Measurement of Turbulence in the Oceanic Bottom Boundary Layer with an Acoustic Current Meter Array

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ABSTRACT

A vertical array of acoustic current meters measures the vector flow field in the lowest 5 m of the oceanic boundary layer. By resolving the velocity to 0.03 cm s⁻¹ over 15 cm paths, it samples the dominant turbulent eddies responsible for Reynolds stress to within 50 cm of the bottom. Profiles through the inner boundary layer, from six sensor pods, of velocity, turbulent kinetic energy, and Reynolds stress can be recorded for up to four months with a 2 Hz sample rate and 20 min averaging interval. We can study flow structure and spectra from as many as four event-triggered recordings of unaugmented samples, each lasting one hour, during periods of intense sediment transport. Acoustic transducer multiplexing permits 24 axes to be interfaced to a single receiving circuit. Electrical reversal of transducers in each axis eliminates zero drift. A deep-sea tripod supports the sensor array rigidly with minimum flow disturbance, yet releases on command for free vehicle recovery.

1. Introduction

Ocean currents and waves exert frictional forces on the bottom by transport of momentum through a boundary layer. The flow in this region scales with the velocity shear, the bottom roughness, the unsteadiness in the flow, and the stratification of the fluid. It is turbulent, three-dimensional, possibly unsteady, and varies principally with distance above the bottom (e.g., see Nowell, 1983; Grant and Madsen, 1986).

To study boundary layer flows, vertical arrays of current meters have been used either as mean current sensors (Weatherly and Wimbush, 1980), or as stress sensors (Heathershaw, 1979). The speed within the boundary layer under certain conditions increases logarithmically with distance from the bottom. The slope and intercept of the logarithmic profile provide two parameters, friction velocity and roughness length, needed to characterize the flow. More generally, the flow can be characterized by the turbulent kinetic energy and the Reynolds stress as a function of distance from the bottom (e.g., see Gross and Nowell, 1983). It is the need to resolve small advected eddies contributing to the turbulent kinetic energy and the Reynolds stress that determines the sensor size and defines the sampling rate.

For some measurements where the flow directions cannot be known in advance, the sensor must be omnidirectional and its supports must not shed appreciable wakes into the measurement volume (Wyngaard et al., 1982). At the same time, the velocity fluctuations responsible for the turbulence signal may be small so the structure supporting the sensor must be stiff and not vibrate, lest it contaminate the measurement. A tripod-type platform provides such stiffness with minimum flow disturbance. Instrument pressure cases and buoyancy modules on the measurement platform are severe flow disturbers but these can be confined to a certain height level where measurements can be sacrificed. We have developed a deep-sea tripod-supported instrument to study bottom turbulence. The Benthic Accoustic Stress Sensor, BASS, has been designed to meet these performance criteria and at the same time be deployable in a wide range of oceanic and nearshore environments.

On the continental shelf and in estuaries, additional requirements must be met by BASS. Here the logarithmic velocity profile method often fails because the wave boundary layer is a major influence, while at other times stratification or internal wave excitation is dominant. In these situations, the ability to measure turbulent kinetic energy at a series of sensor heights and to compare the stress estimates derived from them with the velocity profile is valuable. BASS is unique in permitting turbulent quantities to be measured in reversing flows of a wave field with low enough disturbance to estimate stress. Here, fast sampling, 5 Hz, is necessary.

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to avoid aliasing with peak velocities of 75 cm s$^{-1}$. The large datasets are accommodated in shallow deployments by telemetering the data by radio from a moored transmitter near the tripod.

BASS has been proven to be a valuable instrument for turbulent flow measurements. It has been used in nearshore studies of large swell and wind wave current interaction off the coast of California in the CODE experiment (Grant et al., 1984). Measurements of velocity profiles, turbulent energy and velocity spectra resolving the inertial range and bottom wave influence were made. Adaptations to deploy BASS for long-term boundary layer monitoring in the HEBBLE site enabled quantitative evaluation of the effect of benthic storms (Gross et al., 1986; Grant et al., 1985). These 2-month and 6-month deployments allowed changes in bottom roughness over time scales of hours to weeks to be observed using logarithmic velocity profiles and direct measurements of Reynolds stress and kinetic energy. The unique ability of BASS to measure across time scales from half a second to many months with velocity resolution of 0.03 cm s$^{-1}$ has made possible studies of the benthic boundary layer unattainable by any other instrument in use.

2. The benthic acoustic stress sensor
   a. Differential travel time

   A burst of acoustic energy propagates through a fluid medium at the group velocity of sound with respect to the medium. If the medium is moving with respect to the fixed acoustic transducers that generate and receive the sound, the transit time will be modified by the advection of the medium. The acoustic travel time between a pair of transducers contains the integrated effects of velocity along the path in addition to the sound speed in the medium. An acoustic burst along the same path in the opposite direction will give a travel time that differs from the first only in the reversal of the sense of the velocity contribution. These two times are $t_1$ and $t_2$ such that:

   $$ t_1 = d/c - v $$
   $$ t_2 = d/(c + v) $$

   where $d$ is the path length, $v$ is the average flow velocity component along the path, and $c$ is the local speed of sound in seawater. Note that the speed of sound varies a few percent over the oceanic temperature and pressure range, but in general, this effect is well known and can be applied as a correction to the final velocity.

   In BASS, the two travel times are subtracted to yield a differential travel time which depends on the average value of the flow component along the acoustic path:

   $$ t_1 - t_2 = 2dv[1 + (v/c)^2 + \cdots]/c^2. $$

   The time difference is linear in velocity to 1 ppm for oceanic flows. The higher order terms are henceforth dropped.

