Current Measurement Expeditions: Deep-Sea, Shelf-Edge, Near-Surface, Shallow-Water, and Under Ice

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Development of a velocity measurement technology in science is driven by questions requiring the new technology for their answers. Thus application of the new technology is the only reason for its development and expeditions using it are the test of its behavior. Yet from an engineering viewpoint, the expeditions are simply testing milestones on the development path. This paper is tutorial to a degree to explain to less battle scarred oceanic engineers why and how development of instrumentation proceeds.

Keywords— Current meter; instrument development; funding of instrument development; oceanic expeditions that need current measurement

I. Introduction

This paper provides examples of how instrument development can be justified and funded in the modern scientific funding climate. Instrument development per se is rarely funded but if a new observation is needed to understand a scientific problem, the development of instrumentation to make that observation can be included in the budget for that observation and the merit justified by its requirement for the task. For a beginning instrument developer, this process can be frustrating unless understood and complied with. I have gradually adapted to this paradigm over the past forty years and only failed in its implementation in the last 13 years when not following it. So the following examples, based upon scientific expeditions of my own and of collaborative efforts with others serve to inform while the theme that I have pursued since the early days of my scientific and engineering career may have merit for those not familiar with the original papers. In its repetition of some of the items that have appeared in scientific papers of mine over this period, it is review but since these papers are not generally in an engineer's collection nor is the thread of how one development leads to another described anywhere else, this contribution is original.

II. Presentation of the Problem

Differential travel-time velocity measurement has been the rarely employed technology I have developed following scientific questions that existing velocity measurement techniques at the time were unable to answer [1].

A. Shadowgraph

It started with optical observations of microstructure and mixing where chaotic images suggested differential diffusion of heat and salt could not explain all oceanic mixing; that mechanical stirring had to also be at work far beneath the surface on sheared interfaces between layers of different densities of water [2]. Fig. 1 shows an array of images that reveal a mixing process that is almost certainly shear–induced overturning. Measurement of density had already developed to a sufficient state that profiles of stratification could be obtained (used to couple to the microstructure images) but velocity measurements, velocity shear measurements actually, had no existing sensor available with sensitivity and spatial resolution to make such shear measurements.

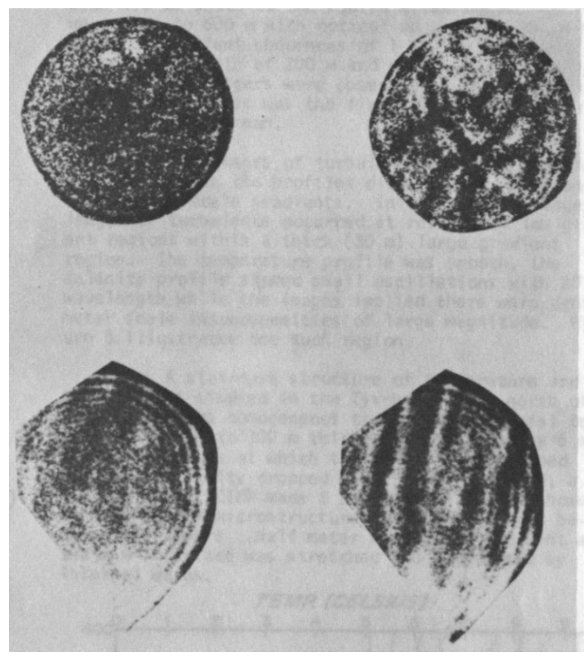

Fig. 1. Shadowgraph images of a horizontal collimated beam of light of 5cm diameter show variously aligned density (index of refraction) gradients indicative of mixing and stirring. Upper left is blank; lower left is an object, possibly a siphonophore; lower right is salt fingers (double diffusion); upper right is stirring, the unknown process.

B. Shearmeter

Adapting a prototype acoustic shear meter [3] became the path and expeditions to measure such turbulent mixing became the test. Fig. 2 shows the shear measuring instrument with Fig. 3 the resulting shear measurement.

