Acoustic Current Meter Zero Offset Drift

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***Abstract-* Acoustic travel-time velocity sensors have a linear response through zero velocity. The benefit this provides in freedom from deadband and hysteresis comes at a cost of zero point uncertainty. One determines the zero flow offsets in still water or in carageenan gel for subsequent subtraction from the travel-time differences that are measured. Salt water immersion, pressure, and temperature affect the capacitance of the transducers and their connections to the electronics and thus the phase of the received signal. Two modes of zero-point shift have been observed: one in which the zero moves upon initial exposure to high pressure salt water after which the new zero is stable, and one in which small offsets appear only while the sensor is subjected to pressure. Details of the urethane bonds within the sensor under hydrostatic compression and their resulting distortion appear to cause these two modes of offset behavior. Temporary offsets are typically 0.3 cm/s while permanent offsets are typically 4.5 cm/s. Compatibility between urethanes to be bonded and flexible sensor tube construction are solutions to the permanent offset shift while matching of the cable capacitance promises hope of reducing pressure related offsets.**

I. Introduction

In the measurement of current, one seeks linearity, accuracy, stability, freedom from flow disturbance, sensitivity, range, and vector truth (cosine response) [1]. This is a long list. Some features are more important than others. Depending on the application, there may be important features not on the list such as wavenumber or frequency response, power, ruggedness of sensor etc. [2,3]. Mechanical flow sensors rarely had a problem with zero point. When the rotor or propeller stopped moving, the flow was assumed to be zero, possibly with a deadband. But this inherent zero point was a liability as well as an asset and really resulted from an inherent non-linearity near zero velocity. The force available to overcome friction was proportional to lift over the stalled surfaces of the rotor or propeller and that in turn was proportional to the velocity squared. Doppler current meters also have a unique zero point where the frequency shift of the scattered sound is zero. Near zero, there can be lock-on to zero from scatterers that are not in the water so there is an effective deadband with Doppler current meters similar to mechanical sensors. Generally this is not a problem unless the scattered acoustic amplitude becomes very low from low turbidity water. But for acoustic travel-time current meters, the zero point is not unique at all, the down side of being perfectly linear through zero. Uncertainty in zero point affects accuracy and vector truth. If the zero point is not stable, there is a concern that even careful calibration will be insufficient to get the accuracy and cosine response that is expected.

II. Instrumentation

Two issues must be addressed: the effect of zero offset error on measurements of current and the sources of offset drift.

A. Effect of Zero Offset Error

Acoustic travel-time sensors have electronic offsets in general that can only be corrected up to a point without a physical zero-point measurement. The sensor is placed in still fluid: water, seawater, gelatin or some other stationary fluid and a measurement is made [4]. This becomes the zero-point calibration and it is subtracted from all subsequent determinations of velocity.

1) *Bucket Zero:* An open container of water is not as quiet as it looks. Surface cooling by evaporation and warming of the sidewalls is sufficient to create convective currents in a bucket. Fig. 1 shows a piece of an overnight record of such velocities. Small buckets have less velocity from these thermal sources but they may have acoustic echoes that larger containers do not. The speed of sound in the fluid does not make much difference to the zero-point determination as long as the acoustic signal reaches the receiver within the receive time window. This permits using alternative fluids. Gelatin is nearly pure water but has no net flow, being a solid. The sensor of velocity can be cast in molten gelatin and the flow can than be assumed to be zero. Carrageenan is more useful than gelatin because it turns solid at a higher temperature and does not need refrigeration. Viscous fluids might be reasonable choices as well although I have no experience with them. Covering the surface of the water in a bucket with foam "peanuts" used in packing is a retardant to evaporation and surface cooling. This can decrease the convection in a larger bucket. None of these precautions is necessary unless a zero-point more accurate than 1 cm/s is required. Electronically, nothing special happens when the actual velocity goes from slightly positive to slightly negative.