   The factor $2d/c^2$ is 1.3 ns/cm s$^{-1}$ for the 15 cm acoustic path in BASS. This requires resolution of very small time differences to achieve the flow speed resolution desired. The noise level for this measurement is about 40 ps, so that by averaging two measurements, 0.02 cm s$^{-1}$ can be resolved. To resolve this time interval, the phase of the transmitted signal must be measured.

   b. Sensor geometry

   Boundary layer flow is essentially parallel to the boundary in the mean. In BASS, wake-generating sensor supporting structures are of minimum size and are removed wherever possible from the level at which measurements are made. On the sensor, the transducers are mounted on rings outside of the measurement volume (Fig. 1). All paths are inclined 45$^\circ$ to the horizontal. The thin support rods of the cages shed minimum wake and the electronic cabling is dressed away from the measurement level to prevent wake from that source. The wake of the transducer molding is the most important disturbance and is noticeable only when the flow vector is less than 20$^\circ$ from the acoustic axis. This requires not only that the velocity be close to the azimuth of an axis, but that it have sufficient vertical component to elevate it at least 25$^\circ$ from the horizontal. Because the sensor contains four acoustic axes and the flow cannot be closer than 20$^\circ$ to more than one axis, it is always possible in principle to recover the true flow vector from three undisturbed axes.

   The dressed sensor cage was towed horizontally in our tank at constant speed with various azimuthal angles between the towing direction and the plane of an acoustic axis. The error between the computed projection of the flow vector along the acoustic axis and the flow measured acoustically was less than 5% of the towing speed. In our tow tank, reflections of the support strut's bow wave from the side walls produce cross flows of this magnitude so that no more precise constraint can be placed on the tank measurement. There was no cosine error, only cross stream noise.

c. Transducer

   Large diameter transducers have high gain but require precise alignment and disturb a significant portion of the acoustic path by wake effects near the transducer face. Wyngaard and Zhang (1985) consider the transducer wake for sonic anemometers. If the transducer is comparable in size to the cable, reducing it further does little to reduce the flow disturbance at much cost in signal gain. BASS uses a lead titanate-zirconate piezoceramic transducer 9.5 mm in diameter and 1.27 mm thick, resonant at 1.75 MHz. The central lobe of the acoustic beam is about 6$^\circ$ wide, giving a spot size of 15 mm at the location of the opposite
transducer. This requires alignment within $2^\circ$. This may not be the optimum size. A 5 mm-diameter transducer would be more tolerant of alignment errors and have lower flow disturbance than the existing one and might still have enough gain for a good signal-to-noise ratio over a 150 mm path. However, the 9.5 mm transducer is a reasonable compromise for gain, flow disturbance, and alignment sensitivity, as well as manufacturability and cost.

As Fig. 2 shows, the transducer is cast in a rigid urethane (Conap DP-10767), and faced with a soft urethane matching the acoustic index of water (Conap EN-4). It is exposed to hydrostatic pressure and transmits a pressure wave equally from both faces when electrically driven. The mold accurately aligns the transducer with its faces elevated $45^\circ$ from the mounting flange and aligned with its center 2.3 mm from the inner corner of the rectangular cross section support ring. Since a burst of many cycles is transmitted and reflections from the early part of the burst transmitted from the back face could add to the later portion of the burst transmitted from the front face, it is important to minimize the amplitude of the reflections along the acoustic axis. The avoidance of any surface parallel to the transducer in the back seems to do this and the scattering from edges is too diffuse to contribute a measurable effect at the opposite transducer. Little refraction or reflection occurs at the EN-4 facing, and since this is slightly convex, what reflection does occur is defocused and thus attenuated at the opposite transducer.

The effect of reflections is not as severe as might be feared. Reflections detected by the receiver generally propagate through solid materials until they emerge quite close to the direct beam. The effect of speed-of-sound changes in these solid materials, from temperature or pressure, changes the phase of the added signal due to reflection, but this is not a source of error since the reciprocal path has the same phase offset. The only net error that reflection introduces is a contribution from a different acoustic path in the flow, and the attenuation of reflections makes this error quite small.

The transducer is connected through an integrally

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**FIG. 1. Sensor Cage:** Transducers mounted to the upper ring form acoustic axes with transducers mounted opposite to them on the lower ring. All axes are inclined $45^\circ$ to the horizontal and are spaced $90^\circ$ in azimuth. The rings are 117 mm in diameter and 117 mm apart, supported on 3.2 mm rods. Cross bracing rods are 1.6 mm in diameter and add no detectable flow disturbance. Cables are tie-wrapped to the coupling rings.

**FIG. 2. Transducer:** The piezoelectric element, a lead zirconate-titanate ceramic disc, is connected to a premolded connector by fine wires soldered to its faces. This assembly is then potted in rigid urethane to maintain alignment when mounted. The front face is covered with a soft urethane, matching the acoustic impedance of water. The disc, 1.27 mm thick and 9.5 mm in diameter, is resonant at 1.75 MHz.
molded connector to urethane-jacketed RG-316 coaxial cable and then to the electronics pressure housing endcap. This cable compresses under hydrostatic pressure and changes its capacitance. Since the capacitance of the cable is part of the load seen by the transducer, it affects the phase of the voltage at the input stage of the electronics. Compensation for this phase shift is important. Reversal of the transducers can help, but the switching of transducers must be done very near the sensor (and capacitance changes of the transducers themselves may invalidate improvements made this way) or the impedance of the input circuit must be lowered to the point where capacitance variations do not introduce a significant phase error. The latter approach has been taken in BASS.

