Performance of a new generation of acoustic current meters*

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Abstract

As part of a program aimed at developing a long duration, subsurface mooring, known as Ultramoor, we tested several modern acoustic current meters. The instruments with which we have the most experience are the Aanderaa RCM11 and the Nortek Aquadopp that measure currents using the Doppler shift of backscattered acoustic signals, and the Falmouth Scientific ACM that measures changes in travel time of acoustic signals between pairs of transducers. Some results from the Doppler-based Sontek Argonaut and the travel-time based Nobska MAVS are also reported. This paper concentrates on the fidelity of the speed measurement but also presents some results related to the accuracy of the direction measurement. Two procedures were used to compare the instruments. In one, different instruments were placed close to one another on three different deep ocean moorings. These tests showed that the RCM11 measures consistently lower speeds than either a Vector Averaging Current Meter or a Vector Measuring Current Meter, both more traditional instruments with mechanical velocity sensors. The Aquadopp in use at the time, but since updated to address accuracy problems in low scattering environments, was biased high. A second means of testing involved comparing the appropriate velocity component of each instrument with the rate of change of pressure when they were lowered from a ship. Results from this procedure revealed no depth dependence or measurable bias in the RCM11 data, but did show biases in both the Aquadopp and Argonaut Doppler-based instruments that resulted from low signal-to-noise ratios in the clear, low scattering conditions beneath the thermocline. Improvements in the design of the latest Aquadopp have reduced this bias to a level that is not significant.

1 Introduction

In the late 1960's engineers at the Woods Hole Oceanographic Institution developed the Vector Averaging Current Meter (VACM) (McCullough, 1975) and this instrument became the Institution's standard for making horizontal velocity measurements on subsurface moorings. Mooring technology was also under active development and by the 1970s had become increasingly reliable to the point where 2-year measurements have become routine (Heinmiller and Walden, 1973). Although data retrieval from these moorings often exceeds 90%, common failure points are the mechanical sensors (e.g. Savonius rotor, vane, compass and vane follower) and the cassette-based data recorder. As physical oceanography has evolved in the past three decades to place more emphasis on long time scale problems associated with climate variations, the 2-year limitation of the present mooring technology has become increasingly burdensome and expensive. Time series of at least decadal length are of interest and the need for frequent replacement and refurbishment of moorings has made the existing technology very expensive. Therefore, we initiated the development of a subsurface mooring system that would last up to five years and periodically release capsules that telemeter data back to the laboratory (see Frye et al., 2004). As part of this development, we decided to investigate a new generation of low power, acoustically-based current meters because they have no mechanical subsystems, can function for five years at reasonable sampling rates, and have the capability of electronically transferring data to acoustic modems. Naively expecting to make the choice of which instruments met our requirements based on price and advertised capabilities, we made a short list that placed emphasis on those with which we had some familiarity and fit within our budget (Table 1).

To narrow the field we initiated a modest at-sea testing program. All tests were performed at approximately the same location about 80 km southeast of Bermuda and took two forms: moored intercomparisons, which are described in Section 2, and those done by shipboard lowerings as outlined in Section 3. The instruments used in each of these situations are tabulated in Table 1. Conclusions are discussed in Section 4.

Very close to this site a similar intercomparison was done earlier by Gilboy et al. (2000) utilizing a surface mooring known as the Bermuda Testbed Mooring. In this study velocities near 72 m depth measured by a VMCM, an ACM and an Acoustic Doppler Current Profiler (ADCP) were compared and found to be in agreement within statistical error except for a 20^o—30^o direction discrepancy attributed to the ACM. The reader is also referred to the review of modern current measuring techniques given in Dickey et al. (1998) and to a comparison of the ADCP with a VACM and VMCM reported by Irish et al. (1995).

2 Moored tests

The Ultramoor development schedule provided two opportunities to compare instruments (see Table 2). Problems revealed by the first deployment and telemetered data from the second led to a third mooring called Minimoor because it rose just 300 m above the bottom, unlike the other two that came within 150 m of the surface. All moorings were deployed in about 4300 m of water close to the same location southeast of Bermuda using the R/V Weatherbird. They are discussed chronologically below.

2.1 Ultramoor-1

This was the first field test of the Ultramoor system and it lasted about 3.5 months from Aug. to Nov. of 2000. All of the current meters on the mooring were located near 2000 m depth with a spacing of about 10 m (Fig. 1, Table 2) and all returned some data, although not all lasted through the full deployment. The instruments available from this mooring for intercomparison are an ACM (see http://www.falmouth.com), an AQD1 (http://www.nortek-as.com), a MAVS2 (http://www.nobska.net), and an RCM11 (http://www.aanderaa.com), all sandwiched by 2 VACMs. The AQD1 was the first delivered for deep water work and the transmit pulse resonated with the pressure case (Lee Gordon, pers. comm.) rendering its velocity data unusable. The 2D-ACM was the only instrument to be interfaced with an acoustic modem and the handshaking with the modem caused the time base to be variable and the batteries to be consumed early. As a result, only comparisons between the VACMs (it makes little difference which one we use because the data are essentially identical) and the MAVS and RCM11 instruments are shown in Fig. 2. In order to make these comparisons, the east and north components of the more rapidly sampled instrument (in this case the VACM) were interpolated onto the time base of the other instrument yielding time series of synchronized velocity components. From these data, speed and direction differences between the test instrument and the reference (the bottom VACM) were calculated and scatter plots produced.

Considering the speed differences first, we see that there is little to distinguish the two VACMs: the straight line fit has a slope very close to zero though there is substantial scatter in the data. On the other hand, it is clear that there are significant speed differences between the other two instruments and the reference VACM, with the RCM11 generally reading lower by an amount that increases with speed. This suggests a linear relationship, but with the RCM11 lower by about 25% (roughly 4 cm/s when the VACM reads 15 cm/s). The MAVS2 shows a relatively constant offset toward higher speeds than the VACM of about 2 to 3 cm/sec with somewhat more scatter in the data.

The upper two scatter plots of speed in Fig. 2 give the impression that the noise in the VACM measurement is higher than that of the RCM11 as the scatter of the difference between the two VACM measurements is about twice that of the VACM - RCM11 difference. However, it must be remembered that the two VACMs are separated by 33 m whereas the RCM11 and the reference VACM are separated by just 7 m: if the RCM11 is referenced to the other VACM the scatter increases to a level comparable to that of the difference between the two VACMs.

The direction differences (right panels, Fig. 2) show that the RCM11 compares very well with the VACM, at least as well as does the second VACM. The MAVS2, however, has much larger scatter and a bias that is a function of direction.