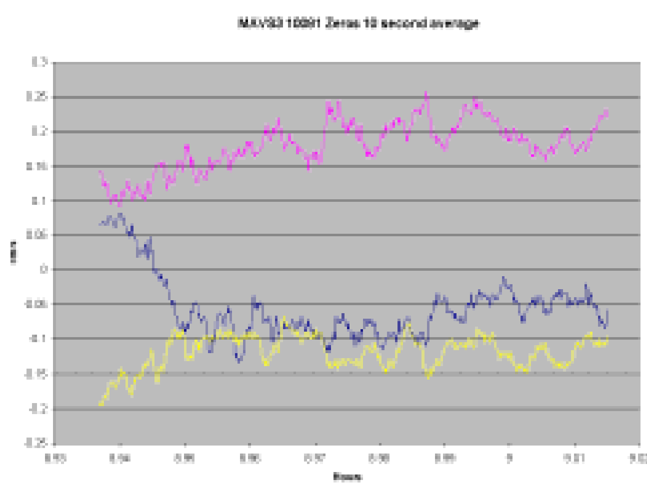

Fig. 1, Residual currents in a bucket overnight. Averages of three orthogonal axes show the currents.

2) *MAVS*: The Modular Acoustic Velocity Sensor, like its predecessor, BASS (Benthic Acoustic Stress Sensor) detects the 15th negative going zero crossing of a received acoustic burst to establish a time mark [5]. The transducers have a Q of about 5 so a burst excites them to higher amplitude than a single pulse of sound. A steep slope (dv/dt) at the voltage comparator reduces the effect of Johnson noise on the time. 10 mv Johnson noise at the input of the voltage comparator results in 50 ps of time uncertainty. This is equivalent to 0.056 cm/s with a 10-cm pathlength and 1500 m/s speed of sound. In principle, the zero point could be determined to better than 0.1 cm/s if the fluid were still. Fig. 2 is a histogram of such a measurement.

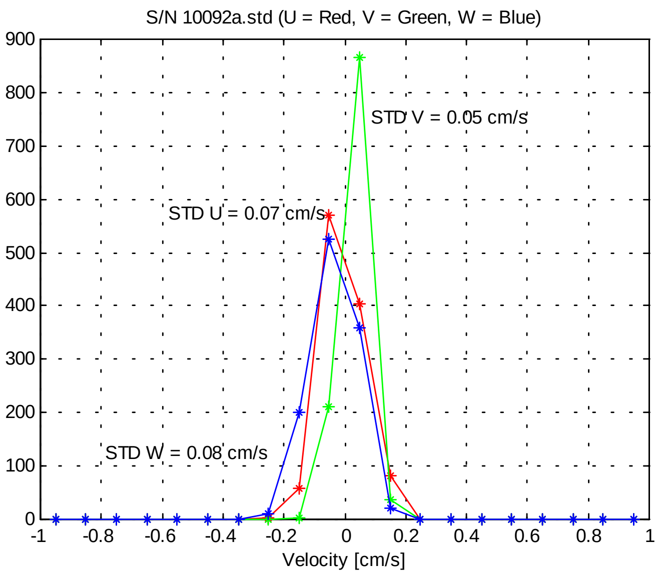

Fig. 2, Histogram of instantaneous velocity measurements in a still bucket over 10 minutes. The electronic noise level is 0.056 cm/s and the velocities are only slightly more than that.

3) *Cosine Response*: An ideal acoustic velocimeter measures the component of flow along an acoustic axis. Combining several axes, 3 or more for a 3-D current meter, produces a flow vector. If one or more axes have a zero-point error, the resulting vector will be skewed. 10 cm/s current with a zero-point error of 1 cm/s can have a vector direction error of 0.1 radian or 5.7°. The ratio of the zero point error to the velocity is the critical determinant of this error. Since the offset is a constant, the direction error increases as the speed decreases.

4) *Turbulent Fluctuations*: Reynolds stress and turbulent kinetic energy derive solely from fluctuations in velocity components [6]. In the case of Reynolds stress, the mean is subtracted from the time series of velocity before the product of downstream component with vertical component is averaged. The average self-product of the fluctuations gives the turbulent kinetic energy, again rejecting the mean velocity. So for these measurements, zero offset error is not a concern. Only a very high rate of zero offset drift would be a concern. But for other purposes, the loss of vector truth and the loss of accuracy in speed are concerns.

B. *Sources of Zero Offset Drift*

Since the zero offset can be measured and applied as a correction, zero offsets themselves are not a problem. It is changes in zero offset that create error.

