Calibration of the BASS Acoustic Current Meter With Carrageenan Agar

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Abstract - **The BASS current meter can measure currents down to the millimeter per second range. Due to the dependence of zero offset on pressure, determining a sensor referenced velocity requires accurate *in situ* zeroing of the meter. Previously, flow was restricted during calibration by placing plastic bags around the acoustic volume. In this paper, bacterial grade and carrageenan agars are used in the laboratory to create a zero flow condition during calibration and are shown to be acoustically transparent. Additionally, the results of open ocean and dockside carrageenan and plastic bag comparisons are presented. Carrageenan is shown to reliably provide a low noise, zero mean flow environment that is largely independent of ambient conditions. The improved zeros make millimeter per second accuracy possible under field conditions.**

I. INTRODUCTION

The Benthic Acoustic Stress Sensor (BASS) [6] has been used in numerous experiments (CODE, HEBBLE, STRESS, NATRE, SMILE, WAVES) to measure turbulence and current shear in the bottom and surface boundary layers and in the mid water. One sensor of a BASS array is shown in Fig. 1. Typically six sensors or pods are mounted along a tower to measure current speed and direction at different heights. The nature of these measurements requires high accuracy in the determination of both small velocities and small velocity differences. By "small" we mean velocities and velocity differences on the order of millimeters per second.

This sensitivity is achieved in BASS by high speed electronic circuits which can discriminate acoustic travel time differences as small as 50×10^{-12} *s*. Signals between the electronics and the transducers are carried on 6 *m* coaxial cables that allow the electronics housing to be removed from the flow field. The high speed of the circuits makes them sensitive to small variations in cable capacitance which is altered by movement of the cables and by compression with increasing depth. The velocity offset due to these capacitance changes can be as high as 2 or 3 *cm/s* [6]. The actual offset is different for each acoustic axis. This uncertainty in the zero flow output levels must be removed during calibration to achieve the millimeter per second accuracy of which BASS is capable.

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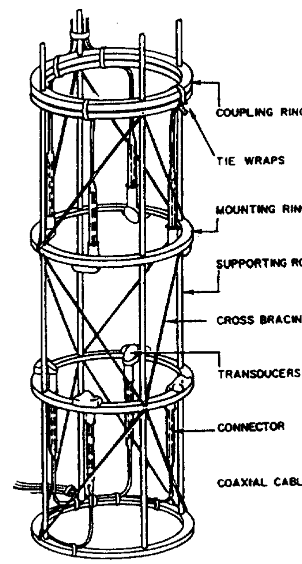

Figure 1. BASS SENSOR ELEMENT - 8 transducers form four 15 *cm* acoustic paths. A high frequency, 1.75 *MHz*, burst traverses each path in both directions simultaneously. The difference in arrival times is proportional to the fluid speed along the acoustic axis.

A preliminary deployment for calibration with plastic bags wrapped around the acoustic volumes of the sensor has provided reasonable results in the past. Unfortunately, flutter of the bags adds noise with a standard deviation of 1 *cm/s* in 20 *cm/s* flow. More seriously, the movement of the plastic can set up vortices with net flow along one or more of the acoustic axes. In this paper we will discuss how these difficulties were overcome by filling the acoustic volume with carrageenan gel to provided a low noise, zero mean flow environment for *in situ* calibration of the BASS current meter.

II. ENCLOSURES AND GELS

We initially considered rigid mechanical enclosures, for example, PVC pipe sections, sheathing the sensor tower. Unfortunately the pipe sections, while they reduce flutter compared with plastic sheeting, cannot ensure a zero mean flow. We also tried inflating a water balloon in the acoustic volume. The tension in the membrane reduces flutter, but the enclosed fluid can still exhibit non-zero mean flow. Also, we found that an almost unavoidable air bubble could fully block one or more acoustic paths.

We then considered filling the acoustic volume with an acoustically transparent gel. Because it would be cast in a mold about the sensor frame we could safely assume any shaking that did not tear the gel had a small amplitude and zero mean velocity. The local speed of sound enters the BASS velocity calculation as a multiplicative constant of a quantity that is necessarily small during calibration [6]. Therefore differences in the speed of sound in a gel compared to water, which are assumed to be small, should not cause changes in the offset. Subsequent observations have supported this assumption. Other requirements to be met were a slow flutter velocity during calibration and handling and preparation procedures that were simple and non-hazardous.

