Development of an Acoustic Current Meter: Lessons Taught by Clients and Colleagues

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Abstract - **In development of the Modular Acoustic Velocity Sensor [1, 2], MAVS, from a research instrumentation project under an NSF grant to a commercial product, I have been taught lessons by clients and colleagues that have led to changes in the product and improved the instrument made and marketed by Nobska Development, Inc. The lessons and their resulting improvements can be grouped by application and by clients who have been willing to share their successes and their difficulties. These applications range from hydrothermal vents to a coral reef, from breaking wave measurements to a very quiet lake, from near-surface wave measurements under a pier to cable connected observatory measurements, and from moored measurements to a profiler tethered to a drifting buoy.**

I. Introduction

An early dream of the author to provide a modular sensor like the SeaBird temperature probe or the SeaTech optical transmissometer that would be connected to a data logging system with battery and other sensors was quickly corrected when only one client was satisfied to provide the rest of such a system. Immediately, a data logger and battery were required to make the velocity sensor into a current meter. Soon after, a compass was required to make its velocity measurement useful in earth heading coordinates and soon after that a tilt sensor was needed to give full 3-D velocity vectors [3]. These customer-generated needs both stimulated improvements in the instrumentation and alerted the designer, me, to the dangers of depending entirely on my own perceptions of what the need in the greater community was for a velocity sensor.

II. Historical Background

Under NSF and ONR support in the 1980s, the Benthic Acoustic Stress Sensor [4], BASS, was developed to measure turbulent, near-bottom flow in the deep-sea to characterize the benthic boundary layer (BBL) as it might impact present day sediment transport;. The vector measurement of velocity at moderately small scale with zero hysteresis, linear through zero velocity, in an array of sensors spaced approximately logarithmically through the lowest 5m of the water column was useful in characterizing the deep-sea BBL at the HEBBLE site in 4800m depth on the Nova Scotia lower rise [5]. Subsequently the BASS tripods were deployed at the shelf edge off northern California in the NSF program CODE [6]. At 90m depth in the Pacific, waves complicated measurement of the stress that generates sediment transport but the vertical profiles of turbulent stress above the thin wave boundary layer were of benefit. Interest in the measurements that could be captured by BASS led to production of about a dozen instruments for colleagues through a company, Oceanographic Instrument Systems, Inc that I had formed with a partner, Al Morton, initially to produce timed releases, bottom finder pingers, acoustic transponders, and acoustic command releases. Initially, I had made these instruments for my colleagues at Woods Hole Oceanographic Institution (WHOI) but later manufactured them for colleagues outside WHOI as well. The BASS tripods were large, expensive, and out of the reach of most scientists beyond a select set of physical oceanographers due to complexity and cost. My dream was that I could put current measurement into the toolbox of nearly every ocean field practitioner, for who wouldn't benefit from knowing what the current had been when their sample was accumulating be it biological, geological, or chemical? Just as temperature measurements were inexpensively available on nearly every instrument, I hoped that current might be available similarly.

III. MAVS

NSF looked with favor (eventually) on my proposal to develop a Modular Acoustic Velocity Sensor that would use the same electronic and acoustic velocity sensing as BASS but be smaller, use a single sensor rather than an array of sensors, be cheap to manufacture and easy to use. While developing the new sensor, two awkward characteristics of BASS were eliminated as well: the velocity defect created by the support rings of the BASS sensor at 45º elevation and the sensitivity that the BASS flexible cables had to dressing on the tripod and to ocean pressure when at depth that affected the zero point of the velocity measurement. MAVS had faired rings supporting the acoustic transducers, injection molded for economy, and buried conductors for rigidity to prevent capacitance change when exposed to pressure. The faired rings reduced the velocity defect to 15% at the worst elevation [7]. The buried wires removed the susceptibility of the zero-point offset to pressure [8].

The printed circuit was done on a single board, eliminating connectors and reducing the size of the pressure housing. The sensor was constructed from injection molded PVC rings attached to a stainless steel tube, filled with urethane and a pressure compensating open ended length of tubing to allow the urethane filler to compress under pressure without excessive distortion. Fig. 1 shows the mechanical design of MAVS, little changed from the original except for subsequent reductions in board size and pressure housing.