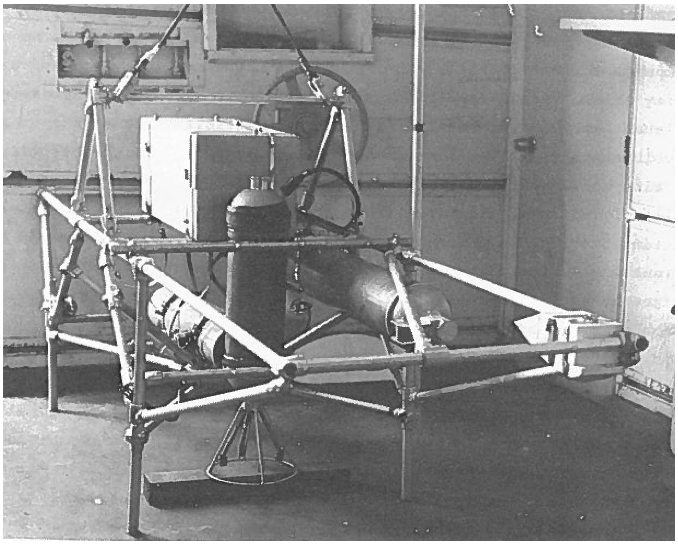

Fig. 2. The measurement of velocity shear in support of a study of acoustic transmission near the Azores in an experiment named AFAR permitted construction of an acoustic shearmeter named SCIMP as the first part of a Self-Contained Imaging Microstructure Profiler. The acoustic shearmeter is in the center, the CTD-supporting density profiler is center right, and variable buoyancy unit for controlling the free-sinking velocity is on the left. The optical imager has not yet been added since it played little role in this funded experiment.

There was eventually another funded opportunity for a revision to the shadowgraph, first for a transition from 16mm movie film to Super 8mm film and then to 8mm video cassette along with expansion of the 5cm beam to 12cm and finally to a prism based system in support of a CSALT expedition east of Barbados. There, mixing of the 18° water with that deeper through salt fingering was demonstrated, but there was no more funding for my own research on mechanical stirring and mixing.

The SCIMP was used in a sewage disposal study at the Deep Water Disposal site 106 miles off New York and by chance settled on the bottom during one deployment in the Hudson Canyon, thus serendipitously measuring a bottom boundary current. This offered a new funding opportunity for development of the acoustic shearmeter into a benthic acoustic stress sensor and BASS became the instrument developed under justification of several expeditions.

III. Expeditions

A. HEBBLE

Sediment transport investigations in the deep-sea needed a BBL (benthic boundary layer) stress measurement. Adapting the shearmeter for near bottom turbulence and measurement of Reynolds stress led to an instrument named BASS, Benthic Acoustic Stress Sensor. A PhD thesis [4] resulted from an early expedition to test its ability to measure tidal flow but its real success was in HEBBLE (High Energy Benthic Boundary Layer Experiment - ONR) [5] and CODE (Coastal Ocean Dynamics Experiment - NSF). The HEBBLE location was deep-sea (4800m) which was lucky because the only issue faced was pressure, and keeping the water out is relatively simple. Getting the instrument back was a threat since I had to develop an acoustic command release and separating tripod (6m tall, see Fig. 4) but I never lost one on the forty BASS deployments in the HEBBLE expedition. And much was learnt about homogeneous, steady, benthic boundary layer flow from BASS. Fig. 5 shows the attachment of a just recovered BASS array into the next tripod base used to anchor the BASS to the sea bed, which remains behind, when the array floats back to the surface upon acoustic command.