Transducer failures were common in the early days, sometimes affecting as many as half of the acoustic axes. Initially the problems were broken wires, then intermittent connectors, misaligned transducers, and delaminated ceramic elements. These faults were eliminated by changing materials, changing construction techniques, modifying designs, and by inspecting subassemblies in the molding process. In 1984 over 500,000 transducer hours were logged and there were no failures (Dunn, 1984). An additional 280,000 transducer hours were logged in 1985–86 on these same sensors, still with no failures. Total immersion is over one year for 80 of these transducers.

d. Electronics

1) INPUT STAGE, RECEIVER MULTIPLEXER, AND TRANSMITTER

The piezoelectric transducer converts electrical energy into acoustic energy. It can be molded (Fig. 3) as a capacitance ($C_1$), inductance ($L_1$), and resistance ($R$) in series shunted by another capacitance ($C_2$). The series circuit (impedance $Z = R + X_C + X_L$) is resonant near the driving frequency with a Q of about 5. Thus $R$ (about 50 ohms) is about one-fifth the reactance of the capacitance and inductance. The shunt capacitance ($C_2$) is about 2000 pF, partly from the transducer and partly from the cable. This has a reactance comparable to the resistance at resonance and cannot be ignored. The transmitter can be modeled as a voltage source ($e_t$) in series with a source resistance ($R_t$), driving the cable and transducer. The receiver can be modeled as a load resistor ($R_L$) driven by the transmitter and cable. This model is used to analyze the sensitivity of the transfer function to source and load resistance.

Radiation is proportional to the power dissipated in the resistance $R_1$ of the transmitting transducer, since this element of the model represents both internal losses and radiation. The radiative path is represented by a transconductance $G$ and a time delay $\Delta$ for the travel time. The current $i_2(t)$ imposed across the series resistance of the receiving transducer $R_2$ is thus a function of the voltage $e_1(t)$ across $R_1$:

$$i_2(t) = e_1(t - \Delta)G, \quad \text{for transmission from 1 to 2},$$
$$i_1(t) = e_2(t - \Delta)G, \quad \text{for transmission from 2 to 1},$$

and

$$i_{out} = \frac{e_1(t - \Delta)G R_1 R_2}{[R_1(1 + Z_1/X_C) + Z_1][R_2(1 + Z_2/X_C) + Z_2]}$$

as explained in Fig. 3.

The transducer transfer function, the current through the load as a function of the source voltage, is symmetric to reversal of transmitter and receiver except for the source resistance and load resistance. If these were identical, the symmetry would be perfect and phase shifts due to operation off resonance or to cable capacitance would be the same for the forward and reverse path, so there would be no net offset in travel time. Alternatively, if the source resistance and load resistance were very small, the terms including them could be neglected and the remaining terms are perfectly symmetric to reversal. It happens that the terms including the source and load resistances have phase shifts of about 45°. A differential phase shift of 1° is responsible for a velocity offset of 1.2 cm s$^{-1}$, so a matching error of source and load resistance gives an offset of about 1 cm s$^{-1}$ per ohm. Note that the static
offsets can be measured and removed in data processing.

If the differential shunt capacitance change upon exposure to hydrostatic pressure is 10% of the total shunt capacitance, the source and load resistance must be balanced to 2.8 ohms to keep offset shifts below 0.3 cm s⁻¹. To make the transfer function completely insensitive to capacitance change, the source resistance of the transmitter must equal the load resistance of the receiver. The lower the impedance of the source and load relative to the transducer, the less sensitive the transfer function is to changes in shunt capacitance. Low impedance of source and load, rather than matching has been sought in BASS.

As shown in Fig. 4, the transmitter drives both transducers of an acoustic axis through two pairs of low voltage Schottky diodes, D1–D4, opposed in parallel. A 3 volt source is square wave switched for a burst of 15 cycles of VMOS transistors Q1 and Q2, and the transformer-coupled square wave appears nearly identically on each transducer, differing only in the variation of the forward voltage drop of the Schottky diodes. The source resistance of the transmitter, determined by the VMOS transistors, is about 2 ohms. One of each pair of diodes conducts in each direction. However, at the time the receiver is enabled, the received voltage is clamped by the grounded base input circuit and neither diode conducts, isolating the receiver from the transmitter. This form of transmit/receive switch is simple yet satisfactory, ensuring that the two transducers of a pair are driven synchronously but received independently.

The receiver input is a grounded base transistor biased at 3.6 ma emitter current, which gives an input impedance of about 7 ohms (Horowitz and Hill, 1980a). In this circuit, there is no voltage gain but the input current signal at the emitter appears on the collector. To keep the operating point of the transducers nearer ground, the bases are not actually grounded, but rather referenced to the base of a forward biased base-emitter junction of a transistor of the same type, the emitter of which is grounded. This tracks the voltage offset of the input transistors within 0.1 V, which is enough to prevent conduction of the transmit/receive

![Figure 4: Low Impedance Source and Load for Transducers](image)

When S1 and S4 are closed, _T_Top_ drives Q7 through Q3 while _T_Bottom_ drives Q8 through Q6. When S2 and S3 are closed, the transducers drive the opposite outputs. Q9 and Q10 bias the common emitter transistors near ground when they are selected to prevent conduction by D1 through D4. The cascode connection of Q3 to Q7 and Q6 to Q8 prevents crosstalk between channels.
diodes that isolate the receiver from the transmitter during reception.

Because the input transistors act as switches and turn off when the bias current is removed from their emitters, a reversing switch can be made to interchange the connection of the transducers to the subsequent stages. A mechanical switch to do this was described by Kalmus (1955), and a commutator included in the circuit of Ymker and Hoogendijk (1983). Transistor Q3 of Fig. 4 connects the top transducer of the first axis to Q7, and Q6 connects the bottom transducer of this axis to Q8 when switches S1 and S4 are closed. This forms a pair of cascode amplifiers to reduce the capacitive coupling between the outputs and the opposite inputs. When switches S2 and S3 are closed, transistors Q4 and Q5 reverse the connection so that Q7 is driven from the bottom transducer and Q8 from the top transducer. Transistors Q9 and Q10 provide the bias needed to keep the diodes D1–D4 out of conduction.