Our first gel was a commercial food product (Knox Unflavored Gelatin©). It is inexpensive, safe, and easy to prepare, and it demonstrated that gelatin could grip the BASS sensor frame without tearing during handling. However gelatin requires refrigeration to set which effectively eliminated it from consideration.

We next investigated the purified agar commonly used for culture media in microbiological research. Bacterial grade agar is safe and easy to handle, but very expensive. For us, the attraction was a setting temperature above $45°C$. For acoustic tests we constructed a mold from 17 *cm* PVC pipe and cast a 8 *l* agar gel (0.5 *l* agar powder in 8 *l* of boiling water, cooled to $50°C - 55°C$ before molding to reduce jelling time) around an isolated BASS pod. In the laboratory we showed (Fig. 2) that the gel was acoustically transparent. We also observed that the agar significantly reduced the noise and gave a zero mean velocity, even during rough handling or agitation of the water in the test tank. Large transients (> 30 *cm/sec*) could be generated by striking the gel sharply as a measurement was made, but no such spikes were observed when the surrounding water was agitated. These were exactly the qualities we sought for a reliable calibration.

With agar as a technically satisfactory if expensive solution, we looked into the feasibility of removing the gel *in situ* to avoid the additional sensor recovery for gel removal. *In situ* removal of plastic bags has proven to be unreliable. In addition to the convenience of a single deployment, the risk of sensor damage associated with deployment and recovery and the chance that the offset will be changed by cable movements are both reduced. One possibility was a biological agent, such as bacteria, that could digest the gel over a period of several hours or days. Barophilic/cryophilic bacteria do exist in the deep ocean [1], but they do not multiply quickly, cannot be programmed to metabolize food at a set rate, and will not generally eat all of the food. Since scraps of gel left on the frame would have compromised the measurements we rejected *in situ* removal by biological agents.

A second possibility was a polyacrylamide gel. A considerable body of research exists concerning the behavior of these gels. For example, volume shrinkage by factors of several hundred on exposure to saltwater was reported in [5]. Other researchers have demonstrated electrically controlled mobility or erosion of polyacrylamide gels [2, 3, 4]. All of these processes could potentially be used to reliably remove a gel from the sensor *in situ* after calibration was complete. Unfortunately, the acrylamide monomer from which the polyacrylamide polymer is built is a neurotoxin. The powder and liquid forms should be handled under a ventilation hood while wearing gloves and a respirator. We felt the safety hazard associated with these gels far outweighed the gain of collecting calibrated flow measurements with a single deployment.

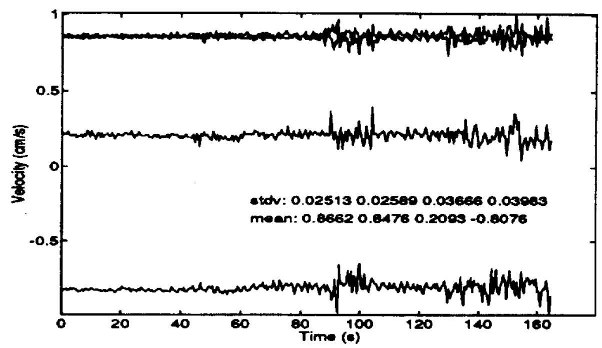

Figure 2. LABORATORY ACOUSTIC TEST OF AGAR GEL - **Each of the four traces shown is a record of velocity measurements taken at 1 *Hz* along an acoustic axis of a single BASS pod. The standard deviation and mean of each trace are shown on the plot. Note the 1 *cm/s* to 2 *cm/s* variations in the zero offsets of the 4 axes. These are typical values for a BASS pod. Axes A and B have nearly the same offset and lie essentially on top of each other. During the test the agar encased pod remained immersed in a small tank of water. The initial 40 *s* of the run show the quiescent velocity readings. The noise floor is well down in the 0.1 *mm/s* range which is close to the fundamental noise floor of the sensor. From 40 *s* to 80 *s* the tank water was agitated by hand and with a paddle. The noise floor remained in the 0.1 *mm/s* range. The final portion of the plot shows the response as the gel was prodded and struck by hand and the framework was shaken. While larger, the excursions are still quite small (millimeter per second range) and, more importantly, they are still zero mean.**