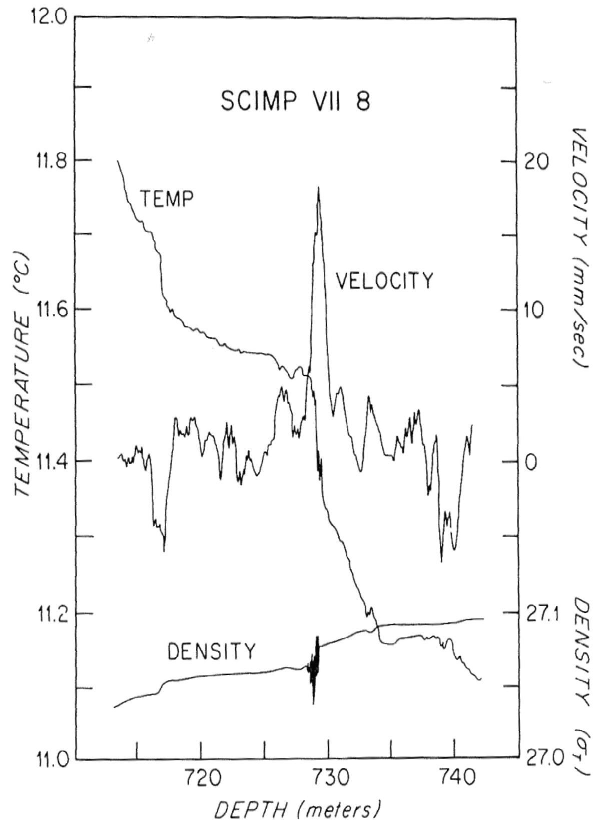

Fig. 3. The velocity shear from the shearmeter on SCIMP did indeed show the anticipated mechanical shear that might be responsible for overturning and mixing. At an interface at 729m depth there was a density step of 0.02 σ_T most clearly seen in temperature. The shear is 15mm/s over about 20cm in depth.

B. CODE

CODE was another expedition that enabled instrument development although it used the same BASS tripods. CODE [6] was a shelf edge expedition to discover how sediment gets over the edge of the shelf. Tripods could not be left on the bottom because fishermen dragged there and didn't want their nets to get hung. The technical issue here was waves, not present in the deep sea. It became necessary to increase the sample rate from 2Hz to 5Hz. Now fully digital, BASS had to have subroutines to allow computations to be done while sound was traversing the sample volume. Fig. 6 shows the schematic development that preceded the enhancement required to measure waves. BASS for HEBBLE by this time needed to internally compute Reynolds stress to extend its deployment time from a week or two to half a year and the digital development from CODE permitted this. It was revealed that waves were not only the new technological challenge but the suspending mechanism that mobilized the sediments so they could go over the shelf edge (17s waves were ubiquitous at 110m depth off California). But the need to recover everything had undesirable consequences with five tripod losses of the forty or so deployments in this expedition, only four of which were eventually recovered by ROV and towed grapnel.