The collectors of the transistor reversing switch can capacitively couple one channel to the other through the off transistor if the load impedance is high. This crosstalk is very undesirable. To prevent it, they are connected in a cascode circuit (Horowitz and Hill, 1980b) to the emitters of Q7 and Q8 biased at a higher voltage, 4 V. The low impedance of the cascode circuit effectively stops crosstalk between the channels.

As shown in Fig. 5, the isolation provided by the cascode circuit permits many sets of reversing switches to be connected to the emitter of a single second-stage transistor of the cascode circuit. For modularity, four sets of switches, for a four-axis sensor pod are connected to one second-stage transistor for each of the two outputs. The collectors of as many second-stage transistors as there are sensors are paralleled and drive the load impedance, 776 ohms, at the input of the comparator. The second-stage transistors are selected one sensor pod at a time so the other channels do not load the circuit.

A separate transmitter is used for each transducer pair, four transmitters with their output transformers per circuit card. Four reversing switches and a pair of cascode output transistors are accommodated on a single receiver card. Thus, each sensor has associated with it two circuit cards, one for transmitting and one for receiving. One set of cards is enabled at a time and one transducer pair is enabled at a time. Thus, multiplexing is accomplished at this level, including transducer reversal at the input stage. Subsequent signal processing may introduce differential time delays in the two channels but as long as these do not change rapidly, they can be removed by subtracting the result with the transducers connected reversed from that with the transducers connected normally. The only offset error uncorrected by this reversal is that associated with differential delays due to the transducers and cable. Voltage drive and low impedance at the input stage minimizes offsets from this cause.

2) Differential Time-to-Voltage Circuit

The voltage waveform at the collectors of the cascode output transistors is a sinusoidal signal modulated by

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**Fig. 5. Cascode Multiplexing:** Each receiver has four sets of reversing switches driving a pair of cascode output transistors. One axis is enabled at a time and coupled normally and then reversed. The cascode output transistors from six receivers are paralleled through their collectors. One sensor is selected at a time and the cascode transistors from the rest are put in a high-impedance state.
a low-passed square envelope. The frequency, 1.75 MHz, is close to the resonant frequency of the transducer and is the drive frequency of the transmitter. The amplitude grows to about 1.8 V with a time constant of 4 μs. The voltage signal is not quite symmetric because the finite impedance of the input stage permits a 15 mV signal to appear at the emitter and the nonlinear load of the transistor emitter makes the current at the collector unsymmetric. This current is transferred from the cascode stage to the load resistor at the input of the comparator.

As shown in Fig. 6, an LM-261 voltage comparator configured as a Schmitt trigger (Snively, 1967), detects the negative-going zero-crossing of its input voltage waveform. The waveform is high-passed with a time constant of 1.8 μs, long compared to the resonant period, but short compared to the growth rate of the amplitude. This introduces a slight voltage error in the determination of zero crossing because of the nonlinearity. However, the error from the reversed connection of the transducers is nearly the same because the amplitude is nearly the same. This voltage error, which gives a time error, cancels when the reversed measurement is subtracted from the normal measurement.

The root-mean-square (rms) current noise of the input transistor at 3.6 ma over the bandwidth of the voltage comparator (50 MHz), is 400 na, which becomes 300 μV across the load resistor at the input of the comparator. When the amplitude of the signal at the comparator has grown to 1.8 volts, the slope at the zero crossing is 20 V μs⁻¹, giving a time noise of 15 ps. Two such errors add incoherently in the differential travel time measurement for an rms noise of 21 ps or 0.016 cm s⁻¹ rms velocity error each for the normally connected and the reverse connected determinations. These are subtracted and again the noise adds incoherently for a final error of 0.012 cm s⁻¹. The observed standard deviation of zero flow measurement is about twice this, 0.021 cm s⁻¹, suggesting this is not the only noise in the system.

The comparators are configured as Schmitt triggers to prevent false triggering before the first cycle of the received waveform. The thresholds are 100 mV positive, high enough to reject noise before the signals arrive, but low enough so the first cycle is always detected. The negative-going signals are detected at zero threshold (Loosemore and Muston, 1978) to prevent slight amplitude variations from shifting the detected crossing times. The outputs of the comparators decrement preset down-counters, enabling a pair of high speed flip-flops to be triggered on the 14th cycle as in Kohn et al. (1982). The falling edge of the comparator outputs
which being TTL output devices, have crisp falling edges) clock their respective flip-flops, which then start integrators effectively triggered by the 14th negative-going zero-crossing of the received signal. The flip-flops are reset together by a delayed coincidence gate, stopping the two integrators when both signals have been received. The delay ensures that both flip-flops turn on fully and that the two integrators move into their linear operating regions before being turned off.

There is no observable discontinuity in voltage out of the differential-time-to-voltage circuit when the difference in arrival time goes through zero, even though this means that the load of turning off the integrators switches from one flip-flop to the other. Thus, there is no indication that coincidence gate loading of the flip-flops occurs. There is no other electronic asymmetry at the crossover point.

Each flip-flop, when triggered, steers a current source from a sink to an integrating capacitor. This can be done with less turn-on transient than if the current source was switched on. The current sources are trimmed to make the integration constants equal. Although the reversal technique makes the measurement immune to an integration constant mismatch, the full range in velocity can only be achieved if the two integrators saturate at the same velocity (one when the connection is normal and the other when the connection is reversed). The charging rate is 32 V μs⁻¹, giving a 5 volt maximum for 120 cm s⁻¹ flow. High-impedance-voltage followers track the integrating capacitors and drive a difference amplifier with a gain of 2 for a full scale range of plus and minus 10 volts, corresponding to plus and minus 120 cm s⁻¹.

