Intercomparison of MAVS with VACM, VMCM, FSI 2-D, and Aanderaa RCM 11 Current Meters from a Mooring

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***Abstract*—An intercomparison of four current meters at 2000-m depth in the Ultramoor experiment of Woods Hole Oceanographic Institution near Bermuda in summer 2000 provided an opportunity to examine characteristics of mechanical, Doppler, and acoustic travel-time current meters in a very low velocity environment. This mooring in 4000 meters depth had subsurface buoyancy at 300 meters. Typical tidal current of only 4 cm/s added to mean current of only 2 cm/s caused the mechanical VACM sensors to stall intermittently. The two acoustic travel-time current meters, MAVS and FSI 2-D, tracked tidal fluctuations well although there was some offset drift over two months of recording. The Aanderaa RCM 11 acoustic Doppler current meter response to tidal fluctuations fell between that of the acoustic travel-time current meters and the mechanical sensors. Energetic vertical oscillations for 24 hours in two events 50 days apart suggest mooring response to possible hurricane passage. Only MAVS sensed vertical velocity so there is no corroborating evidence that the subsurface buoy responded to internal wave oscillations excited by the hurricane passage. In addition to testing three sensing modalities, the intercomparison displayed benefits from alternative sampling schemes, one being the monitoring of mooring motion with a vertical axis of velocity sensing.**

An advantage of acoustic travel-time sensing in such low currents is the linearity of the technique through zero velocity but a disadvantage is the uncertainty in the exact zero point. At 2000-m depth, fouling is not an issue but availability of acoustic scatterers for Doppler sensors is a concern. Dropout of scattered signal from the fluid may lead to spurious lock-on to side lobe signals scattered from mooring hardware. This may contaminate estimates of velocity and mimic the effect of stalling from the mechanical sensor of the VACM. Short intervals in time show these effects during the several months of the deployment. Selection of sensors for deep current monitoring is important for observations of global transport of heat, water, trace gases, and dissolved chemicals. Tests of sensor characteristics in actual moored configurations are invaluable.

I. Introduction

Measurement of ocean current from moorings has been a mainstay of physical oceanography since the 1950s. First with surface supported moorings and later with subsurface buoyancy, current meters developed from mechanical sensors of speed that recorded direction when a rotor turned a fixed amount to vector averaging where each increment of motion was added to east and north registers but recorded at a fixed interval [1]. Mechanical two-axis fan sensors reduced the mechanical rotor's tendency to speed with mooring heave and these Vector Measuring Current Meters (VMCM) became the preferred sensors for surface supported mooring or measurements in the near surface region [2]. In the last 20 years, electromagnetic, acoustic travel-time, and acoustic Doppler sensors have joined the mechanical sensors in moored applications. These each have desirable and undesirable qualities and often their relative performance in moorings is hard to predict from tow tank tests, flume calibrations, and from shallow water or coastal applications. Two intercomparison moorings deployed by Woods Hole Oceanographic Institution have included the MAVS (Modular Acoustic Velocity Sensor), a three-axis acoustic travel-time current meter [3,4].

Qualities that are desirable for moored current meters include: accuracy in measurement of net transport, extended deployment life, ease of use, economy in initial cost and cost of use. As mooring deployments have gotten longer, selection of current meters that meet these criteria have become an issue as well as the anchors, releases, tension members, buoyancy, and data telemetry. Conditions affecting performance, particularly accuracy of measurement, are hard to simulate so Woods Hole Oceanographic Institution deployed intercomparison test moorings near Bermuda in 2000 and 2002 to expose a set of current meters of different types to real conditions. In the first case, the midwater at 2000 m in 4000-m depth, exhibited low velocities and few acoustic scatterers. The mooring had subsurface buoyancy at 300-m depth for purpose of telemetry tests so the mooring was tall. In the second case at 4000 m in 4300-m depth there were more acoustic scatterers and the mooring was short but the current velocity was still very low.

II. Accuracy

Accuracy in measurement of net transport is an essential quality for a moored current meter. While this seems obvious, in fact there are other qualities a current meter may have that recommend it for other uses. In the surface layer, accurate determination of wave orbital velocities may be more important than net transport. Mounted on a tripod on the seafloor, accurate measurement of turbulent fluctuations to determine Reynolds stress for sediment transport studies may be more important.