1) *Electronic Compensation for Drift:* In MAVS and its predecessor, BASS, the connection of each pair of transducers to the measurement circuits is reversible with a transistor switch. The electronic circuits after the switch drift with temperature, age, and voltage variations but these effects cancel out when two measurements are made sequentially, first with the transducers connected normally and then with the transducers connected reversed. The results are subtracted. The drift in electronic characteristics of the cascode amplifier, voltage comparator, charge integrator, voltage follower, differential amplifier, and A/D converter are all cancelled when the second member of the pair is subtracted from the first. So it is only elements before the reversing switch that are suspect. These include the reversing switch transistors, FET shunt transistors, and T/R diodes inside the pressure housing. None of these are subjected to more than temperature changes and aging. In extended zero tests in a bucket in the lab, the zero was not seen to drift. Cooling the electronics with circuit cooler did not have an effect either until condensation occurred on the circuit board, degrading the insulation of the off circuits.

The other elements that precede the reversing switch are the wires to the velocity sensor, the transducers, and the support structure for the transducers. It is reasonable to include the water occupying the sensor volume as well. Pressure, temperature, conductivity, and speed of sound in the water change and the pressure, temperature, and conductivity can also affect the wires and possibly the transducers. It is these exposed elements that appear to be most susceptible to zero offset drift. Pressure would seem to be the most likely environmental factor but the evidence is that it is more complex than pressure alone.

2) *Mechanical Elements:* The transducers are exposed to hydrostatic pressure while the receiver electronics are dry and at one atmosphere pressure. Between them there is a pressure block.

a. Pressure Block: In MAVS, this is at the base of the sensor support tube. Fig. 3 shows the MAVS deployed at 2300 meters at the Endeavour Field of the Juan de Fuca hydrothermal vent system [7]. In this underwater photograph, the sensor is the pair of rings below the pressure housing and the tube connecting the sensor rings to the housing is exposed to 230 bars of hydrostatic pressure. The support tube also carries mooring tension to the anchor on the bottom from the float out of the picture at the top. The organisms covering the instruments in the picture are an interesting feature of long deployments of current meters and they might impede the flow but did not in this deployment.

Fig. 4 shows a detail of the pressure block and water block used in the instrument in the photograph. Solid enameled copper wires pass through an epoxy plug cast into a tapered hole in the lower end of the stainless steel tube that supports the sensor. This plug is the pressure block because it squeezes the wires as the pressure difference across it rises, increasing the normal force on the wire surfaces and resisting the shear that would extrude the wires.

Fig. 3. MAVS current meter at 2300-m depth at the Endeavour Field of the Juan de Fuca hydrothermal vent field. Photograph from DSRV Alvin.

This block has been tested with many cycles at 10,000 psi before being cut apart for examination and there was no creep detectable.

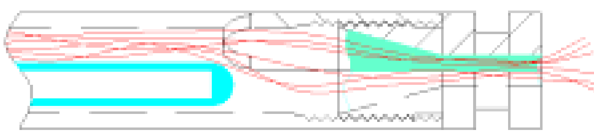

Fig. 4. The original MAVS sensor tube has an epoxy pressure block in the tapered plug and urethane water block surrounding the enameled copper wires and urethane pressure compensation tube. The epoxy is indicated with fill in this drawing. The closed end of the pressure compensation tube approaches the tapered plug but it does not touch the epoxy.

b. Water Block: The epoxy bonds to the wires and to the stainless steel but the epoxy is brittle and forms microscopic cracks when subjected to pressure. These can pass water if water reaches any surface of the epoxy. To seal against water, urethane is injected into the volume between the epoxy plug and the open end of the tube, encapsulating the wires and forming an elastic bond between the wires, the tube, and the epoxy. The urethane is pressure exposed and carries very little stress. It is simply immobilizing filler with good adhesive properties. The compressibility of urethane falls between that of water and four times that of water. This quantity is poorly known. In any case there would be substantial linear movement if the solid stainless tube and copper wires were to fix the cross section area of the urethane. Motion of filler at the entry point of the wires to the tube from the rings would tear the wires. Pressure compensation along the length of the tube was incorporated to reduce the strain in the urethane so that neither it nor the wires would fail.

c. Compensation Tube: Fig. 4 shows the structure of the compensation tube near the pressure block. The other end of the tube is exposed to seawater. Water enters the tube freely and as the urethane compresses with increasing pressure, more water enters and the inside diameter of the compensation tube increases. In this way, the length of the urethane filler is fixed but the cross section area decreases. The strain is less because the distances are less; at most the inside diameter of the stainless steel tube. The compensation tube bonds to the urethane filler because it too is urethane. In effect, the tube is simply a way to keep insulating filler between the wires and the seawater. The assembly process cannot position the tube at the center of the cavity so that the expansion of the tube would be symmetric and minimize the strain. Generally the tube is pressed against one inside wall of the stainless steel tube.