Fig. 1 MAVS current meter is displayed in an early mooring frame that carries tension around the electronics housing to the sensor tube where it is carried in the stainless steel tube to an eye bolt at the end of the sensor. The two rings support 8 acoustic transducers that define the four oblique measurement axes along which components of the flow are measured. Except for reduction in housing size, the mechanical configuration of MAVS has changed little.

The essential four circuit boards from BASS needed in MAVS were the sequencer/transmitter board, the differential receiver board, the power supply board, and the controller board. The first three were simply laid out on the new printed circuit board while the last, which was an interface to the Tattletale 4 (TT4) single board computer by Onset was mounted separately on the thick plastic chassis so that there would be minimum surprises electronically with the MAVS. The TT4 contained RAM memory and an A/D converter and was programmed with Tattletale Basic to execute the measurement program and allow some operator selection of sample rate, averaging, and burst sampling. The clock could be set as well although it was assumed that time would be recorded along with the velocity components in Cartesian coordinates by the instrument to which the MAVS would be connected. The configuration - sample rate, averaging, burst sampling length and burst sample interval – were stored along with the MAVS program in volatile memory (RAM) maintained by a lithium coin-cell until changed.

While the core of the Tattletale Basic program that controlled MAVS remained unchanged over each unit, every user received an individualized program, on floppy disk as well as loaded into the RAM of the TT4. Individual programs had a header indicating the serial number, short listing of features of the individual program, and short operating instructions so that the user could remind himself what was needed to operate MAVS by connecting the MAVS to a PC and typing LIST within 5 seconds after power was applied. The intention had been that after the deployment schedule had been entered once, just applying power by plugging in the external connection to the main instrument including its source of power (later the internal battery) would start execution within 5 seconds.

IV. Customers as Clients

Although NSF supported the development of this instrument, it was clear that without a manufacturer there would be little benefit to the scientific community. I sought a business partner capable of duplicating the prototype instrument to my satisfaction and distributing it to a market of needy scientists - clients and colleagues as I imagined them. I chose General Oceanics, Inc. (GO) in Miami because they were interested, had an injection molding machine, and had a salesman, Dan Schaaf, who was enthusiastic about adding a quality current meter to the GO business line. Designers at GO provided a housing closure of remarkable simplicity that kept size small and built half a dozen MAVS current meters for the first customers. Electronics and programs were produced in my office in Woods Hole. The sensors were also built in Woods Hole from GO injection molded rings.

A. Internal Data Logging

The very first customer/client was a biologist, studying coral reefs in Florida, whose student communicated with me about data format. My plan had been to export data in binary to an external logging instrument, as I had done with BASS for my own work. Binary, although compact, was not easy to capture and translate, an argument I appreciated, so I provided an offloading part of the program to reformat the data as ASCII in words with separation. The student asked if separators could be commas rather than spaces to interface more easily to Excel and other spreadsheet programs with which he was familiar. So that option was included in the offloading menu.

More significantly, the instrument needed to be self recording and self powered so that it could stand alone, not be part of a larger instrument system. Again this request was reasonable, even though it did not match my original “Modular” concept. The TT4 had sufficient RAM memory to store the program and permitted a modest remaining part of RAM for storing data, but insufficient for a standalone data logger. But Onset had provided a memory expansion option to the TT4 called RAMBO that quadrupled the memory and there was room by splitting the stack of TT4 boards (a stack was required for the RAMBO option) into two shorter stacks that would fit within the MAVS housing. By connecting these two short stacks with many wirewrap wires as shown in Fig. 2 I was able to incorporate internal logging into MAVS. On the opposite side of the chassis was room for an assembly of 15 AA alkaline batteries beneath an aluminum bar as shown in Fig. 3 making MAVS self powered. Thus the very first customer taught me that my modular velocity sensor concept had to be subordinated to the need for a fully self-contained current meter. The customer was not impressed by the precision and accuracy of the acoustic measurement of velocity but in fact was impatient for exchanging this MAVS 1 instrument for the next generation when it should be produced at a smaller size, a development I was already anticipating.