A. High Velocity - Linearity

In high velocity flow, say 20 to 70 cm/s, the scale factor relating reading to actual transport past the sensor becomes important. But direction resolution is more frequently the limit. In steady flow, each of these can be tested in the lab or tow tank. But on a mooring, fluctuations in velocity from mooring motion or from surface waves at the depth of the current meter or surface or internal waves at the depth of the subsurface buoyancy can add a large signal. This is a wave perturbation with a zero mean. But if there is non-linearity in the sensor, the wave motion may be rectified and affect the net transport. Or the speed may be steady but the direction may vary and the behavior of the compass or direction following sensor may introduce error.

B. Low Velocity – Zero Offset, Stall

Two problems can cause error at low velocity. If at zero velocity an offset in reading continues to indicate velocity, this leads to an error in net transport, particularly if the flow is never large enough to swamp these contributions. Such an error is common to sensors that are linear through zero such as electromagnetic or acoustic travel-time velocimeters. The other error, common to mechanical sensors but possible with other sensors that have a unique zero flow output, is stall. This is a kind of hysteresis where the flow becomes low enough that the sensor cannot distinguish it from zero and then the sensor indicates zero velocity even when the flow increases. Stall is only a problem (as is zero offset) when the flow is low, say below 10 cm/s, for extended periods.

C. Loss of Signal

Failure to obtain a velocity signal takes several forms but obviously has negative impact on accuracy of net transport. In the case of mechanical sensors, fishing line or marine growth can stop rotor, fan, or vane. Acoustic travel-time sensors can lose transmission from fouling by bubble-containing seaweed. In addition, electromagnetic, acoustic travel-time, and other small volume sensors can have restricted flow in their sensing volume from debris or marine growth. Acoustic Doppler sensors can lose signal from very clear water. Any sensor can be broken or flooded.

III. Observations Ultramoor 2000

Fig. 1. shows the data from one of the instruments, MAVS for the deployment in the year 2000. MAVS is the instrument with which the author is most familiar and towards which he has a certain bias. For example, MAVS in the first deployment did not run the full length of the deployment but the MAVS deployment interval is the one that will be examined.

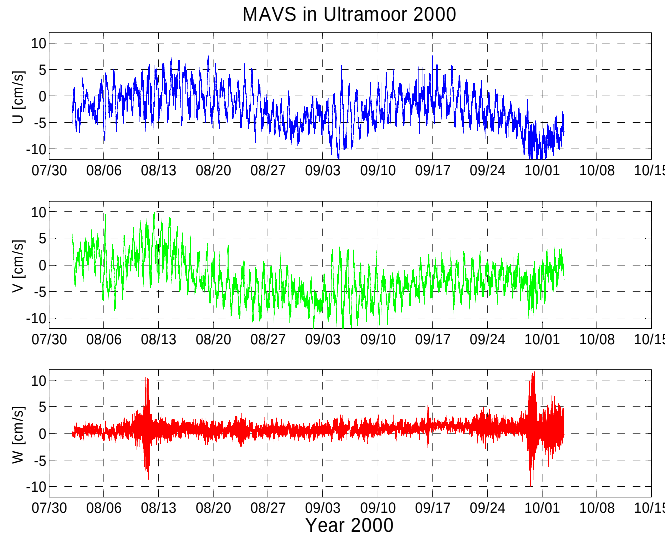

Fig. 1. Two-month record from Modular Acoustic Velocity Sensor sampling at 5 minute intervals at 2000-m depth in 4000 m water depth east of Bermuda.

In Fig. 1 the dominant signal is tidal but it is telling that the three axes can be represented for the entire interval on a scale of ± 12 cm/s. This instrument test was a low velocity challenge. There are two vertical velocity events associated with passage of hurricanes. Figs. 2 and 3 show tracks of Alberto and Isaac with passage near Bermuda on 8/12/00 and 9/29/00 respectively. Bermuda is at L 32°20'N, λ 64°30'W.

A. Mooring Motion

The vertical velocities seen on 8/12/00 and 9/29/00 have zero means and were not seen in horizontal velocities. Fig. 4 shows an expansion of the vertical velocity from MAVS and the pressure signal from one of the VACMs. MAVS sampled at 5-minute intervals while the VACM sampled at 7.5-minute intervals. There is no sign of changes in depth to correspond to the vertical velocity. Frequency less than 10 cycles per hour would be resolved in the MAVS record but they are not. So the vertical velocities measured on MAVS are presumably high frequency, possibly surface wave frequencies that are transmitted down the mooring line from the buoyancy package at 300 meters depth, in the thermocline. All that can be deduced from this record is that wave excitation of the buoyancy package was in excess of 10 cm/s.