Sampling the output voltage of the differential-time-to-voltage converter and digitizing it is standard except for the timing. The output voltage of the current meter is multiplexed with the output of the ancillary sensor amplifiers before it is sampled. This permits the digitizer to process all variables identically. For the current measurements, the sample window is typically 8.6 μs from the time the integrators have ramped up until the A/D converter is started and the sample-and-hold is held. This permits the difference amplifier of the current meter (LF 355) to settle to 0.01% (6 μs), and the sample-and-hold (SHM-LM-2 with 1000 pF hold capacitor) to also settle to 0.01% (6 μs). That they are slewing together makes the total settling time only slightly longer than that for one alone. The successive approximation 16 bit A/D converter (ADC 1148K) converting in 100 μs takes 6 μs to make the most significant bit decision, while the hold mode settling time to 1 mV is 0.8 μs. The total error from settling is thus less than 0.025%, giving 12 bit accuracy.

Sensitivity and linearity of the differential time delay measurement has been checked on the bench with ns delays (switchable coaxial cables). The local slope of voltage difference plotted against delay difference over any eighth of the range lies within 4% of the slope for the full range of the ns delay (plus to minus 128 ns). The linearity is thus better than 96%, and the integrators have the same integration constant at the top of their voltage range as at the bottom. This means the velocity calibrations vary at most by 4% across the range -120 to +120 cm s⁻¹. Expected turbulent fluctuations of ~5 cm s⁻¹ in a mean flow of 5 cm s⁻¹ are locally linear to 4%×5/120 = 0.17%. The product error is <0.34%.

Local linearity is important for a turbulence sensor where large mean currents must often be subtracted before the products are formed. It is encouraging that there are no offsets in the transfer function. Such offsets could result (and did in a previous design) from crosstalk, in which the comparator that switches first puts a noise spike on the input of the comparator switching second, delaying or advancing the detected time difference, depending on whether the spike occurred just before or just after the zero crossing. There remains a possible artifact due to the asymmetry of one comparator triggering first. However, the slopes for positive and negative delay (current up and current down) are the same to 1%, so this is corrected by the reversal strategy.

Early deployments were marred by a persistent drift of the zero point. The uncertainty in offset for each current record made interpretation difficult. In 1981, this problem was solved by the input circuitry described in this paper. Comparisons of the zero measured before a deep-sea deployment with that after deployment (and one measurement of the offset at depth for a bagged sensor in which there was no flow) show the mean offset to be less than 0.02 cm s⁻¹, while the standard deviation of velocity offset is about 0.3 cm s⁻¹ (Williams, 1985). Offsets greater than 0.5 cm s⁻¹ occur less than 10% of the time (sample size: 88 acoustic axes in a single long deployment) while the worst offset was 1.4 cm s⁻¹. These offsets were measured by placing the sensor tower in a trough of stationary water and recording and analyzing the flow. The water was permitted to thermally stratify to stop convective motions. Typical 2 Hz samples 1 h long give a standard deviation of 0.02 cm s⁻¹, the assumed noise level for the cross products.

3) TIMING

A flag on the differential-time-to-voltage circuit indicates if both flip-flops have triggered by the time the sample-and-hold circuit captures the voltage. This identifies acoustic signal dropout before data processing. While dropout occurs less than 0.1% of the time in a typical experiment, it accounts for more than 90% of the points contributing to large variance. During data editing, points more than three standard deviations away from the mean are removed and this process drastically reduces the variance of records with significant dropout, since when one or both signals fail to
trigger the flip-flops, one integrator may go full scale or they may both remain at ground, producing a wild point in the first case and a bad point in the second case. For data processing in situ, dropout screening is essential.

Including this screening, a cycle of measurement starts with the microprocessor program selecting from a data list the next sensor axis to be measured. The data byte from this list is latched in an output port and decoded by hardware to point the multiplexers that steer the acoustic transmit-and-receive circuits. Three bits determine which sensor will be used. Only one transmitter and receiver board will be selected at a time. Two more bits select which acoustic axis of the sensor will be used. Another bit determines if the transducers will be connected normally or reversed. The latching of the byte starts a hardware timing circuit which uses a CPU (central processing unit) timing pulse. Running from the CPU timing ensures that the phases of the subsequent actions are fixed with respect to the microprocessor instructions. Hardware timing controls the transmitter oscillator, gated transmission, blanking of the receiver, enabling of the receiver, and the sample time.

Figure 7 shows the timing of the measurement cycle. The CPU executes a tight program loop, in which the multiplexer data byte is latched, the next byte is examined to see if the end of the list has been reached, the input buffer pointer is advanced, and the flag is examined that tests if both channels have detected an arrival. If they have, two bytes are input and the cycle repeats. If not, the high byte of the bad word is set to zero (a condition occurring naturally only if the velocity were more than 120 cm s\(^{-1}\)) to serve as a flag when subsequent processing is done. The cycle repeats until the test for end-of-multiplexer list is satisfied. Two special cycles are used to exit the loop.

While the hardware timer and CPU are running in concert, the acoustic pulse transmitted in the third clock cycle of the sequencer is traversing the measurement volume. Transit takes 100 µs, but the actual zero crossing of the signal that is responsible for the measurement occurs at 108 µs plus or minus 5 µs. This is the time when the CPU is checking for the end of the list. Reflection at the receiving transducer sends an acoustic pulse back to the transmitter but this echo arrives at a time when the receiver is blanked during the transit of the next pulse.