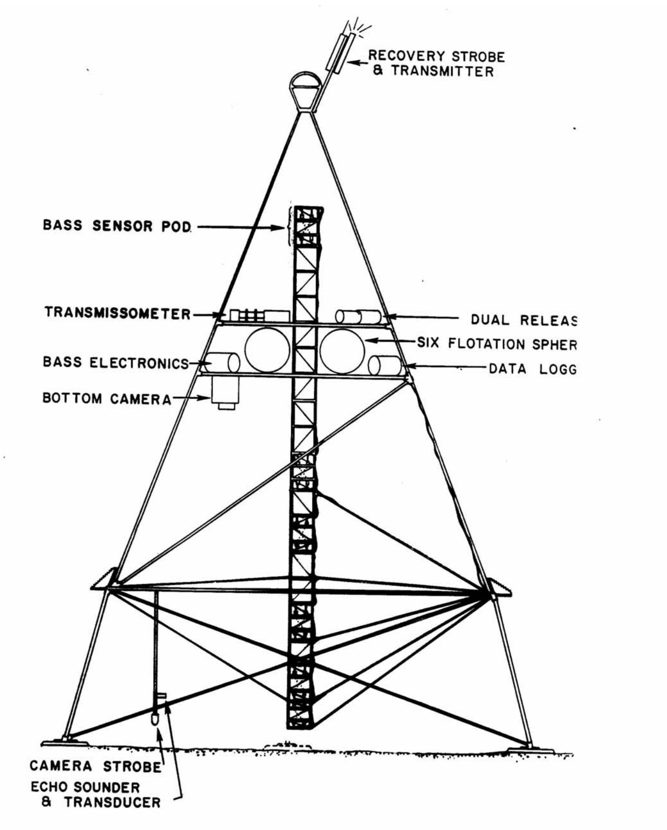

Fig. 4. BASS, for Benthic Acoustic Stress Sensor, measured Reynolds stress over an interval from 35cm above bottom to 5m above bottom from a recoverable 6m-tall tripod in the deep sea. This development from the simple shearmeter was possible through a series of NSF and ONR funded expeditions to understand sediment transport in a benthic boundary layer and to understand the formation and longevity of benthic bedforms for ONR as they might influence acoustic reverberation in the deep sea.

C. STRESS and Surface Layer Expeditions

STRESS, Sediment Transport Events on the Shelf and Slope [7], continued to operate on the bottom while SMILE, also sponsored by NSF occupied the near surface and surface. Surface Mixed Layer Experiment required floating a BASS tripod upside down from the surface in waves to discover how small breaking waves mixed heat and momentum down into a surface mixed layer. (STRESS for Sediment Transport on the Shelf and Slope moved CODE farther offshore.) The floating BASS became SASS, Surface Acoustic Shear Sensor and required a gyroscope to determine orientation in waves. While this movement into the surface layer offered opportunities to further develop the differential acoustic travel-time sensor, it created deployment, mooring, and recovery nightmares. But it too yielded a PhD concerning air-sea interaction with surface mixing [8]. Near-surface measurements with this BASS sensor technology were soon transported to an air-sea interaction tower and BASS sensor arrays without a tripod were clamped to the pipes of the Air-Sea Interaction tower in Lake Ontario on a three-winter expedition to more precisely discover exactly how surface-layer mixing depended upon breaking wind-waves. It was revealed that the penetration of slightly cresting waves was three times their wavelength when they were developing and still fetch limited [9]. Improvements were made in the subroutine construction of the acquisition coding so that temperature and pressure sensors could be added and their measurements made again while sound was in transit across the measurement volume.

Fig. 5. The insertion of a recovered (floated to the surface) BASS array of sensors required careful alignment with the next expendable tripod base. The release system was justified by the need to get simultaneous data from as many as four of these BASS tripods over a period of half a year at the HEBBLE site on the lower slope off New England.

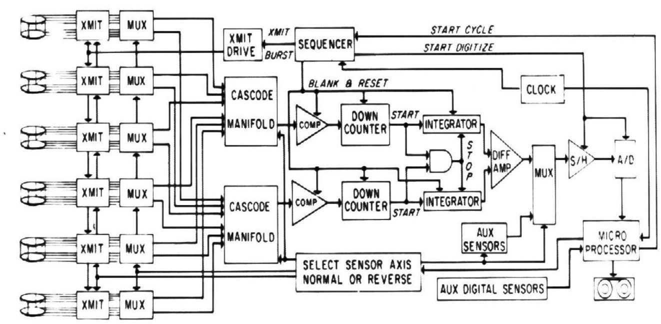

Fig. 6. The BASS electronics migrated from a digital form using shift registers to a fully µP based system with an 1802 µP. This is the schematic before the transition in which each expedition required hardware programming. But only when required by a more demanding expedition was this development fundable.