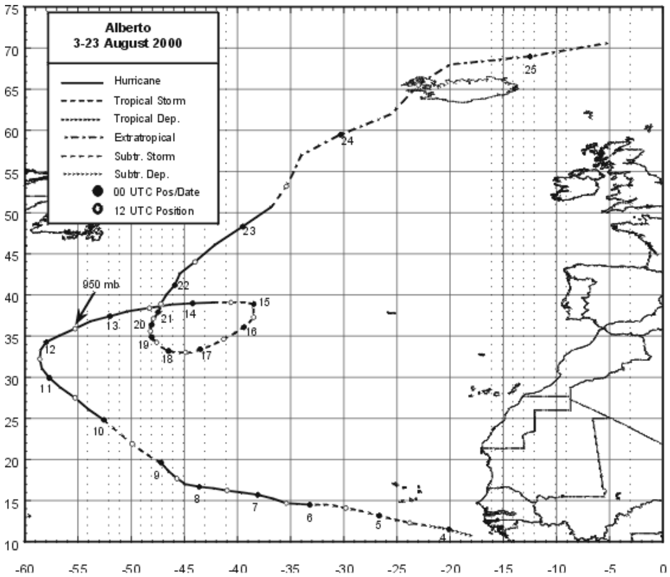

Fig. 2. Track of hurricane Alberto

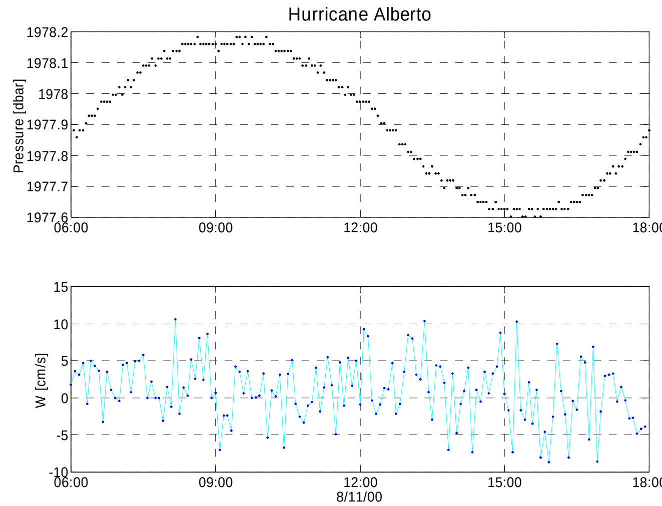

Fig. 4. Pressure and vertical velocity at 2000-m depth under passage of Alberto

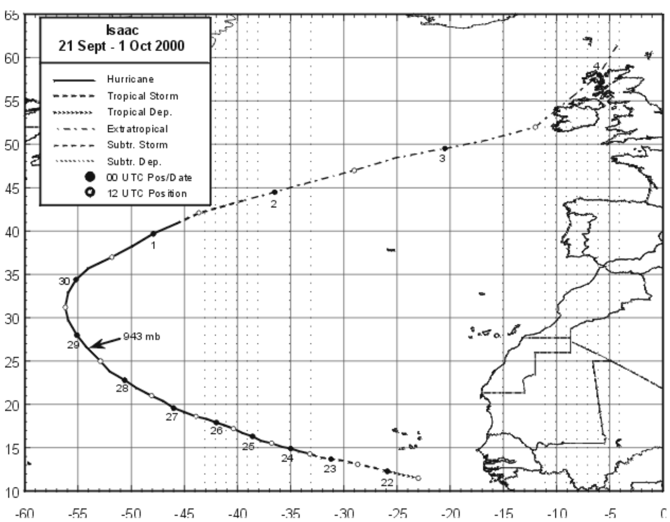

Fig. 3. Track of hurricane Isaac

B. Net Transport

Integrating the vector velocity components produces a progressive vector diagram that is a surrogate for net transport. Since accuracy in this measurement is one of the most important criteria for moored measurements, the net transport is plotted in Fig. 5. In black and white, the middle three lines in the east excursion and the top three lines of the north excursion are the two VACMs and the Aanderaa RCM 11 instruments. These are in close agreement and thus appear upon initial inspection to be the best. MAVS is the lowest line on both presentations and thus seems farthest from correct. However, both VACM records show that the rotor was stalled much of the time when the MAVS showed currents below 4 cm/s.