Shortly after the acoustic pulse has been received, the output of the differential-time-to-voltage converter is captured and the A/D converter started. An A/D converter matching the travel time of the pulse was chosen to optimize power and timing. A slower A/D would prevent rapid cycling while everything waited for it to finish the previous measurement. A faster A/D would use more current and wait for the next pulse to cross the measurement volume before digitizing the next measurement.

The full measurement cycle takes 156.3 µs. It takes two cycles before everything is going, acoustic transmission, A/D conversion, and CPU testing of position in the multiplexer list. After the last pulse is sent, two more cycles are required while the pulse crosses the measurement volume and while the measurement is digitized.

4) POWER SAVING

While the measurement cycle is running, power hungry operational amplifiers, comparators, and fast switches are used. However, the six sensor pods with their four axes measured normally and reversed can be sampled in only 7.5 ms. The rest of the time the circuits can be powered down. Figure 8 shows the relative time for the major tasks, and the time power is on. Of course, upon application of power before the
between measurements and if they can process many measurements in rapid succession.

An extreme power saving is possible in theory if one were to separately switch the power to the comparators for the time that the received signal was being compared, a period of 13 $\mu$s every 156.3 $\mu$s. These components turn on fast, so it would be possible. This would reduce the average power during the measurement cycle to 450 mW and the average overall to 11 mW. However, this has not yet been done in the instrument described here.

Ancillary analog measurements were made with the same A/D converter, and it was convenient to extend the measurement cycle by extra cycles and set a seventh multiplexer bit to select the alternate signal source for these measurements. Micropower amplifiers were used for temperature and transmissometer signals, and thus these devices did not add significantly to the power budget but were slow to slew, so that after an ancillary sensor was selected, 2 ms were required to allow the amplifiers to settle. This extended the measurement time from 7.5 ms to 15 ms when the measurements were made. However these were only made every 5 min, in general.

5) Power Budget

Table 1 shows the power consumption for the components that used a substantial amount of power, arranged by circuit board and device. Two scenarios are shown: one in which power is provided only during the time the device is actually working, and the other in which power is provided for the time that the measurement cycle is running. The first is called Micro Power Programming and the second is called Batch Power Switching. The latter is what was used.

Power for the actual measurements was modest. Between measurement cycles the power did not go to zero, however. The processing of data acquired during the measurement period required power, as well. In fact, the power budget illustrated in the table shows the major energy user to be memory, with the CPU's next. They consume 35% of the total energy. The energy expended during warmup is 24% of the total. The measurement circuits used 30% of the energy. Power circuits, the switching regulator with no power out and the multivoltage converter used during measurements, consumed an additional 10%. Multiply-and-divide circuits, clock, and UARTs took only 2.5%.

Although the measurements took a major portion of the power, the savings possible by microprogramming the power to the comparators and measurement amplifiers would only achieve a 20% reduction in total power. Reducing the warmup time would save as much power. The energy source was a battery which had 20 V when first turned on but dropped to 14 V at end-of-life. Power at 5 V, the level at which most of the power was used, was provided by a switching regulator with
very low standby power drain. The switching regulator permitted the conversion of variable battery voltage to 5 V with reasonable efficiency, 65%, in fact. Full power efficiencies greater than this are possible with switching regulators working at these voltages, but generally these regulators have higher standby losses which makes their overall performance worse.

3. The platform and complete measurement system

a. Ancillary measurements

To gain more information about the interaction of current with sediment in the benthic boundary layer, a number of measurements in addition to velocity are made. The ancillary quantities measured are: optical transmission, temperature at three to eight heights, instrument tilt and compass orientation. Temperature is sensed with a thermistor, the signal being a resistance. This resistance is converted to a voltage in a precision bridge, then amplified and offset to a voltage with the same range as the acoustic current meter for multiplexing to the same A/D converter. The thermistors are switched between their outputs are conditioned, although all are powered on during the measurement cycle.

The optical transmissometers, Sea Tech 1/4 M, are positive output voltage devices and are level-shifted and amplified to the same levels as the acoustic current meter. Tilt is measured with Humphrey potentiometric pendulum angle transducers. These operate with the same voltage range as the transmissometers so they are multiplexed with the transmissometers before being level-shifted and amplified. Selection of which of eight thermistors and which of eight high-level analog channels (transmissometers and angle transducers) will be measured is performed by the low three bits of the multiplexer word. Selection of whether thermistors or the high-level analog ancillary data channel will be digitized is performed by the sixth bit of the multiplexer word. The seventh bit selects between ancillary inputs and the acoustic current meter input to the digitizer. The eighth bit is not used.

Multiplexers are the most troublesome components to power-down since they are partly analog and partly digital. To save power, it is necessary to remove positive and negative supply voltage from the multiplexer devices, but it is also necessary to continue to run control lines at digital levels to them. All inputs voltages are removed from most devices before they are powered down, including latching the byte 00 to the multiplex-
ers. The transmissometers present a special problem, however. They must warm up for 2 sec before a measurement is made of their output. For this period, they produce a voltage at the input of one multiplexer. Although the multiplexer is disabled by the power-down condition, these voltages on the input would cause malfunction were it not for a pull-up diode to the transmissometer power source to keep the multiplexer from latching.

The compass has a digital output which must be shifted into the microcomputer, and at times, frequency output devices such as the Paros Scientific Digiquartz pressure transducer are counted to produce other digital signals. These are latched into a serial shift register and clocked into the microprocessor a byte at a time.

b. Tripod

Deployment of the BASS as a deep-sea instrument requires a rigid recoverable vehicle with minimum flow disturbance. A tripod with expendable base was selected to minimize chance of loss due to footprint. We attempted to have every structural element be part of a triangle (truss-type structure) to maximize stiffness and minimize projected area. The tripod that resulted (Fig. 9) is 5.5 m tall and 4 m on a side, with a heavy base 1.5 m high. The base is welded from galvanized steel pipe 5 cm in diameter, with single-splayed legs at the corners ending in 35 cm² steel footpads 4.5 cm thick. All this is cross-braced with 2-cm steel pipe from footpad to upper corner, crossing at the center of each face. The upper corners contain a striker plate, against which the latches bear holding the upper tripod to the lower part. Figure 10 shows the latch engaged and held by a tensioned cable. The cable is released on command with an electrochemical link (Williams and Fairhurst, 1977).