2.2 Ultramoor-2

This mooring was deployed in Nov. 2001 and subsequently recovered in Feb. 2004 after about 2.5 years in the water. The mooring contained different groups of instruments at three depths for cross referencing (Fig. 1 and Table 2). Unfortunately, the shallow RCM11 near 600 m flooded and did not return useful data so its comparison with the co-located VACM could not be performed. Surrounding a VACM near 2000 m, the same intercomparison depth as in Ultramoor-1, there were two Doppler instruments, an RCM11 and an AQD2 whose transducer had been redesigned to prevent the ringing that occurred on Ultramoor-1. In addition, at 4000 m an RCM11 and a 3D-ACM were installed.

At the 2000 m level, the scatter plot for the RCM11 referenced to the VACM (upper left panel, Fig. 3) documents lower speeds for the RCM11 and the least-squares fit is similar to that for Ultramoor-1 (middle left, Fig. 2). The AQD2 (middle left, Fig. 3) shows consistently higher speeds than the VACM across the range of speeds observed. This behavior was found to be the result of the low scattering levels at this depth and led to changes in the transducer and data processing algorithms (see Section 3). At 4000 m depth there was no reference instrument and the RCM11 and 3D-ACM measured speeds that were consistently different with the 3D-ACM recording speeds more than 50% higher on average than the RCM11 throughout the measurement range. The overall energy levels recorded by the RCM11 were similar to those seen at 2000 m and by other instruments that have been moored in this area (see e.g. McKee et al., 1981) so we suspect that the 3D-ACM is over estimating the current.

The righthand panels of Fig. 3 show that the lowest scatter in direction and most consistent results across the range come from the RCM11, although there is an offset of about -10^o relative to the VACM. Although the AQD2 suffered from bias in its transducers, this did not greatly affect the computed directions, suggesting that the bias is the same for each transducer. The greater scatter most likely results from the fact that the AQD2, although sampling at 23 Hz, can only keep up this rate for 2 min. out of each hour that a value is recorded, unlike the RCM11 that collects 150 equally spaced samples over the hour and thereby does a better job of filtering out high frequencies. It appears that the compass in the 3D-ACM (Fig. 3 lower, right) is not performing properly, assuming that the RCM11 at 4000 m performed as well as the instrument at 2000 m.

2.3 Minimoor

Because of the indication of biases revealed both by both the data from Ultramoor-1 and that being telemetered from Ultramoor-2 (here the comparisons were between the RCM11, the AQD2 and the 3D-ACM as the VACM data were not telemetered), a short mooring, named Minimoor, was set close to Ultramoor-2 in spring 2002 for about two months. Five instruments were placed near 4000m depth in water of about 4300 m (see Table 2). Some concern that the VACM was not performing adequately in the weak flows led us to use a Vector Measuring Current Meter (VMCM, Weller and Davis, 1980) as the reference instrument. Unfortunately, one of the rotors on the VMCM stopped turning after two days reducing the usefulness of this instrument for this purpose. However, with the experience accumulated from the two Ultramoor deployments we decided to construct scatter plots from both the two day period when the VMCM was functional and, additionally, for the full two months by using one of the two RCM11s as a reference with its speed adjusted to take into account the observed difference with the VMCM. We chose a factor of 9/8 from inspection of the VMCM-RCM11 differences, a factor that is somewhat lower than that indicated by either of the Ultramoor deployments (see next subsection).

Two, four-day snapshots of the speed measured by the four different comparison instruments are given in Fig. 4 with the top panel displaying data from the beginning of the deployment and the RCM11 adjusted by the 9/8 factor. For the first two days or so, the MAVS3, the RCM11 and the VMCM closely track each other as does the 3D-ACM but at a cm/s or so lower. Later in the deployment (lower panel) the MAVS3 is consistently higher than the adjusted RCM11 while the 3D-ACM continues to measure lower speeds.

The short duration comparisons of the VMCM with the adjusted RCM11 speed and direction (Fig. 5, upper panels) are now quite similar. The two day comparison of the VMCM with the MAVS3 has a slight trend: speed differences increase with speed such that the MAVS3 observes higher speeds by about 1 cm/s than the VMCM at low speeds but this difference vanishes around 10 cm/s (black dots and line, middle left panel Fig.5). A similar trend is found when comparison is made for the full two months with the adjusted RCM11. Subsequent to the deployment, an electronic design problem was discovered in the MAVS3 that contributed a positive bias of about 1.5 cm/s at 25 cm/s (Sandy Williams, pers. comm.). The direction differences with respect to the VMCM indicate a nonlinear bias, although the number of data points from the first two days (black dots) is not very large. The direction comparison between the MAVS and the RCM11 over the full two months show little bias. The 3D-ACM speed comparison is reasonably good although the comparison with both the RCM11 and VMCM suggest that the 3D-ACM is biased low by close to 1 cm/s (see also Fig. 4). The directions of the 3D-ACM are offset from those observed by the VMCM and the RCM11 by about 10^o.

2.4 Mooring results summary

Using the VACM or the VMCM as the standard for comparison, the results presented above suggest the following with respect to the other instruments:

RCM11: This instrument was the most reliable in terms of general data collection and had the most consistent performance. Fig. 6 shows the behavior of the RCM11 compared to the VACM and VMCM from the three moored tests. With respect to both the VACM and VMCM the RCM11 measures lower speeds by 10%–25%, depending on mooring deployment, with indications that this difference levels off to a more uniform 2 cm/s above about 15 cm/s. It must be remembered that our testing locale near Bermuda is a very low speed regime with low scattering levels, a challenging environment for both mechanical and acoustic Doppler instruments.

AQD: Two generations of this instrument have been used on the moorings. The first did not return useful data. The second, used on Ultramoor-2, did but the data is significantly biased, apparently by noise in the electronics circuits and signal processing issues.

ACM: Two versions of this instrument were evaluated, each of which had the same transducer configuration, but the Ultramoor-1 version was configured to return only two-dimensional velocity information. Both Ultramoor deployments suffered from performance issues. Although considerable effort was taken to calibrate the instrument that was used on Ultramoor-2, its speeds were about 50% high relative to the RCM11 and directions were unreliable (bottom panel, Fig. 3). Contrasting with this experience, the 3D-ACM on Minimoor performed very well in measuring speed although a small bias was found for direction.

MAVS: The MAVS2 used on Ultramoor-1 ran out of energy 2/3 of the way through the 3-month deployment and returned speeds consistently higher than the VACM by 1–2 cm/s (bottom panel, Fig. 2). Performance of the MAVS3 on Minimoor was improved but had an offset in the speed measurement amounting to 1.5 cm/s at 25 cm/s, traceable to an electronics issue. Direction differences with respect to the reference instruments indicate large offsets of a nonlinear character for the MAVS2 instrument on Ultramoor 1 but very good performance by the MAVS3 on Minimoor.