C. Stalling

The effect that stall has on net transport is illustrated in Fig. 6 in which the MAVS data were artificially set to 0 for both components when the speed dropped below 8.5 cm/s. This is artificial since the mechanical sensors do not generally stop until the speed falls well below this value but the mechanical sensors also exhibit hysteresis and do not start at the same point where they stop. Again, within a sampling period at low velocity, the mechanical sensors may stop and start and not give a zero count for the interval yet are caused to under read due to undetected stalling. By a process of trial and error, it was found that MAVS could be made to track between the two VACM current meters with a threshold for stall set between 8 and 9 cm/s. In black and white, this is the cluster of four lines. The stall effect was not applied to the FSI current meter.

Fig. 7 is a typical example of the stalling of the VACM sensors. It is one of 12 such blocks that equally well illustrate this effect but take too much space to show here. The VACMs are at zero almost half the time in the interval shown. Fig. 8 shows histograms of the speeds recorded by the two VACMs and MAVS. The zero readings are those where they are stalled but there may be intermittent stalling at higher speeds as well and VACM 1 shows readings below 1 cm/s 31% of the time and below 0.3 cm/s 25% of the time. There is also a suggestion that the VACMs consistently read about 3 cm/s lower than the MAVS.

Calibration of both VACMs and MAVS after the deployment did not show any such systematic error. Both the rotor assembly and the MAVS were towed at speeds from 5 cm/s to 20 cm/s and were correct. MAVS, when corrected for the difference between the speed of sound in fresh water and that at 2000 m off Bermuda reads about 4% low.