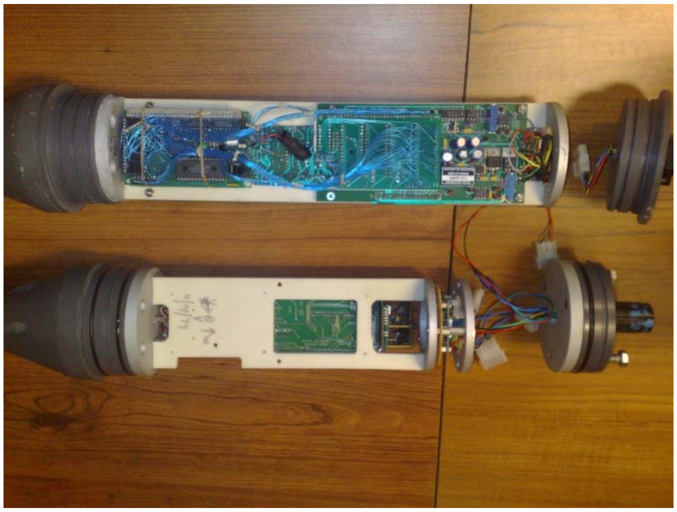

Fig. 2. MAVS 1 is shown at the top and MAVS2 beneath. Internal logging, a revision of a standard MAVS 1, displays the adaptation of the standard TT4 board to a RAMBO extended RAM memory option so that data can be stored in the instrument rather than only being transmitted for logging elsewhere. There had been a compass mounted in the space between the two parts of the TT4 with RAMBO but it has been removed and its leads are left flying. The MAVS2 beneath has a compass mounted off the end of what is a much shorter chassis since the circuit board is stuffed with denser surface mount chips rather than the original leaded parts.

Fig. 3. MAVS 1 is shown above and MAVS2 beneath as in Fig. 2 but with each chassis inverted. The battery of 15 AA cells is visible on the back of MAVS 1 beneath an aluminum bar. Part of the MAVS 1 circuit board is visible above the thick plastic chassis. It is almost double the size of the MAVS2 circuit board that uses surface mount chips rather than the leaded parts of MAVS 1.

B. *Current Speed and Direction*

The second customer was in Malaysia and an email correspondence with him revealed that he was puzzled by the Cartesian coordinate display of data as U, V, and W for two horizontal components and one vertical component of the velocity vector. He enquired whether it would be possible to have speed and direction instead. My first reaction was that this customer was not able to truly appreciate the power of the MAVS in its ability to represent the instantaneous velocity vector in a form that could be used to determine stress and possibly wave spectra in addition to current but reflection led me to realize that I would be similarly dissatisfied by a weather report that provided me with east and north components of wind velocity instead of the more traditional speed and direction. So while I explained by email that he could obtain speed and direction by squaring and adding together U and V and then taking the square root for speed while the determination of direction would require taking the arctangent of the ratio of U to V being careful to get the correct quadrant as the arctangent is ambiguous without paying attention to the sign of the components, I was able to add that to the offload program. The customer said that he recalled something like what I described from his high school education but he would be grateful for software that did it for him. So another menu item was added for choice of display during the offload from memory.

There was no concern about the quality of the velocity measurement although the original sensor broke and was returned for warranty repair since I had decided that fiberglass reinforcement in the injection molded rings was needed where the seats for the transducers were machined and that without this reinforcement, easily added during over-molding with epoxy, the rings were vulnerable to breakage. My assumption that this had been the cause for the breakage was proven wrong when the instrument arrived. It had gone through a propeller and the stainless steel tubing was bent and a large section of one ring was missing entirely. But this lesson was an important one to learn for me; don't assume a cause without seeing what the problem is.

C. *Modification of Sensor Tubes*

A welcome client from South Korea requested a special version of MAVS with a very long bent sensor so that the housings of three instruments could be mounted on one leg of a tripod with the sensors positioned in a vertical array, like the sensors in BASS, with minimum wake from the housings intruding on the measurement volume. Since this was very early in the production experience with MAVS, it was a little troubling that such a risky special variation was to be the next delivery and in fact the very long sensor tubes proved troublesome to keep tuned since the inter-wire capacitance was so great these instruments required repeated adjustments. But the application to tripod measurements using an array of sensors brought back my own application of BASS measurements for benthic boundary layer studies and I was happy to help.