While the effort to eliminate the second deployment was in progress we also searched for a low cost alternative to the bacterial grade agar. This effort proved more successful. Carrageenan agar, derived from the seaweed Irish Moss (*Chondrus crispus*), possesses all of the desirable qualities we had previously found in bacterial agar. We used Gelcarin© GP 812 from the Marine Colloids Division of FMC Corp. in Rockland, ME. Gelcarin is marketed as a food grade product which permitted the use of shipboard kitchen facilities. It is safe (edible) and easy to prepare. The transition from liquid to gel occurs between $45°C$ and $50°C$, well above normal shipboard ambients. Carrageenan is acoustically transparent and it grips the sensor structure sufficiently strongly to withstand rough handling at half the concentration necessary with the bacterial agar (0.25 *l* carrageenan powder to 8 *l* of water). After calibration the gel can be completely removed without disturbing the cable harness. Finally, the cost by weight is 1/10 that of bacterial grade agar.

The field deployment and dockside tests described in the remainder of this paper were all performed with carrageenan gel. The gel was prepared by dissolving 0.3125 *l* of carrageenan powder in 10 *l* of boiling water and pouring the mixture into a PVC mold enclosing an acoustic volume. There it cooled and jelled over a period of sev-

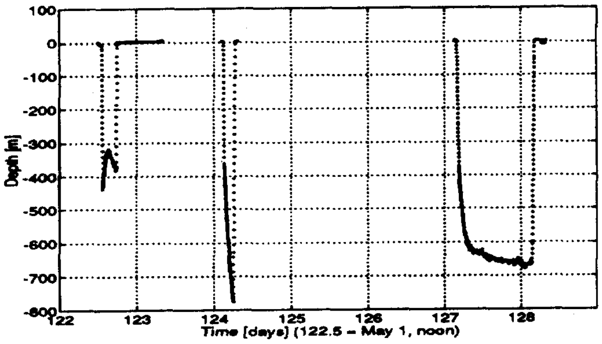

Figure 3. RiNo 3 Calibration Profiles - The deployments on May 1 and 3 (days 122 and 124) were carrageenan calibrations. A plastic bag was used on May 6 (day 127).

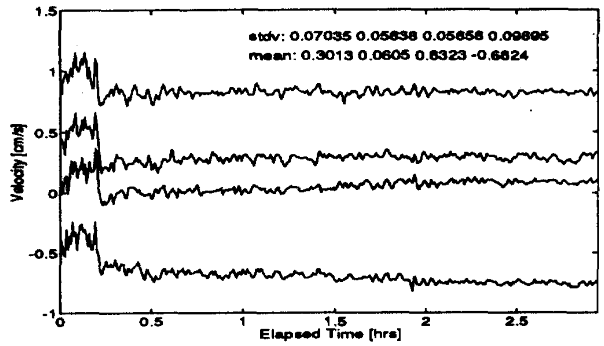

Figure 4. RiNo 3, Pod 1 - The traces show 30 s averages of 1 Hz velocity measurements taken as the probe descended from the surface to 800 m on May 3 with carrageenan gel filling the acoustic volume. Changes in zero velocity offset due to strain and pressure during the descent are clearly visible.

eral hours. The molds were constructed from clamshell halves of 17 cm PVC pipe with slotted endcaps that slide onto the BASS structure. The mold was made water tight with duct tape and an adhesive putty, Plas-dux©, a product of the Babbitt Development Co., Inc., Mattapoisett, MA. A successful casting is time consuming but not difficult. The measure of this method may well be that it yields essentially the best possible zero without any recourse to extreme delicacy.

III. RINO FIELD DEPLOYMENT

In April of 1992, as part of the North Atlantic Tracer Release Experiment (NATRE), two 6-pod, free drifting, Richardson number (RiNo) [7] probes were deployed. The floats were designated RiNo 3 and RiNo 4. Prior to final deployment, calibration runs were made using both plastic bags and carrageenan. The results of these calibration runs for RiNo 3 are presented here. Velocity measurements were made at 1 Hz. Thirty second averages of the raw measurements covering the entire deployment were logged. Additionally, a ten second burst is recorded every ten minutes and a fifteen minute burst is logged at midnight and noon as determined by a real time clock [8].

The profiles of the RiNo 3 calibration deployments are shown in Fig. 3. The deployment on May 1 was done with carrageenan. The probe spent the night on the surface and was located and recovered on the 2^{nd}. The second deployment, May 3, was also done with carrageenan. The probe carried too much ballast and continued a rapid dive after the descent weight was released at $\approx 400\ m$. The ascent weight was released at $\approx 800\ m$. The final calibration dive was done with a plastic bag on May 6 and 7.