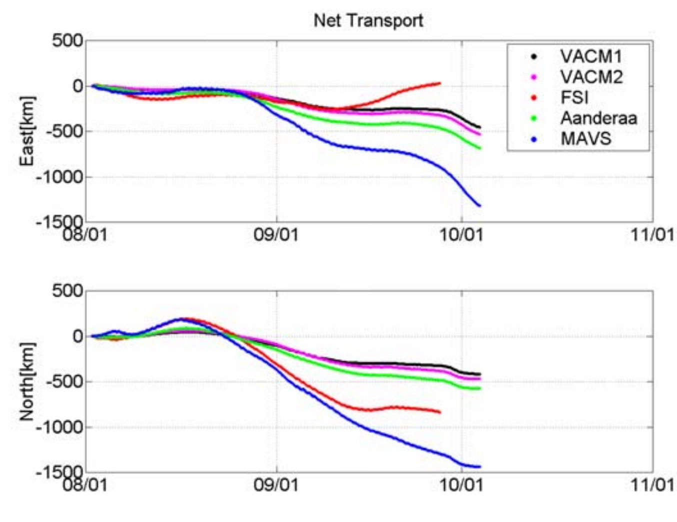

Fig. 5. Integrated velocities from five instruments

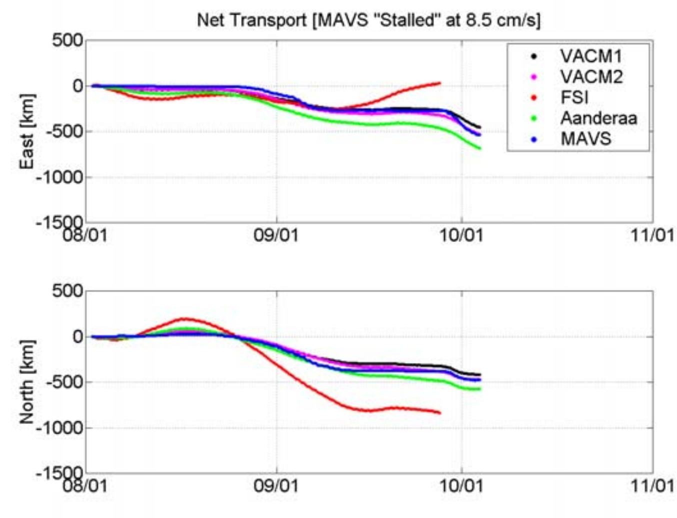

Fig.6 Net transport as in Fig. 5 but with MAVS "Stalled" below 8.5 cm/s

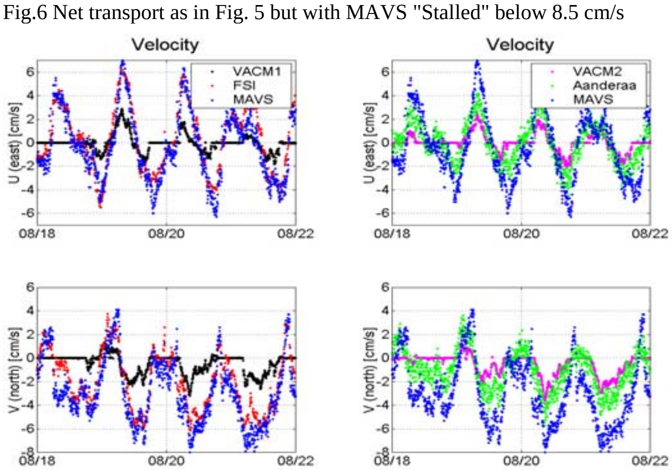

Fig. 7. Four-day section of record to show typical stalling of both VACM sensors

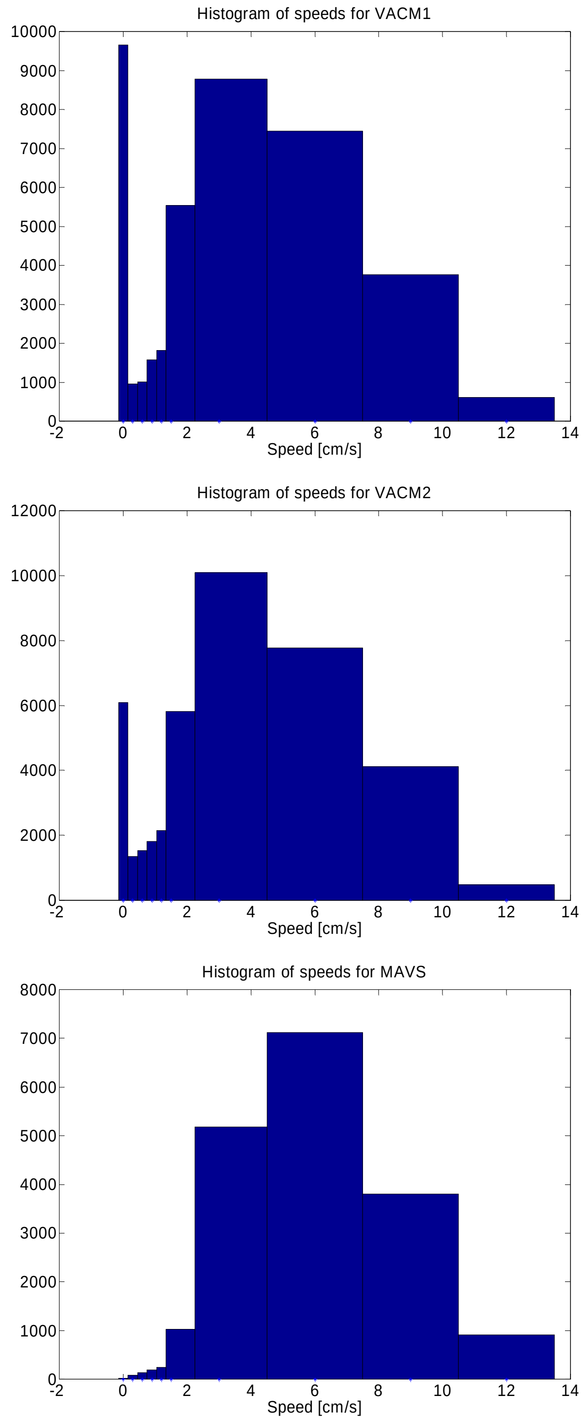

Fig. 8 Histograms of VACM1, VACM2, and MAVS readings

IV. Observations ULTRAMOOR 2002

In April 2002, a short mooring was deployed by Woods Hole Oceanographic Institution at a location near that of year 2000 in 4300-m depth. The instruments were at 4000 m with the buoyancy close above the instruments. It is probable that the instruments were sometimes in a bottom nepheloid layer where there were significant concentrations of scatterers to help the Aanderaa RCM 11 acoustic Doppler current meter. Instead of VACMs, a VMCM, fan bladed mechanical sensor was deployed. The MAVS was a MAVS3 instead of the older MAVS2A [4] used in the intercomparison experiment in year 2000. The FSI acoustic travel-time current meter was a 3-axis instrument instead of the 2-D current meter deployed in year 2000. Fig. 9 shows the velocities for the four instruments in this deployment and again the current did not exceed 10 cm/s so it was another low flow challenge.