D. Compass

Then a customer asked how direction could be determined when the MAVS was lowered on a cable over the side of a ship and I realized that my reliance on fixed tripod support with BASS and a massive compass or even diver supported compass determination to convert the U, V, and W instrument frame coordinates into East, North and Up coordinates was inadequate for a cable supported instrument so MAVS needed a compass, a further excursion from the modular concept. Precision Navigation, Inc. was then producing a compact gimbaled two-coil magnetometer compass that I was able to incorporate into the MAVS with additional machining of the plastic chassis although the proximity to the batteries was worrisome. Degaussing the batteries and including a magnetic deviation routine in the setup portion of the program along with a zero-point calibration satisfied the magnetic disturbance concerns but added complexity to the operator's pre deployment task list.

E. Tilt Sensor

The next customer, a sophisticated user of current measuring instruments, asked why any velocity sensor for measuring flow, possibly turbulent, near a boundary would not have a tilt sensor to correct the housing orientation for true earth coordinates? This sensible observation led to incorporation of a liquid tilt sensor and its incorporation with the compass into an output of Cartesian coordinate velocity vectors in earth coordinates as an alternative to instrument coordinates. In fact, the transformation to earth coordinates was done before averaging so that what was stored was vector averaged in case the instrument was moving during the averaging interval. This gimbaled compass and fluid tilt sensor is shown in Fig. 4.

Fig. 4. MAVS2 is shown here with a gimbaled two-axis magnetometer compass and a fluid-filled tilt meter above the compass.

By this time, battery and extended memory were designed into the MAVS as well as provision for the compass and tilt since the original boards were coming to an end and a new layout using the more compact surface mount components replaced the original leaded part board. MAVS2 became the next generation instrument in a smaller housing. Transition to MAVS2 coincided with a transition in business partnership away from General Oceanics and a new corporation, Nobska Development, acquired the GO interest in MAVS.

F. Temperature, Pressure, Light Scattering, and Conductivity

At this point, consulting companies hired to monitor river and estuary conditions for municipalities began to request additional sensors for MAVS. Temperature measurements were already available on the TT4 but this temperature sensor was inside the housing and there was desire for a more representative water temperature requiring an external probe containing the thermistor and a more sophisticated temperature calibration since the external thermistor could be immersed in an ice bath for zero offset determination.

Pressure was also not difficult to add with a port through the endcap and an Omega pressure sensor with analog output mounted inside the housing where there was space. Initially this addition was made on the endcap away from the sensor but subsequently, the sensor endcap was used.

Next, customers wanted conductivity measurements and an Aanderaa inductive conductivity sensor was mounted to the sensor endcap opposite the temperature probe and a conductivity circuit board was included inside the housing piggybacked above the MAVS circuit board.

These ancillary sensors concerned the customers more than the velocity measurements. For example, to inhibit corrosion inside the pressure sensor, its internal volume was filled initially with oil from the pressure calibrator and this oil was capped with a plug of higher viscosity grease as was done in the Mark III CTD, produced at that period by GO. However, this attenuated the pressure signal from waves and the grease had to be scraped out to restore the expected pressure performance.

Other customers wanted light scattering measurements or light attenuation measurements and the Optical Backscatter Sensor from D&A was used for the former and the SeaTech Transmissometer was used for the latter. These consumed more current than some of the other ancillary sensors and decreased the battery life to at most two weeks. But the biggest change was necessitated by the requirement of long deployment duration for deep-sea applications.

V. User Interface

The menu structure of the program on the TT4 had begun to get complex. There had been an intention from the beginning to be able to deploy the MAVS without a conversation with a computer and this meant that any query presented by MAVS to a user that went unanswered in 5 seconds was assumed to revert to the previous answer. Thus, applying power would start the MAVS running at the sample rate previously selected, the averaging previously specified, the burst sample length and burst interval previously entered. However, if the intention was to do a zero-point calibration of velocity, a pressure calibration, and a temperature offset determination as well as to change the output format from comma separated variables to space separated variables or to hexadecimal format, one had to enter keystrokes within 5 seconds, a burden for users. To minimize this we planned to provide a GUI (Graphical User Interface) for setting these conditions. This effort was begun but was soon postponed while a more fundamental revision was put in place. This revision was a new controller to permit long deployments with modest battery consumption.