D. Vorticity Meter

Arranging the four acoustic axes of BASS in a square and differencing the differential travel-time going one way around the square from that going the opposite way gives a measure of circulation and by Green's theorem, the line integral around a closed curve equals the areal integral of the curl over the surface bounded by that curve. In this way, vorticity can be measured with a new arrangement of BASS transducers. Using three sets of BASS sensors in such an arrangement with three squares arranged perpendicular to each other, a vector measurement of vorticity can be obtained. This was proven at the normal BASS path length of 15cm but then seeking a funding opportunity to develop this further, an ONR need was exploited with an expedition to measure vorticity in a tidal inlet where the vortices of ships (submarines) might be distinguished from the non-vortical motion of waves and current. Detection of submarine wakes led to such an expedition in the Strait of Juan de Fuca. The full six-sensor set of BASS electronics provided two three-axis vector vorticity sensors (gradients in vorticity measurements being possible). The path length was increased in one vorticity meter from 15cm to 45cm while in another it was increased to 1.5m. In fact, for the second one the tripod structure itself was the vorticity meter. The development of the vorticity sensor, immune to mean flow, thus rejected velocity due to simple waves, only retaining vortical motion in the plane of the set of axes bounding the plane. A PhD was produced by this development, still using the BASS electronics but larger transducers for the 1.5m path-length vorticity meter [10]. This represents a case where an instrument development fit nicely with a scientific expedition permitting the development without having it stand alone.

IV. LESSONS NOT LEARNED

A. XBL

Now there are several counter examples of failure in instrument development. Indications from HEBBLE were that sediment transport events in the deep sea result from intermittent and possibly distant energetic erosional stress followed by moderate turbulent intensity that keeps the sediment in suspension followed by a depositional period at a location possibly hundreds of kilometers from where the sediment was eroded. I designed an instrument that could be produced inexpensively yet embodied the sensitivity and resolution of BASS to characterize these benthic storms, XBL for Expendable Benthic Lander was the name, and Fig. 7 shows the bottom lander version while Fig. 8 shows an inverted version that could measure wave-generated resuspension. Expendability was only to be employed in case weather or funding difficulties prevented a recovery cruise to pick the XBL instruments up; normally they would be recovered by ship about 3 to 6 months after deployment. Since it wasn't known where the erosional event might occur the plan had been to populate a region of the seafloor with several score of the XBLs in an intense seeding cruise and then on schedule have them pop to the surface every 2 hours until they were all up and recovered. If not recovered their compressed data would still be recovered by satellite relay and thus the expendable title. However there was no expedition in the works for this deployment and the proposal failed, repeatedly. The lesson wasn't learned until too late that instrument development isn't funded except when hidden in an expedition budget. Even with excellent reviews by NSF reviewers, it wasn't a major target of the scientific agenda to understand deep-sea storms, simply to observe them. And that had been done in HEBBLE.

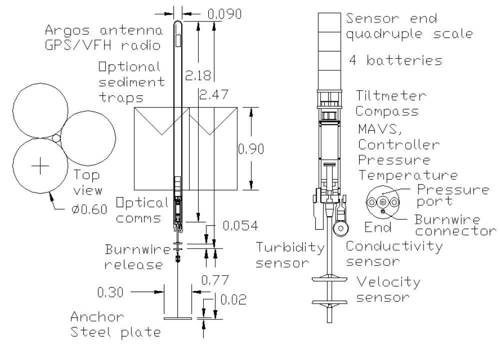

Fig. 7. XBL, Expendable Benthic Lander, in the down configuration can make Reynolds stress measurements for 3 to 6 months on batteries and then release an anchor and rise to the surface for pickup or for data transmission by satellite of compressed records for the deployment duration. Glass buoyancy keeps cost low, storage aboard ship economical, and provides radio transparency at the surface. In this configuration a sediment trap can be attached to support sediment deposition studies as well as erosion and transport. The expanded view to the right shows the instrumentation at the lower end of the glass tube.

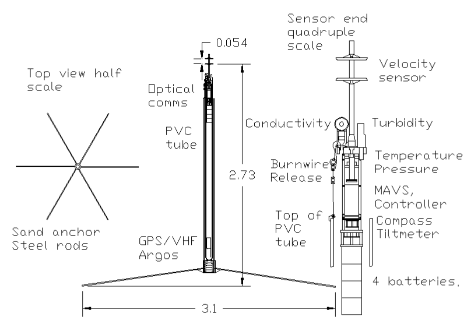

Fig. 8. Inverted, the XBL with a sand anchor instead of a weight as anchor, can measure waves as well as Reynolds stress for shallow water sediment transport experiments. The expanded view to the right shows the instrumentation at the upper end of the glass tube before inversion upon release from the sand anchor for recovery.