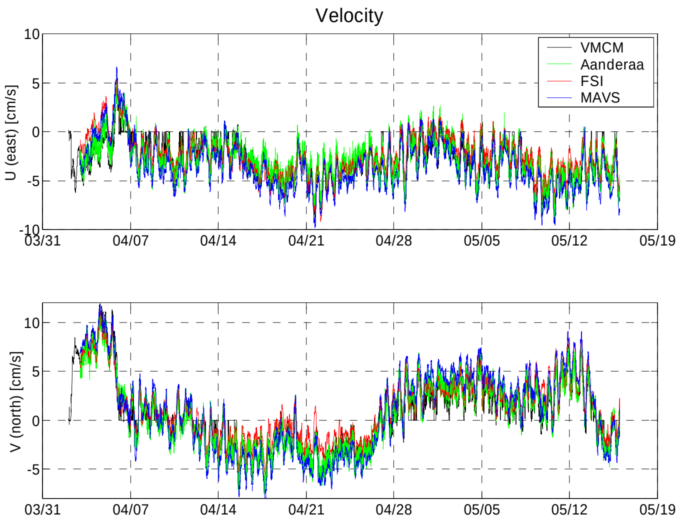

Fig. 9. Velocities measured by the four instruments in Ultramoor 2002

A. Net Transport

Fig. 10 is the progressive vector diagram of the four instruments. In black and white the MAVS is the bottom line in the East plot and the lowest line at 4/28 and the middle line at 5/12 in the North plot (note the expanded scale on the North plot). FSI is the top line in both plots. There are times when the four current meters track well and times when they are seeing different flow. Perhaps they span the benthic pycnocline and the flow in the more mixed water is slightly different from the more stratified water several meters higher.

B. Stall

The stall phenomenon was again observed in the Ultramoor 2002 deployment and Fig. 11 shows a typical four day section of data. The VMCM was stalled 2/3 of the time in this piece of the data but when it ran, it tracked the MAVS and the FSI well. The Aanderaa shows more scatter and reads lower than the VMCM and MAVS.

V. Sampling Strategies

Power, data, drift, and sensor degradation limit deployment times in each instrument in different ways. Summarized in Table I, these elements are discussed below.

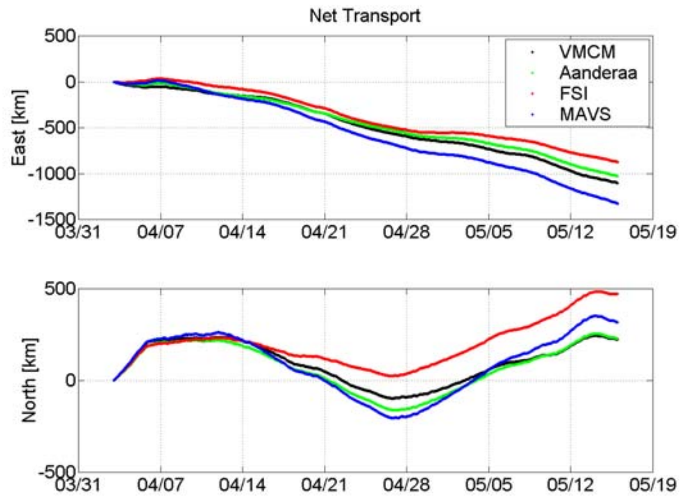

Fig. 10. Integrated velocities from four instruments. The scale in the North plot is expanded.