3 Shipboard lowerings

When the telemetered data from Ultramoor-2 began arriving, it was clear that there were discrepancies in the velocities coming from the two RCM11s and the AQD2 and 3D-ACM instruments with which they were co-located. In both cases the RCM11 measured substantially lower speeds than the other instruments, similar to the experience on Ultramoor-1 where the reference instrument was a VACM. The Minimoor was one attempt to resolve the issue.

A weakness of these moored comparisons is that they rely on a decision as to which instrument is considered the "standard". Certainly our bias is toward the venerable VACM and VMCM because we have had a great deal of experience with them over the past 3 decades, and because considerable effort has been made to calibrate their sensors in controlled situations (i.e. tow tanks). On the other hand, the new acoustic instruments rely on simple physical principles with which it is difficult to argue. However, their implementation depends on signal processing methods and sophisticated electronics that can introduce bias (Lee Gordon, pers. comm.). In addition, it is very difficult to find a tow tank large enough to perform controlled calibrations of the Doppler-based instruments because of the large volume that is insonified and the resulting problem of acoustic reflections from the walls of the tank.

Therefore, it was decided to attempt to calibrate the acoustic instruments by lowering them at a controlled and easily measured rate from a ship in roughly the same waters in which the moorings were located. This was not as easy as it might sound because neither the ship from which they were lowered nor the ocean were at rest, and these relative motions combined with the different sampling rates of the instruments complicate the results. For example, in Fig. 7 the vertical velocity of an AQD3 being lowered from the ship is shown for a l00 m segment of the water column. Two methods of measuring vertical velocity are illustrated, one computed from the rate of change of pressure and the other from the Doppler information received by the instrument. They agree well at the 1 Hz sampling rate and show an average descent of about 1 m/s. An oscillation of order 0.5 m/s amplitude with a period of around 6 sec from swell-induced ship motion is superimposed. As we will see below, the different sampling strategies of the test instruments have differing degrees of success in filtering out this motion.

3.1 Lowering-1

This lowering took place in late September, 2002. Three test instruments were suspended, with about 10 m separation, well beneath a CTD and kept vertical by hanging 200 lb of lead 10 m below the bottom instrument. The order of the instruments, from the bottom up, was an AQD2, then an RCM11 and finally a 3D-ACM. Both the AQD2 and the RCM11 were mounted horizontally with transducers aimed downwards. In its normal vertical orientation this AQD2 was configured to have two orthogonal transducers in the horizontal plane and one midway between them at 45^o to this plane. For the RCM11 to function in this orientation, it was necessary to manually freeze the output from the compass and tilt sensors. Sampling rates and averaging intervals are given in Table 2. Through an oversight the 3D-ACM was not averaged over its sampling interval but was set to return instantaneous values every 15 s. At this low sampling rate the substantial ship motion was inadequately sampled and thus aliased into the results.

As it turned out, the CTD was superfluous to this test as the pressure sensor on the AQD2 was adequate to determine the lowering rate. The downward portion of the first cast is representative of the results (Fig. 8). To reduce the large swell-induced noise in the lowering rate, the different data streams were low-pass filtered to remove energy in periods shorter than about 2.5 min (or about 150 m at the 1 m/s lowering rate). The scattering levels upon which the two Doppler instruments depend vary considerably from the surface to the bottom, and reached a minimum a few hundred meters above the bottom (Fig. 8, right panel). With its rapid sampling rate and short sampling interval, the filtered data from the AQD2 (green line) is the least variable and there is good correspondence between the computed lowering rate (black line) and the vertical velocity computed from the Doppler data in the upper water column where signal strength is above about 35 counts. At lower signal strengths, found below about 1500 m, the two curves gradually diverge and indicate a bias of order +0.1 m/s at the lowest signal strengths.

The curves for the other two instruments are considerably noisier. For the 3D-ACM (red line) this is not surprising given the inadequate sampling scheme, but the RCM11 deserves a little more comment. In "continuous mode" this instrument samples each transducer at 5 Hz, less rapidly than the 23 Hz used by the AQD2. The equally spaced pings are then simply averaged over the sample interval of 18 s. With the large vertical oscillations produced by the ship's roll happening at a 6 s period, shorter time scale energy leaks through the side lobes of this crude low-pass filter and contributes to the higher variability.

A possible cause of the bias low and two periods of very low speeds near 700 db and 3400 db was pointed out by the RCM11's manufacturer: the AQD2 and RCM11 instruments operate at very nearly the same frequency and there could have been some acoustic interference between the two. In addition, the RCM11 transducer was pointed directly down at the AQD2 leading to the possibility of the low speeds being a result of the wake above it. With these potential complications we undertook a second lowering cruise.

3.2 Lowering-2

By the time this second lowering took place, almost a year later in August 2003, we were able to use an AQD with transducers equally spaced by 120^o and pointing up from the horizontal plane at 25^o, allowing it to be lowered in the more conventional upright configuration and still measure the vertical component of velocity. The test RCM11 was again mounted horizontally but this time at the bottom of the instrument string and within a streamlined and weighted pod such that its transducers, and the associated measurement volumes, were well clear of the pod itself. Above these two a 3D-ACM was included, also in a horizontal position, but with a fin at its rear to orient it into the flow so that the transducer sting would be "upstream" of the lowering cable. In addition, there were as many as two Sontek Argonauts (ARG) included. A decreased lowering rate of about 0.3 m/s was used.

The results are shown in Fig. 9 and a similar pattern to the first lowering emerges. The AQD3 has a bias that grows with depth (and decreasing signal strength) to reach about 0.1 m/s. This was the only opportunity we had to test the ARG and the associated results that we display came from one filled with transducers twice the diameter (40 mm) than previously had been used to increase its signal-to-noise ratio. Otherwise the ARG transducer configuration is similar to the AQD3 but with a slant of 45^o from the horizontal instead of 25^o. Its performance is similar to the AQD3 with a bias that grows with depth and diminishing scatterers, although the ARG bias is smaller than the AQD3. The larger slant angle of the ARG transducers explains some, but not all, of this difference. The 3D-ACM results are the most puzzling. While it appears that this travel-time instrument measured the vertical velocity accurately between about 2500 m and 3500 m, it shows considerable positive bias at shallower depths. One explanation is that the vane intended to keep the instrument pointed into the flow did not do its job very well and that allowed horizontal motion to contaminate the inferred vertical motion. The RCM11 data was greatly improved over the first lowering and the measured current profile has no visually discernable bias, although it would be difficult to detect visually the 2 cm/s suggested by the moored comparisons in the previous section.