Data from the 800 m dive clearly show the changing offsets caused by strain and compression of the cables (Fig. 4). The data points are 30 s averages of 1 Hz measurements. The probe descended through the first 400 m in the inital fifteen minutes of the run. A 2.3 kg descent weight was released at that point and the remaining 400 m was covered over the remainder of the 3 hr descent. Several effects are apparent. The discontinuity in mean offset is caused by the velocity change when the weight is released. The high initial speed ($\approx 45\ cm/s$) strains the cables, changing the offset. Strouhal vibration and similar effects account for the higher noise level during this period. These descent speed effects are more pronounced in pod 1 which is located at the bottom of the probe and so experiences higher stress during descent than pod 2 (not shown) which is sheltered above it. After the weight is released, the speed drops to $\approx 4\ cm/s$ and changes in the mean are continuous, showing the effect of pressure on cable capacitance. Observe that the degree and direction of offset and offset change in each axis is different. The need to perform calibration *in situ* is clearly apparent. This is the first time we have been able to obtain such a clear demonstration of the dependence of the offset on pressure and dynamic cable flexure. These effects were previously hidden in the flow noise. Carrageenan has reduced the path noise to such an extent that the cables and the electronics now determine the noise floor of the BASS sensor.

Figs. 5 to 8 show the four fifteen minute event records from the three deployments for comparison of carrageenan and bag zero calibration. It is apparent from the plots that the noise level is quite low in both cases ($\approx 0.3\ mm/s$). The statistical results are summarized in Table I. Variations in the means for the two carrageenan deployments are due to movement of the cable harness after one of the pods was damaged during the May 3 recovery.

Although both calibration methods have achieved a satisfactorily low noise level, this was done under very different conditions. The carrageenan zeros were obtained in surface swell (sea state 3) and during a 4 cm/sec descent. The plastic bag zeros were taken under essentially motionless conditions. These are, to our knowledge, the best zeros attained with plastic bags in over a decade of field deployments. This was due to the nature of RiNo as a free drifting probe. At depth, RiNo keeps pace with the mean flow. Variations from the mean due to turbulence and shear (that we wish eventually to measure) are comparatively small and do not significantly raise the noise level by fluttering the bag or vibrating the cables.

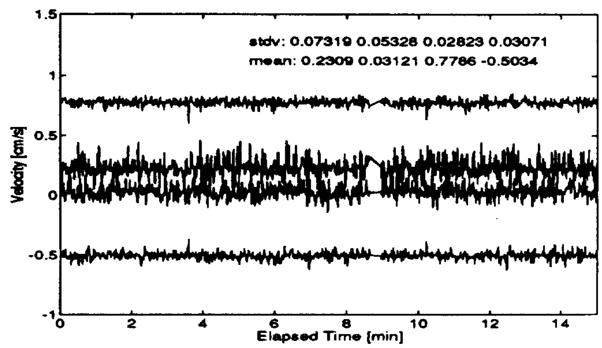

Figure 5. RiNo 3, Pod 1 - Fifteen minute burst at 1 Hz taken during the surface interval of first carrageenan deployment (sea state 3).

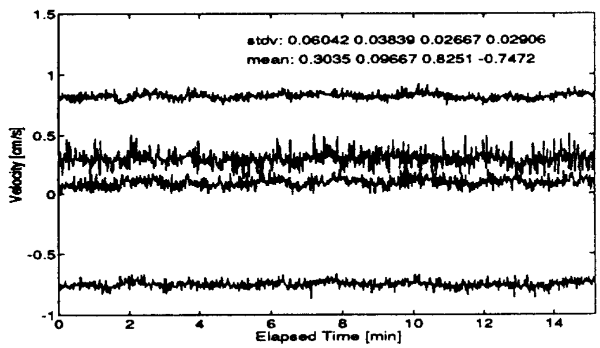

Figure 6. RiNo 3, Pod 1 - Fifteen minute burst at 1 Hz taken during the descent of the second carrageenan deployment ($\approx$ 600 m, 4 cm/s).