The upper tripod supports the sensor tower, instrument cases, and flotation, and provides a strong pickup point. The upper tripod contains release latches at its corners to engage the striker plates of the lower tripod. Aluminum tubing 5 cm in diameter is used for the upper structure, with stainless steel fittings to interconnect the aluminum tubes. Straight pieces define a tetrahedron fitting just inside the lower tripod and extending up to 5.5 m above the deck. A platform, 4 m above the bottom, carries the instrument cases and the buoyancy modules (six 43-cm glass spheres and 0.027 cubic meters of syntactic foam). Two electronics housings of 18-cm outside diameter and several smaller tubes for acoustic releases and transmissometer are tucked between the other obstructions at this level. Because there is a mass concentration at this point along the midspan of the rising struts, cross braces to the lower corners have been included. Without these cross braces, torsional oscillations can be excited, which in turn move the sensors on the tower.

The stainless cages of the acoustic current meter sensors are bolted together to make a stiff tower 5 m tall, broken at 3.5 m for mounting to a rigid ring in the bottom of the instrument case/buoyancy module platform. The tower extends downward to within 20 cm of the bottom when the upper and lower tripods are connected. Guy wires from the corners to the tower at five heights further stiffen the structure and provide paths along which to dress the electrical cables from the acoustic transducers. Irregular wire and cable lengths and spoilage by cable dressing is believed to inhibit sharp Strouhal oscillation resonances. Frequencies would be above the sampling frequency of BASS, so Strouhal oscillations would be aliased and appear as enhanced turbulence at high currents. It is not likely that this effect would be noticeable, but should be considered when analyzing data.

c. Performance

There have been about 40 deployments of BASSes in the deep sea from 1979 to 1986. The release based on a triple latch held cocked by an electrochemical corrosion link has worked reliably and held for as long as 205 days without signs of fatigue. When recovered, the lower part of the sensor tower is exposed and must be carefully placed in a waiting base. Occasional minor damage has occurred due to brushing the rail or pressing a guy wire into the base while nesting sections, but there have been no losses in deep-sea deployments.

In addition to the deep-sea deployments, there have been about 30 shallow deployments of BASSes lasting from several hours to three months (Grant et al., 1985). In these deployments, an aluminum tripod is used with a recovery line, released by electrochemical link if the depth of deployment exceeds free diving depth (30 m). The shelf has proven a harsher environment than the deep sea. One tripod was lost when the recovery line snagged the tripod corner and another was hit by a fishing dragger. However, no data has been lost as a radio transmitter sends the data ashore or to a ship where it is recorded.

Leaky underwater bulkhead connectors have now become a significant cause of failure with three leaks in 300 connector deployments. These leaks were slow and only affected the signals on the faulty connector. Human error in mounting tapes, setting timers, programming, and plugging things together are the greatest causes of failures at present. Data loss from mechanical damage to electronic components and insufficient battery capacity marred several deployments in 1984. However, the overall predictability of success is now high.

4. Turbulence measurements

a. Stress computation

Tape capacity limits data storage to 28 000 instantaneous measurements of velocity and ancillary quan-
Fig. 9. Tripod: Six acoustic sensors are joined into a tower guyed within an aluminum tripod 5.5 m tall. The upper part containing buoyancy, electronics, and recovery aids is latched to a weighted base by an electrochemical release. When commanded, the base is released and the tripod floats to the surface. Flow obstructions are confined to a layer centered 4 m above the bottom. Included with the flotation spheres in this layer are the BASS electronics, data logger, acoustic command releases, optical transmissometer and bottom camera. Low-angle illumination to reveal small scale topography in the bottom photographs is provided by a strobe on a strut mounted to the upper tripod. A recording echo sounder, the transducer for which blocks the direct flash from the camera strobe, provides an estimate of the tripod sinkage and the accumulation rate or erosion rate of sediment under the sensor tower.

Atmospheric and oceanic quantities or 4 h of raw data at half-second intervals. To extend the observation of bottom stress to months, in situ averaging must be done (Gross et al. 1986). Vector velocity averaging has become standard with oceanographic current meters, but higher order averaging necessary in turbulence research has not. There is tape capacity for 8600 records of mean velocity, turbulent kinetic energy, and Reynolds stress. This allows 20 min averaging intervals for four months or one hour intervals for a year. Stationarity of the flow and spectral resolution set the averaging interval (Soulsby, 1980). In the deep-sea data sets examined at various data rates, 20 min averaging is adequate to achieve stationarity, but not necessarily short enough to resolve internal waves. To monitor internal waves, thermistor chain measurements are recorded at 5 min intervals.

It is not necessary to store an entire 20 min block of raw measurements before removing the means and
A zero stored in the high byte position of the data word indicates this condition. Before forming products, successive words representing the normal and reversed measurements of velocity of one axis are subtracted to remove the electronic drift, and the two high bytes are checked to see if the measurement is marred. If either contains zero, the difference is replaced by zero and an error count word for that axis is incremented.

When the products are formed, a zero in one of the multipliers forces a zero in the product, which is detected when the product is added to the accumulator and the accumulator counter for that cross product is not incremented. In this way, bad data does not contaminate the accumulated quantities; nothing is added to the accumulator and nothing is added to the counter. Each velocity mean has an error count recorded with the mean so that a bad acoustic axis can be flagged. Means and cross products will be accurately calculated unless the error count-indicated dropout rate exceeds \( \sim 10\% \) (a very rare occurrence unless the pod is physically obstructed).