Cured sensors are assembled into endcaps where the stainless steel tube is sealed with a radial O-ring. External pressure forces the O-ring to the bottom of the groove where it seals the sensor assembly to the endcap. The final stage of the assembly is gluing the sensor assembly into the endcap with urethane. But before this final assembly, the sensor can be pressurized to test its watertight integrity. Some sensor assemblies failed the test and were cut apart. In each case, the bond between the compensation tube and the urethane filler had failed and the bond between the urethane filler and the epoxy plug had also failed. The path for water appeared to be along the outside of the compensation tube to the stainless steel inner wall and past the epoxy plug. Failure of the bond between the urethane and the epoxy decreased the stress-carrying area and the urethane peeled from the inner wall of the metal tube. This is a clue about how the zero offset can drift.

In May 2000 the tapered epoxy pressure block was abandoned in favor of glass to metal hermetic sealed feedthrus epoxied to a drilled out plate with an O-ring shown in Fig. 5. The wires were connected to the feedthrus, the plate was bolted to a bell shaped cavity welded to the end of the stainless steel tube, and the tube was filled with immobilizing urethane. When cured, the assembly was screwed to the endcap with a face O-ring seal. Most high-pressure MAVS instruments have this construction. The compensation tube is positioned as before.

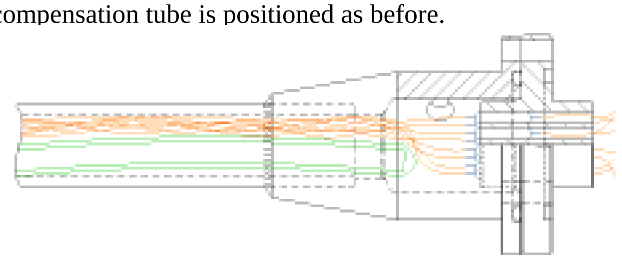

Fig. 5. Hermetic sealed feedthrus provide the pressure block in the new MAVS sensor tube. Urethane serves as a water block. A pressure compensation tube extends nearly to the end of the urethane to prevent longitudinal strain from breaking the wires.

C. Zero Offset Drift

Each MAVS instrument has a zero point calibration logged before shipment. Some instruments have been returned for modification or repair permitting a later zero offset determination. These provide the data about zero offset drift.

1) *Zero Offset Shift:* Drift implies an extended change. The evidence is that when changes do occur, they are abrupt and permanent. They are related to pressure exposure. In a few cases, zero offsets were measured before and after pressure tests including Alvin submersible certification tests

consisting of 9 cycles to 450 bars and a 2 hour soak at 450 bars. Some were tested at 600 bars (10,000 psi). In two cases, the instrument was bagged in salt water for the pressure test to see if the conductivity played a role. The short answer is that in one case it did and in the second it did not. There appear to be two classes: the drifts of about 1 cm/s or less and those above 4.5 cm/s. The latter are those that were exposed to high-pressure seawater or to salt water in a pressure test. All except one. Table I is the history of zero-offset drift pressure-exposed instruments. Note that drifts greater than 1 cm/s were experienced in all but #10059 exposed to high-pressure seawater. High-pressure oil had no appreciable effect as does high-pressure fresh water (not shown).