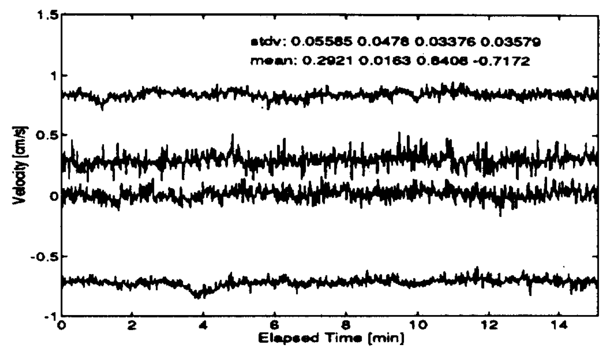

Figure 7. RiNo 3, Pod 1 - Fifteen minute burst at 1 Hz taken as the descent of the plastic bag deployment was leveling off ($\approx$ 550 m).

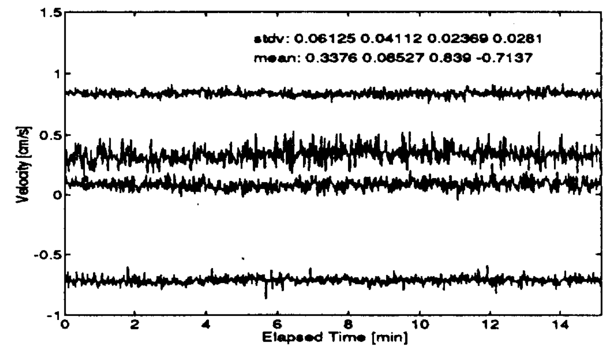

Figure 8. RiNo 3, Pod 1 - Fifteen minute burst at 1 Hz taken at a steady depth ($\approx$ 650 m) during the plastic bag deployment.

This is not the case during a normal BASS measurement when the sensor array is fixed on the sea bed and experiences relative flows of 20 cm/s or more. As will be seen in the dockside tests in the next section, the noise level using a bag for calibration rises dramatically when the sensor is fixed in a moving flow. The gel calibration noise level will remain small and constant through a range of environmental conditions.

A carrageenan calibration dive comparable to the plastic bag calibration on May 6, which included a substantial period at constant depth and two fifteen minute bursts of 1 Hz data, would have been useful both for comparison with the plastic bag calibration and for determination of the zero offsets. Nevertheless, the performance of carrageenan in the field was excellent. In its first use it equalled or surpassed the best plastic bag zeros we have ever achieved. More importantly, it is far more robust to the nonideal conditions usually encountered while calibrating BASS.

IV. DOCKSIDE TESTS

In August of 1992, we performed a direct comparison of carrageenan, canvas bag, and plastic bag zeros in the 16 m well of the Woods Hole Oceanographic Institution dock. There are mooring bumpers at the surface on two sides of the well. Below the surface it is open to the harbor in all directions. A two pod BASS array was suspended from a mobile crane and held for several minutes at each of four depths while data were taken and logged at 1 Hz. This test was repeated with carrageenan, custom made canvas bags, and plastic bags preventing or reducing flow in the acoustic volume. The depth profiles of the three trials are shown in Fig. 9. The cables were securely attached to the structure after the carrageenan had jelled and care was taken to avoid disturbing them when the gel was removed and replace with canvas and then plastic bags. All three trials were run on the same day under similar environmental conditions. The data from pod 2 are presented here.

The results of the trials are shown in Figs. 10 to 12. The plots are all on the same scales. Natural and human noise sources clearly have a strong corrupting effect on the canvas and plastic bag measurements. Wave noise is particularly strong at the surface. Note, however, that while the short period (1 second) noise in the bag trials drops to levels comparable to those obtained with carrageenan, longer period (1 minute) variations are still noticeable at 15 m. This indicates some sloshing or flutter of the bags due to currents and wave action.

Figs. 10 to 12 graphically demonstrate the large noise reductions that carrageenan offers during calibration. This observation is supported by the statistical calcu-

	$\sigma_u, \bar{u}$ $[cm/s]$	A1	B1	C1	D1
Fig. 5	σ_u	0.073	0.053	0.028	0.031
	$\bar{u}$	0.231	0.031	0.779	-0.503
Fig. 6	σ_u	0.060	0.038	0.027	0.029
	$\bar{u}$	0.304	0.097	0.825	-0.747
Fig. 7	σ_u	0.056	0.048	0.034	0.036
	$\bar{u}$	0.292	0.016	0.841	-0.717
Fig. 8	σ_u	0.061	0.041	0.024	0.028
	$\bar{u}$	0.338	0.085	0.839	-0.714