In order to explore the RCM11 bias issue more quantitatively histograms of the difference between the RCM11 vertical velocity component and the calculated lowering speed were calculated (Fig. 10). Because the actual orientation of the RCM11 in its pod was unknown, although fixed, the vertical component was determined by low pass filtering the computed direction and then projecting the velocity into this direction, a more accurate calculation of the vertical component than total speed as is used in Figs. 8 and 9. This is overlaid with that computed from the AQD pressure record in the left panel of Fig. 10. In the right panels histograms of the difference between these two are shown, the top panel for the upper 1500 db and the bottom one for the rest. In both cases there is a peak in the histogram close to zero and the mean of all the differences is indistinguishable from zero. However, in both cases there is also a secondary peak near -2 cm/s, the value suggested by Fig. 6.

3.3 Lowering-3

Prompted by results showing a bias in the AQD3 at low scattering levels Nortek made two changes in the instrument (Atle Lohmann, pers. comm.). The biggest improvement came from changing the backing material for the transducers but some enhancement in performance was also achieved by modifications to the signal processing algorithm. Subsequently, a final lowering test was performed in May 2005, once again south of Bermuda off the R/V Weatherbird. The comparison of the calculated rate of descent with the vertical velocity measured by the AQD4 is given in Fig. 11: with this fourth generation of the instrument the bias has become insignificant. A more quantitative display of the performance gains between the different AQD generations is provided in Fig. 12. There is some improvement between the second and third generation of the instrument but more dramatic improvement with the fourth whose bias is consistently 0.5 cm/s or less.

4 Conclusions

The RCM11 appears to have a small but systematic bias with respect to either the VACM or VMCM at low flow speeds, amounting to a 10%–25% reduction in measured speed up to 15 cm/s. Although we cannot be certain which instrument is biased, the fact that this shows up on comparisons with two reference instruments (i.e. the VACM and VMCM) both of which have had extensive tow tank calibrations, suggests that it may be a problem with the RCM11. At the Bermuda site, where the moorings were located, speeds rarely exceeded 20 cm/s but the results suggest that the bias levels off to about 2 cm/s at speeds above 15 cm/s. This bias was consistent with bimodal histograms of differences between vertical velocity and lowering rate calculated using results from the second lowering experiment. Although the primary mode is near zero, a second mode close to -2 cm/s, with the RCM11 being low, is apparent. Directions measured by the RCM11 were consistently high quality as was the general performance of the instrument.

In our initial tests both the ARG and AQD revealed biases that were a function signal-to-noise ratio. In the deep subthermocline waters near Bermuda the water is sufficiently low in scatterers that the signal-to-noise ratio drops and a bias of as much as 5 cm/s along the transducer beam develops, which projects into 10 cm/s in the vertical velocity component. For the latest version of the AQD, Nortek has increased the efficiency of the transducers and improved the detection algorithm in the firmware to the point where a significant bias has been eliminated.

Our experience with both travel time instruments - the ACM and the MAVS - is more limited. Direction and speed issues plagued the ACM, while endurance and minor technical issues hampered our testing of the MAVS. The Minimoor comparisons, however, suggest that, when operating properly, both are capable of making measurements within 1–2 cm/s of the reference instruments.

Acknowledgments

Firstly, it is a pleasure to dedicate this paper to Carl Wunsch whose vision resulted in the Ultramoor development project and, as a byproduct, in this related investigation of the performance of various candidate current meters. Neal Pettigrew participated in one of the "lowering" cruises and provided valuable comments on a draft of the manuscript for which we are very grateful. We would like to thank Lee Gordon and Atle Lohmann of Nortek, Dick Butler, and Helge Menken of Aanderaa, Bob Beede and Mary St. Germaine of FSI, Sandy Williams of Nobska and Todd Mudge of Sontek for much advice and valuable consultation on their instruments. Scott Worrilow, Ryan Schrawder, John Kemp, Kris Newhall and the WHOI Rigging Shop all provided expert help in deploying the moorings and performing the various lowerings. This study could not have been carried out without the frequent and expert help of the officers and crew of the R/V Weatherbird. This material is based upon work supported by the National Science Foundation under Grant No. 9810641.

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Figure Captions

Figure 1: The 3 moorings on which current meters were compared.

Figure 2: Scatter diagrams for speed difference (left panels) and direction difference (right panels) between the top VACM (top panels), the RCM11 (middle panels), the MAVS (bottom panels) and the bottom VACM on Ultramoor-1. The data for the reference VACM, sampled at a 3.75 min interval, have been interpolated to the coarser sampling rates of the RCM11 and MAVS (5 min.). The lines are least-squares fits for VACM speed values greater than 2 cm/s. The darker points on the direction difference plots indicate when the speed is greater than 5 cm/s while the lighter ones are for speeds less than this value. Speed differences with magnitude greater than 4 cm/s are not displayed.

Figure 3: As in Fig. [Fig:U1 Scatter-diagram], but for the second Ultramoor deployment. In this case the data for the VACM, averaged over 30 minute intervals, have been interpolated to the coarser sampling rate of the RCM11 (60 min.) and the 3D-ACM.

Figure 4: Two four-day periods from Minimoor showing the speeds measured by the MAVS3, the RCM11, the VMCM and the 3D-ACM. No VMCM data is shown after the second day when one of its rotors failed. The RCM11 speeds have been increased by the factor 9/8 to compensate for the bias determined from the two Ultramoor moorings.

Figure 5: As in Fig. [Fig:U1 Scatter-diagram], but for the Minimoor deployment, that contained a VMCM rather than a VACM. Because the VMCM failed after two days we have used two means of comparison: the dark black points and lines are derived from differences with the VMCM for the first two days and, for the lighter grey points and lines the RCM11. All RCM11 speeds have been adjusted by the factor 9/8 (see text).

Figure 6: Binned differences between speeds measured by either a VACM or a VMCM and

an RCM-11.

Figure 7: Vertical velocity computed from the rate of change of pressure and from the Doppler shift of acoustic signals as measured by a 3rd generation AQD.

Figure 8: A comparison of vertical velocities measured by three different instruments with that computed from the rate of change of depth (left panel) on the first lowering test. The velocities from the instruments have been adjusted for sound speed variations. In the right panel the Aquadopp signal strength for the three beams is shown as a function of depth. The signal strength scale is arbitrary. The black curve labeled "dp/dt" is computed from the rate of change of pressure in which pressure has been converted to depth.

Figure 9: As in Fig. [Fig:1st lowering] but for the second lowering test cruise.