TABLE I
MAVS Zero Offsets

MAVS2A 10039 Juan de Fuca 2300 m

Before bits	66	275	26	0
After bits	79	274	11	-163
Change cm/s	-0.31	0.02	0.36	3.89

MAVS2A 10041 WHOI test mooring 2000 m

Before bits	19	-62	95	-23
After bits	16	1	97	-27
Change cm/s	-0.07	1.45	0.05	-0.09

MAVS3 10059 Alvin pressure test to 10,000 psi in seawater

Before bits	86	130	183	272
After bits	153	141	210	227
Change cm/s	0.20	0.03	0.08	-0.13

MAVS3 10060 Alvin pressure test to 10,000 psi in castor oil

Before bits	608	475	428	455
After bits	492	448	336	***
Change cm/s	0.34	0.08	0.27	Broken

MAVS3 10060 Alvin pressure test to 10,000 psi in seawater

Before bits	642	573	638	609
After bits	821	672	697	1038
Change cm/s	-0.53	-0.30	-0.18	-1.28

2) *Capacitance:* Based upon the post mortem examinations made on sensors that failed the pressure test, exposure to high pressure may cause the bond to fail between the urethane filler and the urethane compensation tube. If the bond to the epoxy plug also fails, there is a leak. But a cause of the bond failure to the epoxy was discovered and corrected in February 2000. The epoxy had been poured after the urethane was in place and cured for convenience. But the epoxy shrinks during curing and withdrew from the urethane, putting the bond into tension. This problem, that only appeared at high pressure, was solved by inverting the sensor during filling, placing the epoxy first and then placing urethane (low shrinkage compared to the epoxy) after the epoxy had cured and shrunk. This stopped the water leaks but did not solve the zero-offset drift.

Adding 450-pF capacitance from one transducer wire to ground (the stainless steel tube) duplicated the change in the offset. The incursion of conductive salt water to the space between the outside of the compensation tube provided a low impedance environment around the wires at ground potential. The enamel of the wires kept the leakage current low but the capacitance was increased. Since the actual specific conductivity of the water was high enough to be a short circuit for this capacitance, it mattered little what the exact value was. Based upon this model, the first exposure to conductive medium, seawater at high pressure, shifted the zero offset from that of an insulating environment to that of a conductive environment. After that, the zero offsets were stable again.

3) *Bonding:* One exception to this pattern was seen. The pressure test with salt water made on #10059 did not show a zero offset shift. Could the water not have penetrated outside the compensation tube? Shortly before the sensor of #10059 was made, TU-79 urethane filler became unavailable and a switch was made to Liquid Polymers PF 5-7 urethane. Static pull tests of this new urethane indicated it bonded to the compensation tube and the enameled wires as well as TU-79. But it may be a closer match to the unknown urethane of the compensation tube and not fail when exposed to extreme stress. This presents the prospect of a long-term solution to the zero offset drift: better bonding to the compensation tube.

4) *Endoskeleton:* Elastic urethane bonded to rigid epoxy or other plastic is a widely successful technique for underwater cabling. Why does this always work but the compensation tubes not always remain bonded? It is hypothesized that the rigid metal exoskeleton of the stainless steel sensor tube is the problem. Inability of the urethane to distort in all directions, as it can in the potting over solder joints of an underwater connector, concentrates stress where the strain is greatest and bond failure starts there. So another approach one might take to reduce zero-offset drift is to put the stiff metallic strength member inside and the elastic urethane filler outside. Then the compression can be more uniform and avoid the stress concentration that starts peel-failure of the bond. Fig. 6 shows a possible geometry for such a sensor assembly.

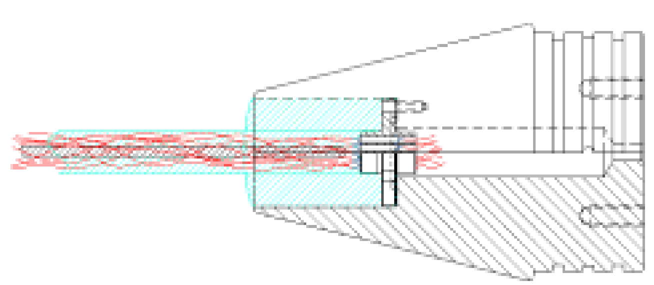

Fig. 6. Endoskeleton version of sensor support with flexible outer skin to reduce stresses in the urethane bond to the wires and pressure blocking feedthrus.