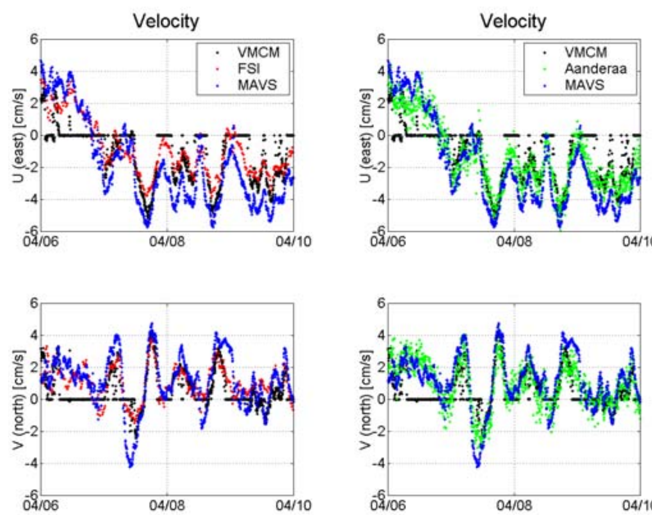

Fig. 11. Four-day section of record with typical stalling of VMCM sensor

TABLE I SENSOR CHARACTERISTICS

Type	Mechanical	Acoustic Travel-Time	Acoustic Doppler
Power	Very low, continuous integration	Moderate, requires burst mode to extend deployment	Moderately high, intermittent sampling to extend deployment
Data	Low data rates, little compression	Moderate data rates, can be averaged and statistically processed	Internal processing of many pings to one result, can be statistically processed
Drift	Stall and bearing degradation	One-time zero offset may bias deployment	No zero drift. May suffer bias from dropout at low scatterer concentration
Sensor degradation	Growth may increase stall threshold	Growth may impede free flow in sensor volume	Little effect of growth until signal is blocked

A. Power

The mechanical sensor current meters have very low power requirements because they use static counters and rotors or fans are powered by the flow. Clock and auxiliary sensors are the principal power drains.

Acoustic sensors divide power drain between acoustic load and computer load. The acoustic load is low for travel-time sensors and moderate for Doppler sensors. The computer load is high for each and this requires burst sampling or intermittent operation so the computer can be shut down between bursts.

B. Data

The mechanical sensors integrate flow continuously (at least above a speed threshold) and need no data compression. But acoustic sensors need a sampling scheme that captures the essential transport of the flow while rejecting averaging over frequencies not of interest. Generally the frequencies not of interest are strumming and waves. Single time samples at the lowest frequency of interest, say tidal, may be aliased by strumming. So burst sampling is valuable to capture these frequencies and averages them to a single sample at the time interval that resolves tidal variations.

C. Drift

An apparent advantage that the acoustic Doppler sensor has is freedom from zero point drift. The scale factor for the Doppler sensor should also be free from changes since it depends on geometry and frequency measurement alone. However the processing of the Doppler signals with many measurements being combined to a single sample can introduce bias if the signal is subject to dropout or to locking onto a stationary piece of hardware with zero relative velocity. This may happen when there are too few scatterers for a strong signal from the water. Acoustic travel-time sensors determine their zero points in still water and the exact reading at zero flow must be removed from all subsequent readings. But changes in capacitance or dimensions of the sensor can offset the zero point. While these effects can be time dependent, most observations of drift have shown discrete jumps in offset between deployments. Even mechanical sensors suffer a kind of drift when the intermittent stalling changes its threshold. This changes the admixture of zero velocity observations with the moving rotor observations.

D. Sensor Degradation

Sensor degradation is generally through corrosion or through biofouling. The rotors of a mechanical sensor are subject to increased friction from this source and can degrade. Acoustic travel-time sensors have an internal volume in which the flow is observed. As marine growth clogs this space, the flow is slowed over what it would be if free and this changes the calibration. Acoustic Doppler sensors are free from the effects of fouling until the acoustic pulse is interrupted and there is no signal returned.

VI. CONCLUSIONS

In the demanding low flow conditions of the two Ultramoor Intercomparison experiments, stalling was evident in the mechanical sensors. It may be hypothesized that non-evident intermittent stalling caused the mechanical sensors to under read even with mean flow above 2 cm/s. Surprisingly, in midwater the Doppler sensor also under read, possibly from intermittent acoustic side lobe lock-on in the absence of scatterers in the water. While this lock-on was less likely in the benthic nepheloid layer of the Ultramoor 2002, there was still some Doppler under reading. The apparent agreement of the Doppler instrument with the stalled mechanical sensors in low flow is an unfortunate accident of these intercomparisons.

AKNOWLEDGEMENTS

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