Figure 10: A comparison of the RCM11 vertical velocity with actual lowering speed for the second lowering test. The left panel shows the vertical component of the RCM11 velocity (thin noisy curve) and the lowpassed lowering speed (heavy smooth curve). The right hand panels contain histograms of the difference between the RCM11 vertical velocity and that calculated in two pressure intervals. The fine vertical line is at -2 cm/s; the heavy one is at the origin.

Figure 11: As in Fig. 8 but for the third lowering. Here just one instrument, a 4th generation Aquadopp was tested.

Figure 12: Transducer bias versus signal-to-noise for three generations of the AQD. The bias is calculated as the difference between the measured vertical velocity and the lowering rate projected into the relevant beam coordinate. The signal-to-noise is calculated as 0.4*(signal strength - signal strength just after instrument recovery) according to the manufacturer's instructions (Atle Lohmann, pers. comm.).

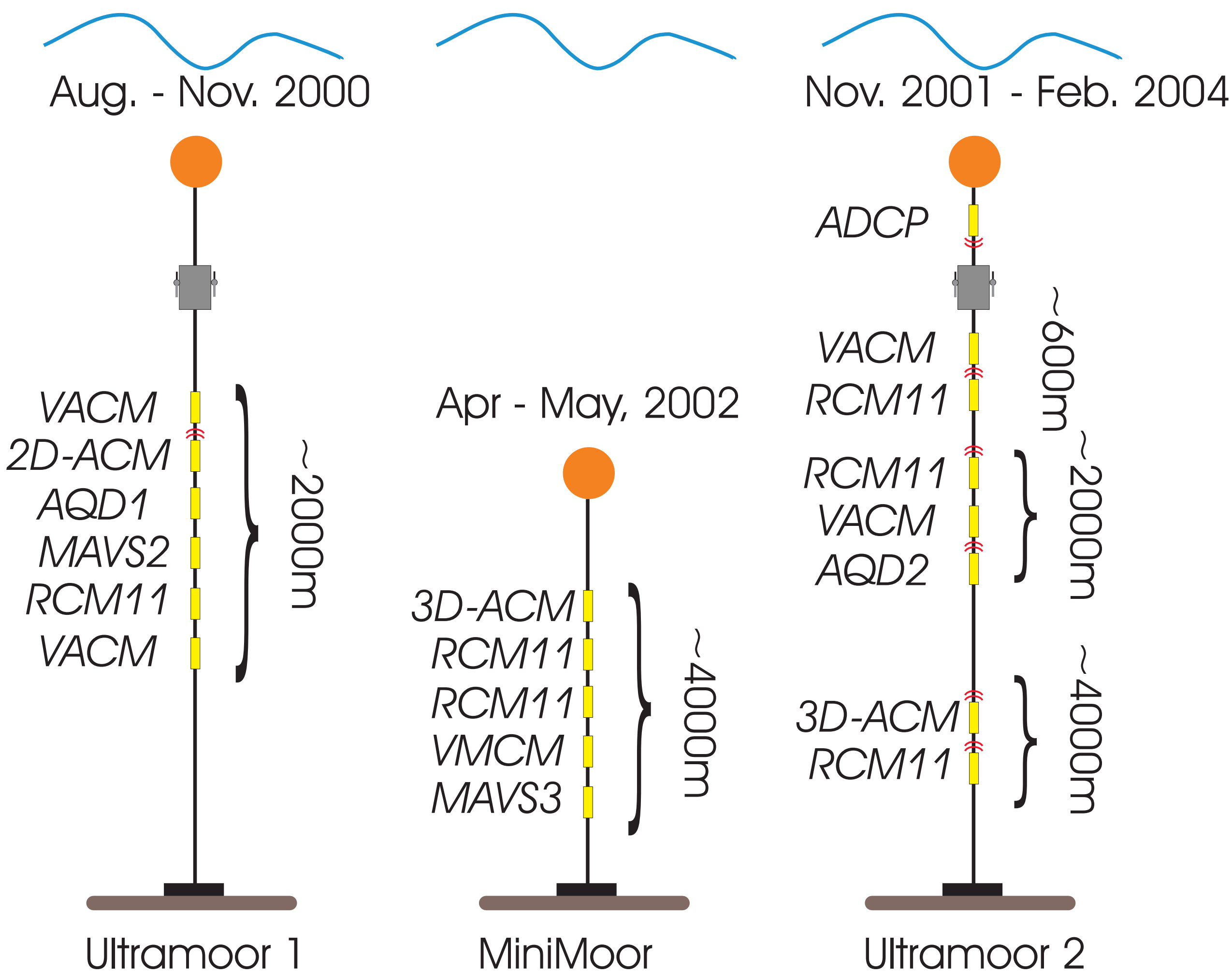

Figure 1: The 3 moorings on which current meters were compared.