B. BASS Rake

In very shallow water, surface waves stir the sand and impact the shoreline through erosion and beach processes including swash, the water motion on a beach after a wave breaks and runs up the sand. There is a boundary layer even in the swash zone but it is very thin because there is insufficient time for growth into a steady flow type of boundary layer where flow can be assumed to be steady and homogeneous. This is often called the wave boundary layer. Yet in this WBL, the stress is that experienced by the sand and this is where erosion occurs. Putting BASS transducers very close together and stacking them like peas on the tines of a fork; it should be possible to resolve stress by the Reynolds stress correlations in the lowest few centimeters of the water column. BASS Rake was the name of this design target and a PhD resulted from the development of this variant of BASS [11]. Attempts to fund the development of BASS Rake into a finished useable instrument failed repeatedly because there was no expedition to attach it to. Again this was a lesson learned too late and thus of benefit to others to pass along.

In the laboratory WBL studies are made in wave tanks using dye or particle imaging velocimetry but no one had done it in the surf under breaking waves. A short record in these conditions was made with a prototype of the BASS Rake during a period when heavy swell came onto the beach where the prototype was anchored and revealed simultaneous velocity records over a profile of distances through the wave boundary layer and above.

The very close spacing of the transducers and the wires powering them created an electronic environment of crosstalk both capacitive and inductive so the unused transducers had to be quenched during the use of one nearby and the circuit to do this was needed in other developments that shared small spaces with potentially cross-talking wires. The development of a circuit to suppress crosstalk was valuable as a spin off and is used today in a commercial instrument. In fact, the frustration of funding development without an expedition led to doing further development commercially, possibly a good alternative model for instrument development.

C. MAVS

An exception to the lessons learned about not being funded to develop an instrument except in support of an expedition is the NSF funding of development of the Modular Acoustic Velocity Sensor, MAVS. BASS tripods fully equipped, were very expensive and there was demand for an inexpensive yet excellent current meter, like BASS but single sensor. NSF funded this development and the MAVS was the result. It was initially farmed out to a manufacturer and marketer as befitted an instrument development but this proved unsatisfactory and the MAVS came back to two partners and me after about six years.

Repackaging the BASS electronics and using the quenching circuit from BASS Rake permitted miniaturizing the BASS from a 6m tripod to a single velocity sensor with faired transducer supports to better measure in waves where the instantaneous flow is often not close to the horizontal plane [12]. Cost of production was reduced by "mass production techniques" for the electronics and patterns and molds for the sensors. This permitted the measurement of velocity to be available to many for whom velocity was simply an ancillary property to their main target, be it chemical, biological, or some other research target. It was used down boreholes, in the surf, and under ice. Its small size and low power permitted it to be deployed several times through holes in the ice. In one expedition in floating ice, it obtained mean currents and mean shear in current as well as Reynolds stress when parked at a single depth yet supported by a profiling instrument on a mooring [13]. In another expedition it has been put through a long hole bored in an ice shelf that subsequently froze shut but from which several years of under shelf melting and heat transport from coastal currents was measured. Under ice at high latitudes, magnetic measurements of heading are difficult and it has been necessary to provide inertial measurement units (IMU) to determine body motion and remove it at high frequency allowing magnetic fields to be averaged at low frequency with improved directional determination. While recovering high latitude measurements that reveal earth processes, the introduction of the IMU into the acoustic differential travel-time current meter has allowed improvements to be made in measuring current from a moving surface buoy, where previously long averaging was the only way to remove surface wave motions [14]. This illustrates how instrument development can be carried out if hidden within expedition requirements.

V. CONCLUSIONS

The use of expeditions to develop instrumentation, current measuring technology in this case, has been standard in science where there is rarely or never funding to develop a technique on its own but there are always opportunities to develop technology in support of a particular scientific goal.

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