Table I

RINO 3 - This table shows the standard deviation (σ_u) and the mean ($\bar{u}$) of the velocity measurements along each axis of pod 1. The data sets are each a fifteen minute burst of 1 Hz measurements taken as follows: Fig. 5 - carrageenan calibration with the probe floating at the surface in sea state 3 conditions, Fig. 6 - carrageenan calibration at $\approx$ 600 m during a descent at 4 cm/s, Fig. 7 - plastic bag calibration at $\approx$ 550 m while riding an internal wave, Fig. 8 - plastic bag calibration at $\approx$ 650 m while riding an internal wave.

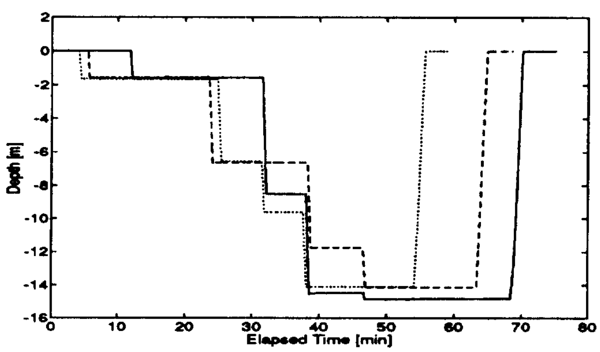

Figure 9. DOCKSIDE CALIBRATION PROFILES - The depth information is derived from pressure measurements. The depth jitter, most visible at 1.6 m, is due to wave action in the well. Trace 1 - solid line - carrageenan; Trace 2 - dashed line - canvas bag; Trace 3 - dotted line - plastic bag.

lations in Tables II to IV. The standard deviation (σ_u) and mean ($\bar{u}$) of the velocity for each trial at each depth are calculated. Clearly carrageenan consistently yields the lowest standard deviation. At greater depths, where ambient flow is less, noise levels for the bag trials have dropped significantly. Carrageenan noise levels have remained near the noise floor of the sensor throughout. The reduction is therefore less, but the gel is still consistently as good as or better than the bags.

A more subtle point can also be made. In Fig. 10 there is no noticeable variation of the mean offset with depth. A 15 m pressure differential is too small to cause a shift. Therefore observed variations in the mean for either of the bags is indicative of a non-zero mean flow, one of the conditions we need to prevent. Some variations of this type are found in the axes of Figs. 11 and 12. In Table V the standard deviations of the means for each axis of pod 2 over the four depths in each trial are calculated. Carrageenan returns a more consistent mean by factors of 4 to 40 with an average gain of 12.

Depth $[m]$	$\sigma_u, \bar{u}$ $[cm/s]$	A2	B2	C2	D2
1.6	σ_u	0.033	0.047	0.034	0.030
	$\bar{u}$	0.382	2.267	-1.186	0.056
8.5	σ_u	0.035	0.032	0.029	0.029
	$\bar{u}$	0.388	2.268	-1.170	0.049
14.5	σ_u	0.036	0.026	0.032	0.030
	$\bar{u}$	0.407	2.277	-1.166	0.056
14.9	σ_u	0.034	0.033	0.034	0.031
	$\bar{u}$	0.406	2.276	-1.166	0.056

Table II

DOCKSIDE CALIBRATION TEST, CARRAGEENAN GEL

Depth $[m]$	$\sigma_u, \bar{u}$ $[cm/s]$	A2	B2	C2	D2
1.6	σ_u	0.472	0.440	0.505	0.505
	$\bar{u}$	0.200	2.256	-0.987	-0.046
6.7	σ_u	0.152	0.140	0.160	0.149
	$\bar{u}$	0.471	2.354	-0.953	0.121
11.8	σ_u	0.113	0.097	0.111	0.121
	$\bar{u}$	0.579	2.474	-0.881	0.260
14.2	σ_u	0.077	0.075	0.080	0.099
	$\bar{u}$	0.576	2.446	-0.929	0.226