VI. Low Power

Onset had another small microprocessor board, the TT8, that had a real-time clock that ran when the microprocessor clock was stopped. All of the power-consuming digital transitions thus stopped except for those associated with keeping time. In this low-power sleep mode, electric current consumption dropped from 10 or 20ma during running to about 700μa during sleep. Since measurements do not require full time running of the microprocessor, this permitted a vast power savings without losing the clock and extended the deployment duration available from weeks to a year or more. Changing to the TT8 controller required that Tattletale Basic be given up in favor of C programming and Todd Morrison was brought on board to implement this transition. The GUI was similarly adapted to the C program and the new electronic interfaces required led to MAVS3.

One customer, however, couldn't wait for the delivery of the new MAVS3 for a long deep-sea deployment and this required a patch to a MAVS2 board, termed MAVS2A, that had a low power alarm real-time clock and power shut down for the TT4 with wake up every minute [9]. The power of this MAVS2A in sleep mode was even lower than the MAVS3 in low power sleep but it was awkward to use and as soon as MAVS3 became available, the MAVS2A was retired from service.

The TT8, in addition to having a real-time clock that allowed the microprocessor clock to be stopped, could contain a Persistor CF2 piggyback board that permitted data storage on a compact flash card. Compact flash cards went from 128k bytes to several G bytes in only a few years and the need to average went away. In fact, power again became the biggest limitation to deployment duration.

Fortunately, this MAVS3 version became available just in time for a substantial delivery of instruments for a yearlong deployment at a hydrothermal vent at 2700m depth. Low power was necessary for this deployment. But the customer had an additional requirement, triple thermistors to measure temperature gradients near the bottom and pressure measurements with sufficient sensitivity to sense tides in 2700dbar average ambient pressure. A circuit combining the precision differential operational amplifier bridges for the three thermistors with an offset amplifier with expanded scale for the pressure measurement was piggybacked on this almost brand new MAVS3 board. Temperature calibrations were done with great care but unsuspected contamination of the boards made them humidity sensitive and it required significant effort to track down the problem and clean the boards sufficiently to remove the sensitivity. Again, it seemed to me that measurement of velocity, my original target had become sidetracked by an ancillary measurement. No problem was found with the velocity (or pressure in this case), only in the precision temperatures. All was worked out in time for the main deployment but there were anxious moments.

VII. Pressure

A customer in Montana wanted precise measurements of pressure to monitor lake level and its response to a hydroelectric dam in affecting shoreline position. Current and pressure signals revealed seiches with reasonable periods from the length and breadth of the lake but there seemed to also be a pressure signal of diurnal period that seemed certainly caused by drawdown of the lake from the hydroelectric demand for flow as the power demand varied during the day.

Pressure sensors are generally of two types, absolute pressure sensors and gauge pressure sensors. The first compare the external pressure to a vacuum while the gauge sensor compares the pressure at the sensor port to a reference pressure inside the instrument housing but outside the sensor. We had already experienced the thermal effects of solar insolation on pressure measured with a gauge sensor where, as the pressure in the instrument housing increased by warming of the housing, the apparent pressure dropped anomalously. So for this application, an absolute sensor was used.

At high altitude, there is an offset at lake surface due to the drop in pressure with altitude but submersion from the lake surface allows the instrument depth to be determined with significant precision due to the head of water from the pressure sensor port to the lake surface if the pressure at the lake surface is subtracted from the reading. Unbeknownst to us, this absolute sensor also measured atmospheric tides and half or more of the diurnal signal was due to pressure changes at the lake surfaces from this source. Again, the ancillary measurement dominated the use of the MAVS and largely eclipsed its benefit in measuring current.

