current meters on the seafloor to capture benthic storms that we know must occur from the turbidity event evidence but have never seen develop and die away [13]. There have been and are electric-field measurements across straits, which monitor the total flow through the strait. These use abandoned or donated telephone and telegraph cables. The flow is conductivity weighted so that in stratified waters the measurement is not necessarily the total flow. Large scale 2-D mapping of surface current by HF Radar is notable. Nothing has been said about satellite mapping of currents and wave fields but the former is possible using altimetry with the pressure gradient resulting from the surface slope balanced by the Coriolus effect in the current, geostrophy. Wave fields can be mapped with space-borne scatterometers.

Future goals for current meter developments include finding ways to lower price through reducing cost and increasing volume of sensors produced (and sold), establishment of standards for sampling and reporting current, wave, and turbulence measurements, greater simplicity of instruments, increased deployment time for meters, and (a personal choice) an Expendable Benthic Lander array [33] for rapid deployment in unknown benthic regions when the need arises. There is certainly plenty more to do even as new applications arise.

III. Conclusion

Physical Oceanography at the Woods Hole Oceanographic Institution defined the principal question for itself several decades ago to be, “Where does the water go?” I would extend that to a question many other ocean scientists and engineers should ask, “What is the velocity of the fluid at scales of interest to my study?” We in our specialty of current, wave, and turbulence measurement technology are prepared to provide answers to such questions.

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