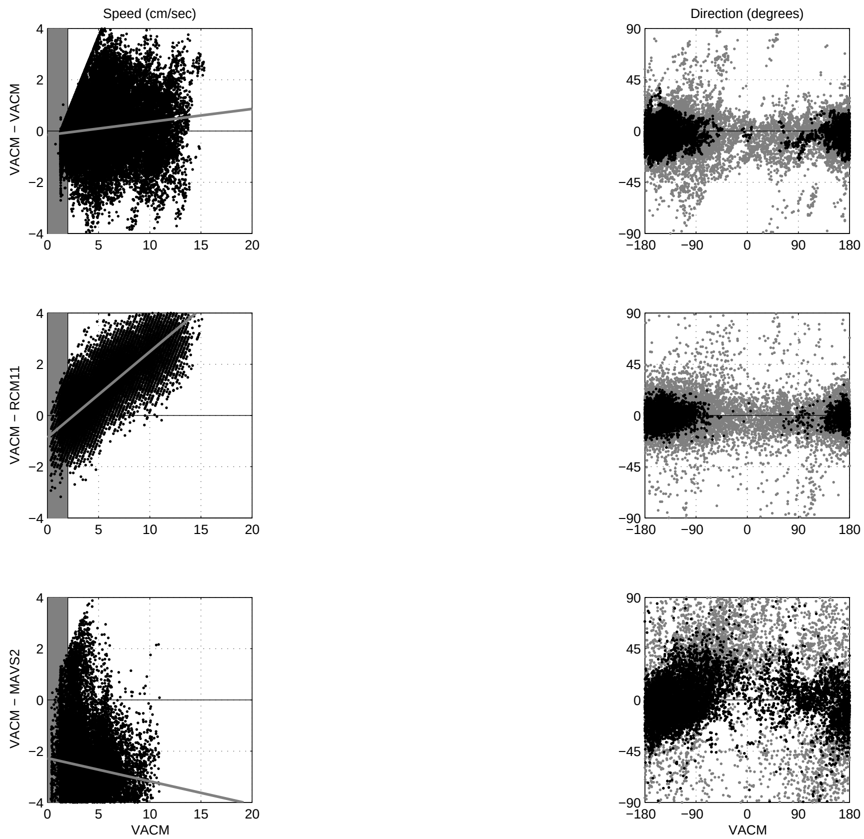

Figure 2: Scatter diagrams for speed difference (left panels) and direction difference (right panels) between the top VACM (top panels), the RCM11 (middle panels), the MAVS (bottom panels) and the bottom VACM on Ultramoor-1. The data for the reference VACM, sampled at a 3.75 min interval, have been interpolated to the coarser sampling rates of the RCM11 and MAVS (5 min.). The lines are least-squares fits for VACM speed values greater than 2 cm/s. The darker points on the direction difference plots indicate when the speed is greater than 5 cm/s while the lighter ones are for speeds less than this value. Speed differences with magnitude greater than 4 cm/s are not displayed.

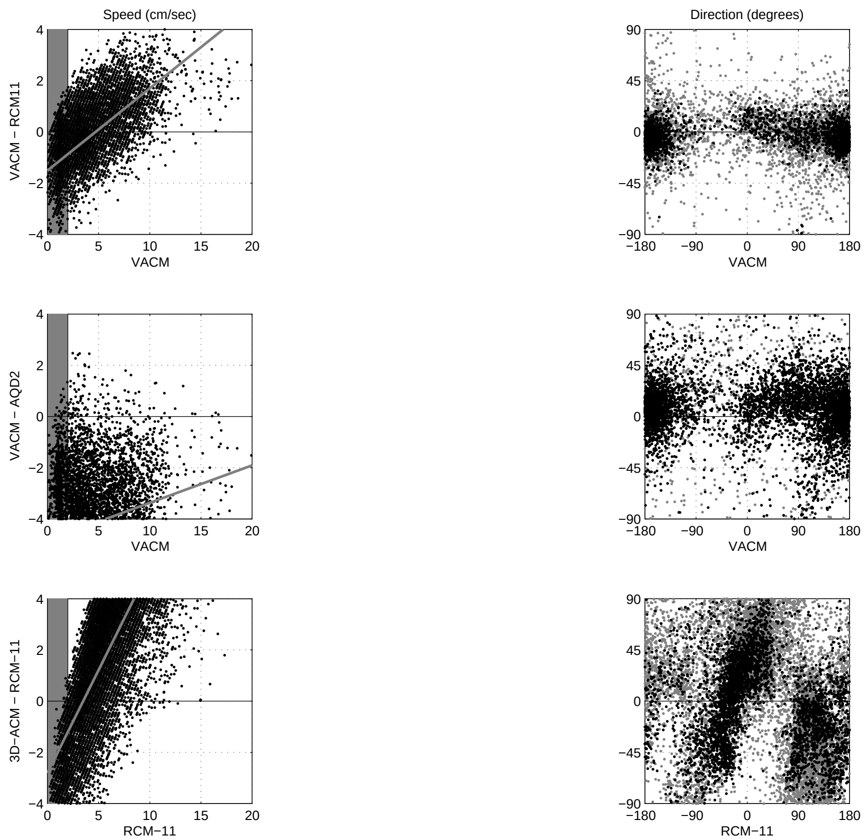

Figure 3: As in Fig. 2, but for the second Ultramoor deployment. In this case the data for the VACM, averaged over 30 minute intervals, have been interpolated to the coarser sampling rate of the RCM11 (60 min.) and the 3D-ACM.