5) Matching Capacitance: The wires from the electronics to the near ring are shorter than the wires to the farther ring. The capacitance of these shorter wires is less than that of the longer wires. If the capacitance of all wires change proportionally with increase in pressure, the capacitance of the longer wires increases more. This appears to be the case. One deployment in which the sensor was encased in carrageenan gel and subjected to a lowering to 1000 meters and recovered showed no net offset but at depth, each axis was offset about 0.3 cm/s, two of the three in the negative sense. Fig. 7 shows this deployment. This is consistent with the temporary net increase in capacitance of the longer wires over the shorter wires. A fix in a practical assembly is to make all the wires the same length and fold those for the nearer ring into the assembly so that they also experience the effects of pressure.

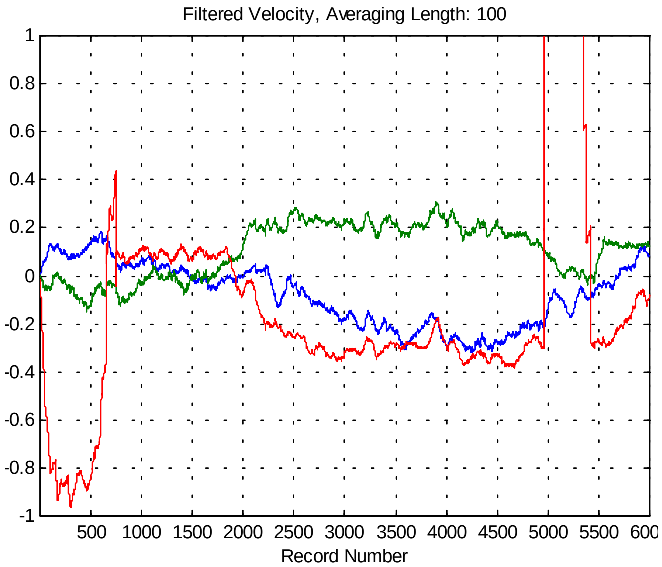

Fig. 7. Zero velocity offset dependence on pressure. MAVS sensor cast in solid carrageenan gel during a lowering to 1000 m and return. The net change in offset was about 0.1 cm/s but at 100 bars the offset was about 0.3 cm/s.

III. Performance

Since June 2000, 14 MAVS instruments have been deployed deeper than 2000 m. This is the region where zero offset drift may be a problem due to the incursion of seawater along the pressure compensation tube in the sensor assembly. In 11 of them, there were offset shifts by as much as 4.5 cm/s but where the data were stored as raw measurements along the four acoustic axes, this shift was removed by post deployment zero offset measurements in still water. In three cases, only earth coordinate [8] velocities were logged and the stability of the instruments was relied upon to estimate the shift in offsets for processing.

1) *Moored Measurements:* MAVS was deployed for 5 months at 2000 m on a mooring near Bermuda for an intercomparison with four other types of current meters. The zero offset shift was only 0.3 cm/s on three axes while the fourth axis was 1.45 cm/s. Fig. 8 shows a short section of the earth coordinate velocities. Notable is the burst of vertical velocities with zero mean on day 224 and day 273. Samples were taken as averages of two measurements every 5 minutes. The vertical oscillations lasted for about 8 hours but were not quite resolved at the 5-minute sampling period. The two horizontal components show tidal amplitudes of about 12 cm/s and monthly variation of about 8 cm/s. The speed rarely exceeded 12 cm/s and spent much of its time below 5 cm/s, a speed where a mechanical sensor may well underspeed due to intermittent stalling.

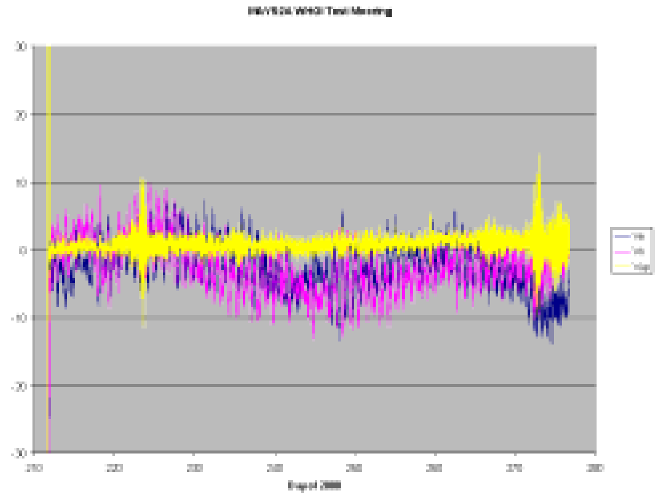

Fig. 8. Moored MAVS at 2000 m near Bermuda. Sampling at 5-minute period, vertical velocities of 10 cm/s amplitude are seen at day 224 and day 273 lasting about 8 hours each time.