Table III

DOCKSIDE CALIBRATION TEST, CUSTOM CANVAS BAG

Depth $[m]$	$\sigma_u, \bar{u}$ $[cm/s]$	A2	B2	C2	D2
1.7	σ_u	0.611	0.567	0.613	0.650
	$\bar{u}$	0.188	2.236	-0.995	0.006
6.6	σ_u	0.183	0.172	0.178	0.196
	$\bar{u}$	0.370	2.236	-1.139	0.006
9.7	σ_u	0.080	0.064	0.070	0.096
	$\bar{u}$	0.379	2.200	-1.110	0.007
14.2	σ_u	0.053	0.049	0.057	0.052
	$\bar{u}$	0.368	2.191	-1.116	0.047

Table IV

DOCKSIDE CALIBRATION TEST, PLASTIC BAG

$\sigma_{\bar{u}}$ $[cm/sec]$	A2	B2	C2	D2
Carrageenan	0.012	0.005	0.008	0.003
Canvas Bag	0.154	0.085	0.039	0.119
Plastic Bag	0.080	0.020	0.056	0.018

Table V

DOCKSIDE TESTS - Standard Deviation of the Mean for Each Axis Taken Over the Four Depths.

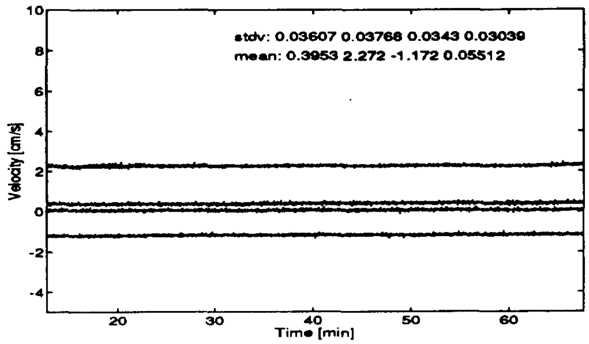

Figure 10. Dockside Calibration Test, Carrageenan Gel - Note that there are no velocity spikes when the sensor is lowered from one depth to the next. Nor are there long duration bursts when dock machinery was operated. Both phenomena can be seen in the corresponding plots for canvas and plastic bags.

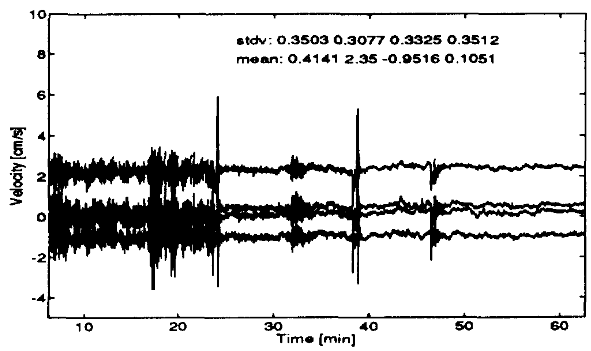

Figure 11. Dockside Calibration Test, Custom Canvas Bag - Large, isolated velocity spikes correspond to sensor depth changes. The large burst of several minutes duration around the 20 *min* mark we associate with the operation of the crane engine. Similar bursts at other times are associated with the crane or other machinery on the dock.

V. CONCLUSIONS

We believe that the data presented here make a strong case for the use of carrageenan for BASS calibration. We have shown, through laboratory, field, and dockside tests, that carrageenan meets the criteria we set out at the beginning of this paper. It creates a consistently low noise, zero mean flow environment for calibration of the BASS sensor. Carrageenan offsets are repeatable and, with a minimum of care, noise levels in the 0.5 mm/s range are obtained. That noise floor, and accurate determination of the true offset, permit BASS to measure flows in mid water and in the boundary layers with millimeter per second accuracy.

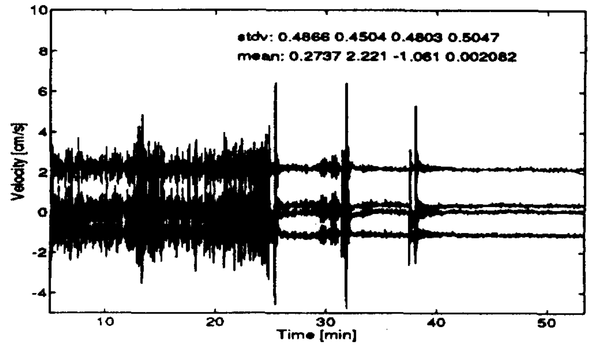

Figure 12. Dockside Calibration Test, Plastic Bag - Large, isolated velocity spikes correspond to sensor depth changes. Several bursts associated with machinery are present as well.

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