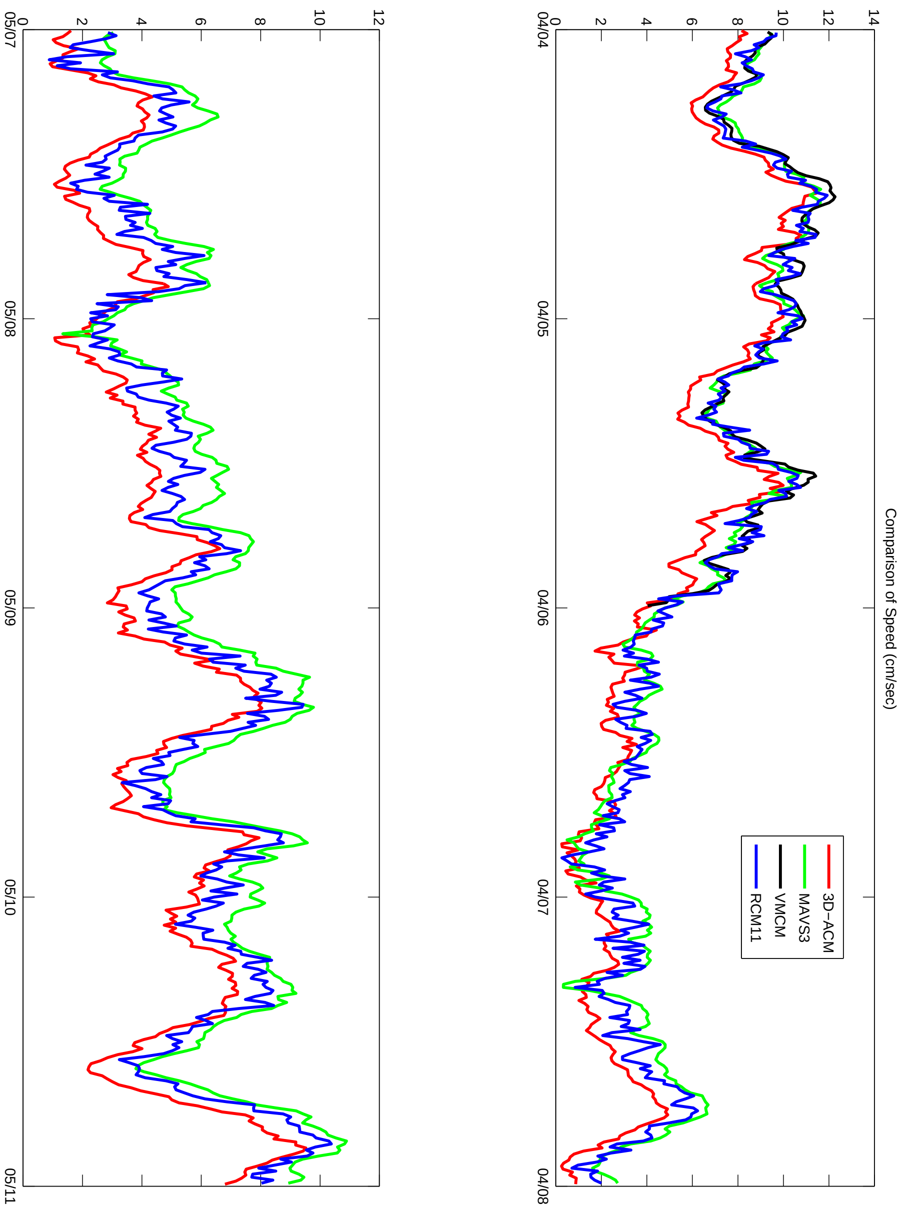

Figure 4: Two four-day periods from Minimoor showing the speeds measured by the MAVS3, the RCM11, the VMCM and the 3D-ACM. No VMCM data is shown after the second day when one of its rotors failed. The RCM11 speeds have been increased by the factor 9/8 to compensate for the bias determined from the two Ultramoor moorings.

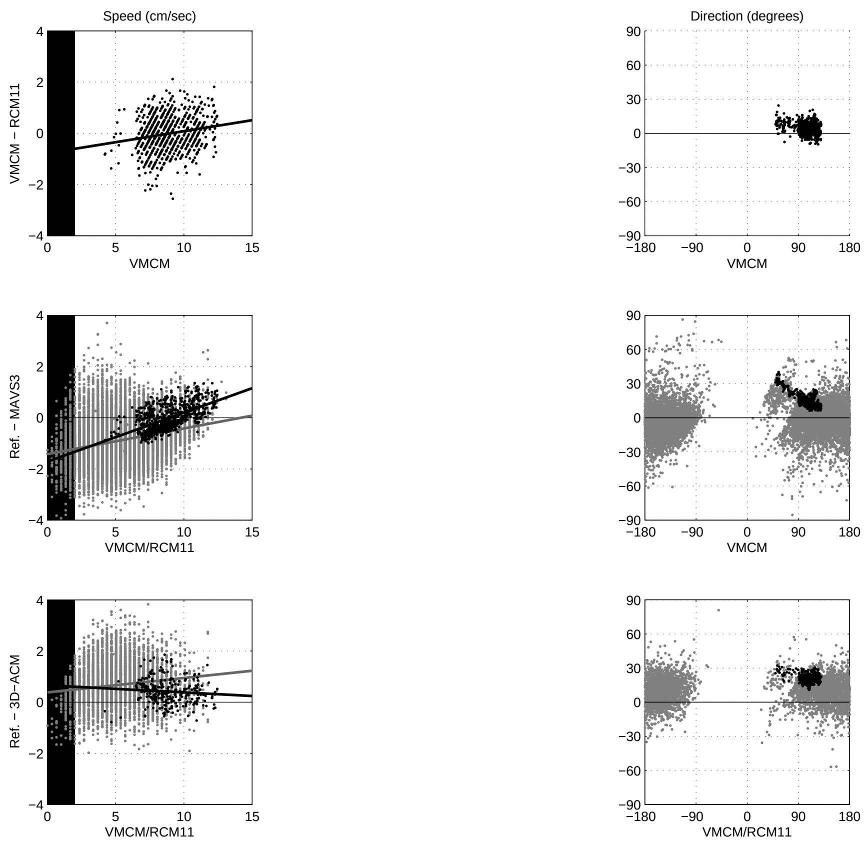

Figure 5: As in Fig. 2, but for the Minimoor deployment, that contained a VMCM rather than a VACM. Because the VMCM failed after two days we have used two means of comparison: the dark black points and lines are derived from differences with the VMCM for the first two days and, for the lighter grey points and lines the RCM11. All RCM11 speeds have been adjusted by the factor 9/8 (see text).

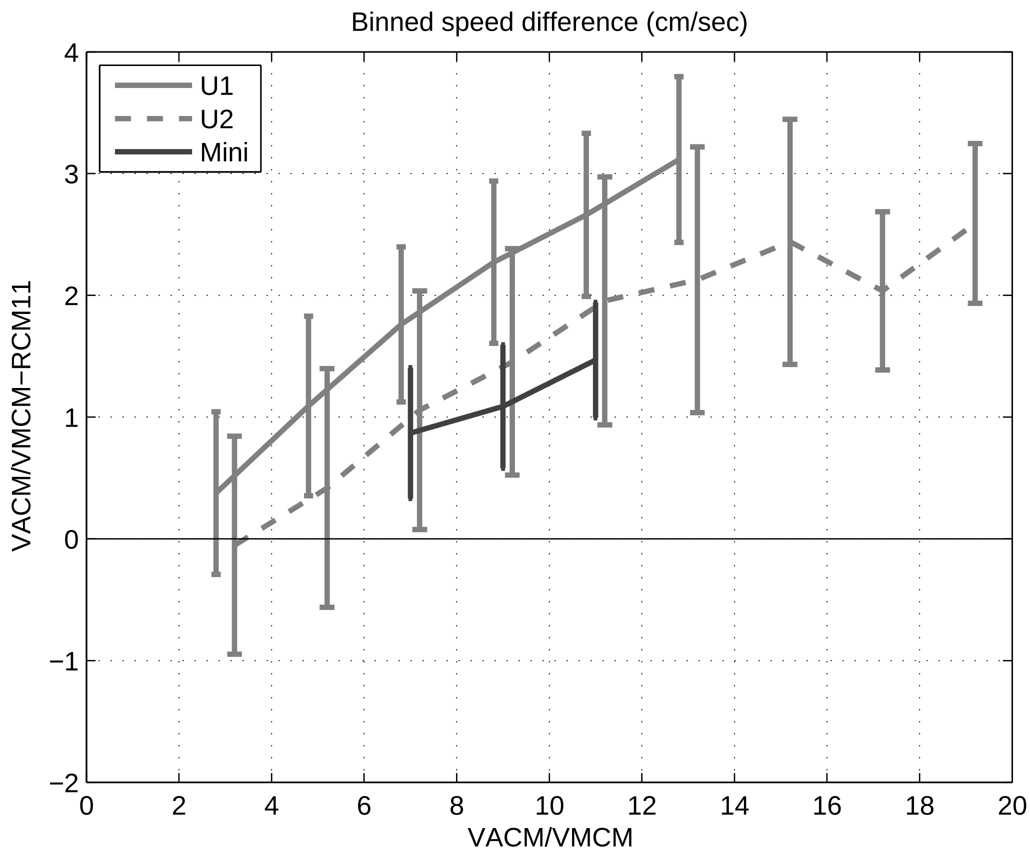

Figure 6: Binned differences between speeds measured by either a VACM or a VMCM and an RCM-11.