At the end of the averaging period, 20 min in HEBBLE 1984, the accumulators are divided by their counters to form means. The velocity means are loaded into an output buffer along with the error counts for each acoustic axis. This computation is easy; a 32 bit dividend and a 16 bit divisor are loaded into the hardware divide unit and the quotient is used. For subsequent computations, it and its remainder are also stored.

Cross product and self product means are more difficult to deal with. The 48 bit sums are mostly the sum of the products of the means. For compactness, these must be subtracted before recording on magnetic tape. Since the accumulated cross product count may be different from the accumulated velocity count, the velocity means must be multiplied by the cross product count before subtraction from the accumulated cross products. Working with the cross product of \( A \) with \( B \), four terms must be formed and subtracted: cross product \( AB \) times the velocity mean \( A \) times velocity mean \( B \), count \( AB \) times remainder \( A \) over count \( A \) times mean \( B \), count \( AB \) times remainder \( B \) over count \( B \) times mean \( A \), and count \( AB \) times remainder \( A \) over count \( A \) times remainder \( B \) over count \( B \). The result of this subtraction is no more than a 40 bit number, except in pathological cases. The lowest 8 bits are dropped as insignificant and the remaining 32 bits are divided by the 16 bit count \( AB \) to give the mean of the cross products minus the cross product of the means.

The arithmetic in the averaging of the 20 min block is lengthy, taking 2.5 sec. However, this interruption to the measurement of flow only occurs every 20 min.

### b. Event triggering

Sediment transport is episodic in the deep sea, occurring for hours or days a number of times a year. It is possible that there are important characteristics to
these high-stress events that would be missed by the series of 20 min averages during the event. To capture a short piece of high-frequency data during an event, raw data is recorded for one hour when optical turbidity exceeds a predetermined threshold for two hours. This recording is the same data as that used in computing the average values, but is recorded on a separate tape recorder. There is room for only four such events, so each time an event is triggered, the turbidity threshold for the next event is set higher.

To test for an event, the transmissometer is turned on every 5 min for 2 sec, at the end of which it is measured and stored. Its reading of optical transmissivity (turbidity) is compared to the next threshold on a list, and if the reading is lower (higher), a counter is incremented. If the count reaches 24, i.e., 2 h without being reset (which happens if the measurement is above the threshold) an event is triggered. A set of records are recorded on the second recorder to indicate a new event and its date and time, then the data are recorded at 2 Hz for an hour. When the Master BASS tripod determines that an event has occurred, it sends an acoustic command to other BASS tripods to synchronize recording of raw data at all points to obtain a spatial picture. This can occur only four times before the event tape is used up.

c. Example data

Decomposition of velocity fluctuations into vertical and horizontal components has been effective since the first BASS deployments; sensitivity, linearity, and freedom-from-flow disturbance have allowed BASS to measure Reynolds stress. Figure 11 shows a short segment of an event record from a 1984 deployment at the HEBBLE site (Grant et al., 1985) The complete 1 h event record and the 6 week Reynolds stress average including the event record are discussed in Gross et al. The 2 Hz measurements, not resolvable in the longer plots of that paper, are shown clearly in the 5 min segment of Fig. 11. The instantaneous product of the downstream velocity fluctuations with the vertical velocity fluctuations (direction and mean defined for the 5 min segment) gives momentum transport (defined positive upward) from the bottom. Very little is upward; most is toward the bottom as expected.

![Diagram](https://via.placeholder.com/150)

**Fig. 11. BASS Data:** The 5 min selection of event-triggered data is an expanded sample of the 110 cm current record from day 245 reported in Gross et al. (1986) (Fig. 1c). The horizontal velocity fluctuations in the top plot when multiplied by the vertical velocity fluctuations in the middle plot give the bottom plot. The average value of the correlation weighted by density of the fluid is the Reynolds stress. While Reynolds stress is an average of this bottom plot, structure in the flow is revealed by the predominant negative correlation in sweeps and ejections.
A sweep, in which high velocity fluid moves toward the bottom occurs for the 30 sec around the 1 min mark. This gives an average stress of \(-2.5 \text{ dyn cm}^{-2}\). Most other momentum transfer occurs by low velocity fluid leaving the bottom in 5 to 30 sec ejections; notably, the ejection from 4.5 min to 5 min has a stress of \(-6 \text{ dyn cm}^{-2}\).

This instantaneous picture fits with the 1 h record and that, in turn, gives the same result as the in situ computed Reynolds stress for the three samples within the 1 h record. Thus, the algorithms are consistent and permit the average record to be used except if the details of the fluctuations are to be examined, or if higher frequencies than the average are to be resolved.

5. Conclusion

The need for high accuracy measurements of the turbulent velocity vector in the ocean has been met with the introduction of the BASS current meter system. The requirements of fast sampling rates and small size have limited previous devices to short-term deployments. By developing a multisensor current meter and ancillary measurement system on a versatile deployment platform, a complete dataset describing the benthic boundary layer can be obtained for long periods of time in a variety of environments. To accomplish this, it was necessary to develop a current meter of small size with a fast and linear response. By using acoustic pulses to measure the velocity vector, it was possible to achieve these goals in a low-power device, with no moving parts to require service or recalibration. Microprocessor control enabled expansion in the time domain by allowing in situ processing of the turbulence data and power conservation by switching on and off the components of the system. The total system has been used reliably in several different oceanic environments with great success. Long-term deployments are now routine. In addition to these boundary layer experiments, work is currently underway using BASS to measure velocities in the upper mixed layer, velocity shear from a Swallow float and as a directional wave gauge.

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