2) *Bottom Measurements:* Three MAVS were moored on short tethers for up to 3 months at the Endeavour Field of the Juan de Fuca hydrothermal vents. One of these is shown in Fig. 3. Because the tethers were less than 1 meter long, MAVS did not rotate in the weak current. This allowed post recovery correction of the zero offset shifts, typically 3 cm/s. Since the four acoustic axes had been converted into earth coordinates, the post deployment determinations of zero were of no benefit for correction of the data. However, by adjusting each component of velocity with a fixed constant for the duration of the deployment, a reasonable velocity record was obtained. Fig. 9 is a record of the speed, direction, temperature, and a product of direction and temperature to dramatize the correlation of north flow with higher temperature and southerly flow with lower temperature. Fig. 10 is the map of the vent field where the three MAVS were deployed. The data of Fig. 9 is from the site north of Smoke & Mirrors (S&M) labeled 40.

IV. Conclusion

Linear sensors of velocity have advantages in sensitivity near zero. They have no deadband. But they must measure their response to zero flow and subtract that from subsequent measurements. Drift in the zero offsets is therefore a problem. The source of this drift in one such current meter, MAVS, has been tracked down and reduced and can possibly be eliminated entirely.

Acknowledgement

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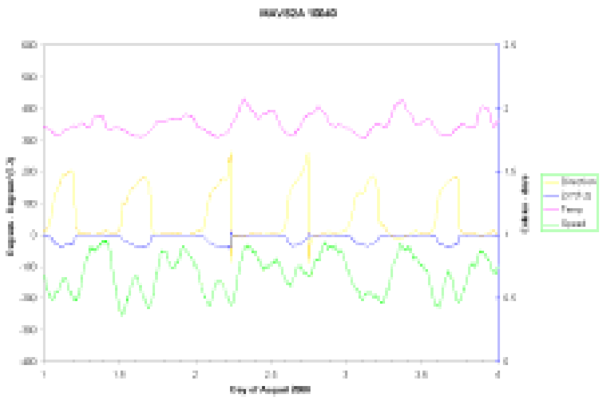

Fig. 9. MAVS velocity measurement from the Endeavour Field of the Juan de Fuca hydrothermal vents. The temperature measured at 1.5 meters above the bottom correlates with direction of flow as dramatized by the plot of direction times temperature offset by 2 degrees.

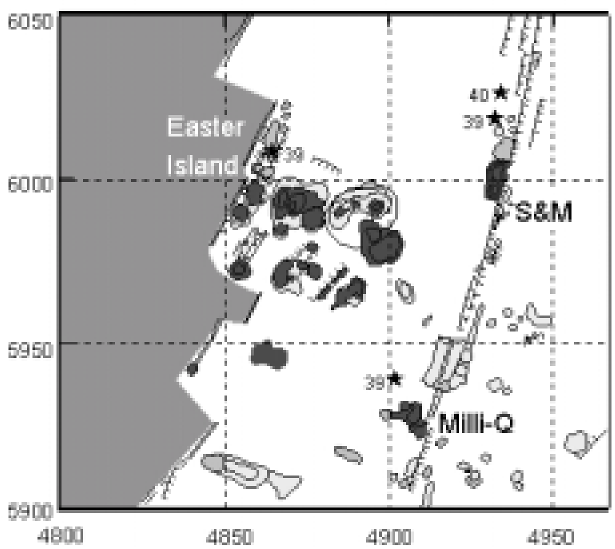

Fig. 10. Endeavour Field of the Juan de Fuca hydrothermal vents. Mooring location 40 north of S&M is the location of the MAVS when it acquired the data shown in Fig. 9. The three locations of 39 were where DSRV Alvin moved one of the MAVS for comparison with the two fixed at S&M and Easter Island. At Easter Island, a record similar to that at S&M was observed but there was little structure in the record from Milli-Q.

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