VIII. Waves

The seiche in this Montana lake was a very long-period wave but measurements of waves in Lake Ontario had been the target of MAVS measurements by another client. Partly in support of this client, code to compute a directional wave spectrum was written by Todd Morrison and released as MWAVES. The application to the wave data from Lake Ontario was a beta test. But even before this application to the wave observations, an apparent noise problem showed up. Waves may contain high instantaneous velocities, greater than we had ever achieved in tow tank tests. During one winter storm in Lake Ontario, our client noted high frequency noise during certain portions of the velocity record. Examination of the plot of velocity revealed over-scaling near 80 cm/s, close to half scale (speeds more than half-scale were logged as those values less half scale). Close examination of the C code revealed that one of the variables cast as a short integer when used alone became combined with three other short integers to sum to a long integer but the assembler did not promote the addends to long integers before addition and the sum over-scaled. The solution was to specifically cast all of the addends to long integers before the summation and this problem was resolved. However, a similar over-scaling was later exhibited during a test lowering from a CTD cage due to such a casting error elsewhere. The lesson to me from these experiences is that customers can often provide test exposures exceeding those available to the developer and such tests must be encouraged and treasured.

MWAVES works on bursts of data of typically 2048 measurements at 2Hz sample rate or 4096 measurements at 4Hz sample rate. This provides a wave spectrum over the 17 minute burst and can return a directional wave spectrum every half hour to track development of waves during a storm. One client required real-time return of these spectra to inform workers of conditions before engaging in construction work at a remote work site. Cable connection to the MAVS at the work site was possible, providing power and returning data to a shore site, but it took new code to form the continuous data into bursts and to perform the directional wave analysis on the bursts without human intervention over days to weeks unattended. Real Time MWAVES was the result [10]. It was more difficult than it seemed it would be because things happened, like power outages. Again it was a development driven by a client's need that caused the new program to be attempted and eventually delivered.

IX. PROFILER

MAVS is not restricted to fixed platforms but its installation on a profiling platform presents new issues. Moored profilers have been used to monitor temperature and salinity unattended for up to a year. Frontal structures are revealed in ways that cannot be easily determined with other instruments. Adding current measurements to a moored profiler can give even more information of benefit to studies of mixing and water mass transport. But the motion of the profiler must be removed from the velocity measurement of the velocity sensor. A client selected MAVS for this task because of its low noise and ability to measure current in clear as well as in turbid water. However, the flow over the sensor due to the profiling motion of the body of the profiler sheds a Von Karman vortex street into the measurement path that masks the more subtle variations in ocean current that the velocimeter is intended to measure. Finally MAVS is being asked to make a velocity measurement, the thing that it was designed to do. Tank tests might have revealed this turbulent vortex street but did not. It took data from the profiler to cause the problem to be addressed. A probable solution is rapid measuring averaged to a more modest sample rate, with only the averaged samples being stored and transferred for analysis. This is one case where the large data storage capacity of compact flash memory is not of any use since all of the samples must be transmitted by satellite back to the lab. A valuable lesson has been taught by a client and colleague and hopefully has been learned by the designer and should be a solution for subsequent beneficiaries.

Profilers also present demands on size solved by folding the electronics board of a new generation of MAVS, MAVS4, to reduce length and repackaging the electronics in a titanium case to decrease the diameter and increase the longevity of the instrument. Addition of an inertial motion package has been necessary on an Ice Tethered Profiler in the Arctic since the earth's magnetic field there is so near vertical that an accurate magnetic heading cannot be counted upon without long-term averaging [11]. Some of these developments in support of one customer should be beneficial to others, perhaps at ocean observatories where long cable-connected deployments are likely to be required.

X. SUMMARY

MAVS was conceived to be a modular sensor of velocity for incorporation into a more complex instrument system. This has hardly ever happened; rather it has been driven by demand to become a stand-alone current meter supporting ancillary sensors of temperature, pressure, conductivity, optical scattering, and optical absorption among other things. It has been cable connected, sometimes at the end of a long cable presenting different problems, and it has been mounted on moving platforms with their own complicating flows.

Observatory and under-ice deployments pushed Nobska Development to offer a titanium housing and to shrink for the fourth time the MAVS electronics to minimize case length for externally powered applications. I hope the story of these requirements and adaptations are of benefit to both hopeful instrument designers and to more sophisticated instrument users. It has been an adventure for me.

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