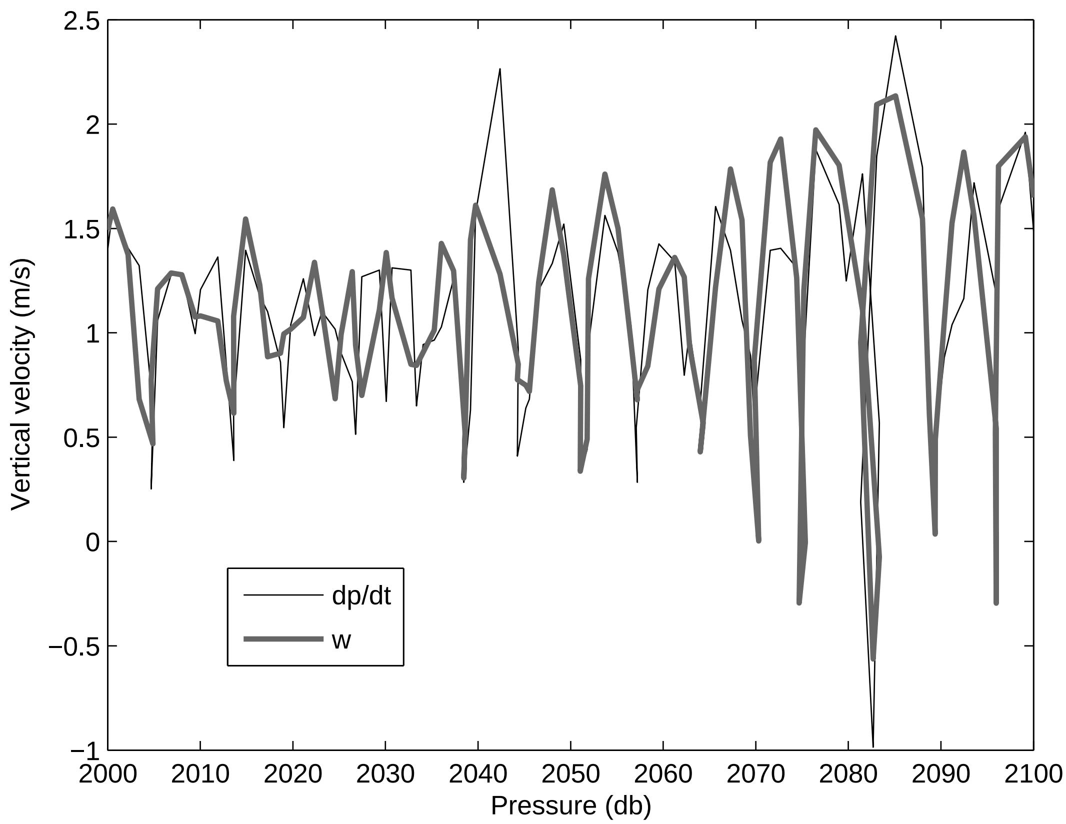

Figure 7: Vertical velocity computed from the rate of change of pressure and from the Doppler shift of acoustic signals as measured by a 3rd generation AQD.

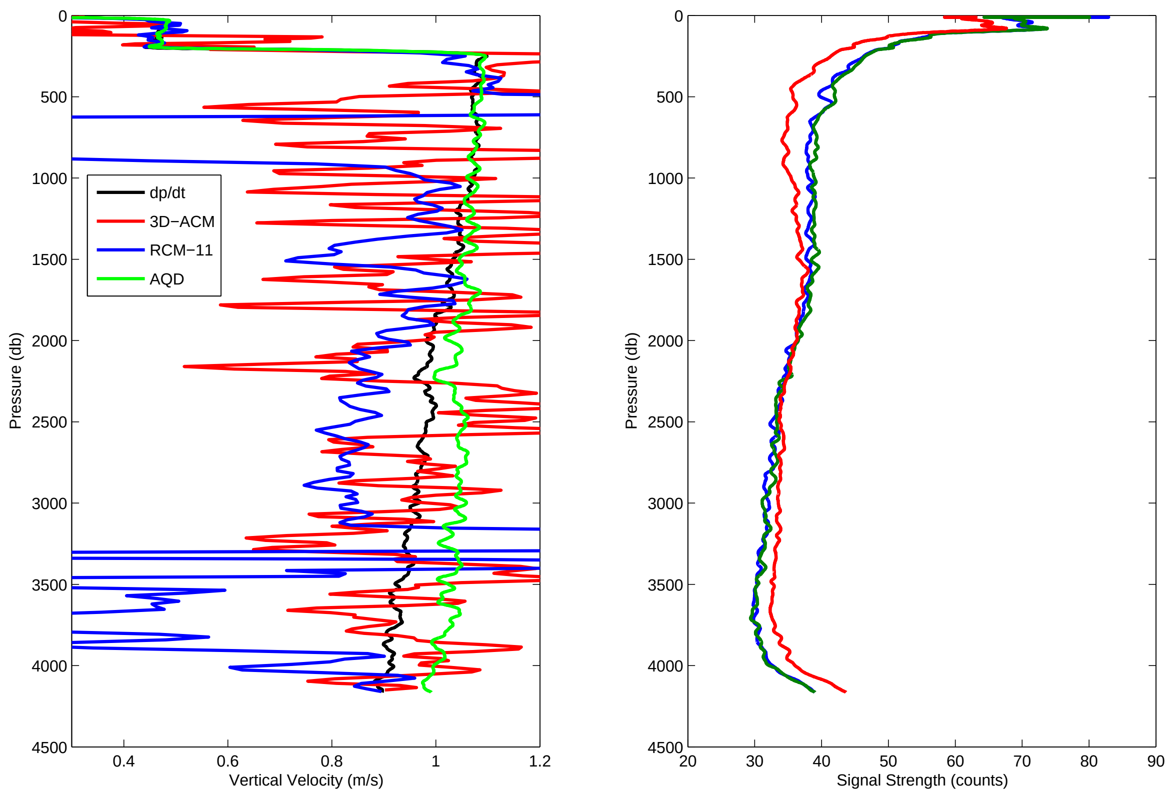

Figure 8: A comparison of vertical velocities measured by three different instruments with that computed from the rate of change of depth (left panel) on the first lowering test. The velocities from the instruments have been adjusted for sound speed variations. In the right panel the Aquadopp signal strength for the three beams is shown as a function of depth. The signal strength scale is arbitrary. The black curve labeled “dp/dt” is computed from the rate of change of pressure in which pressure has been converted to depth.

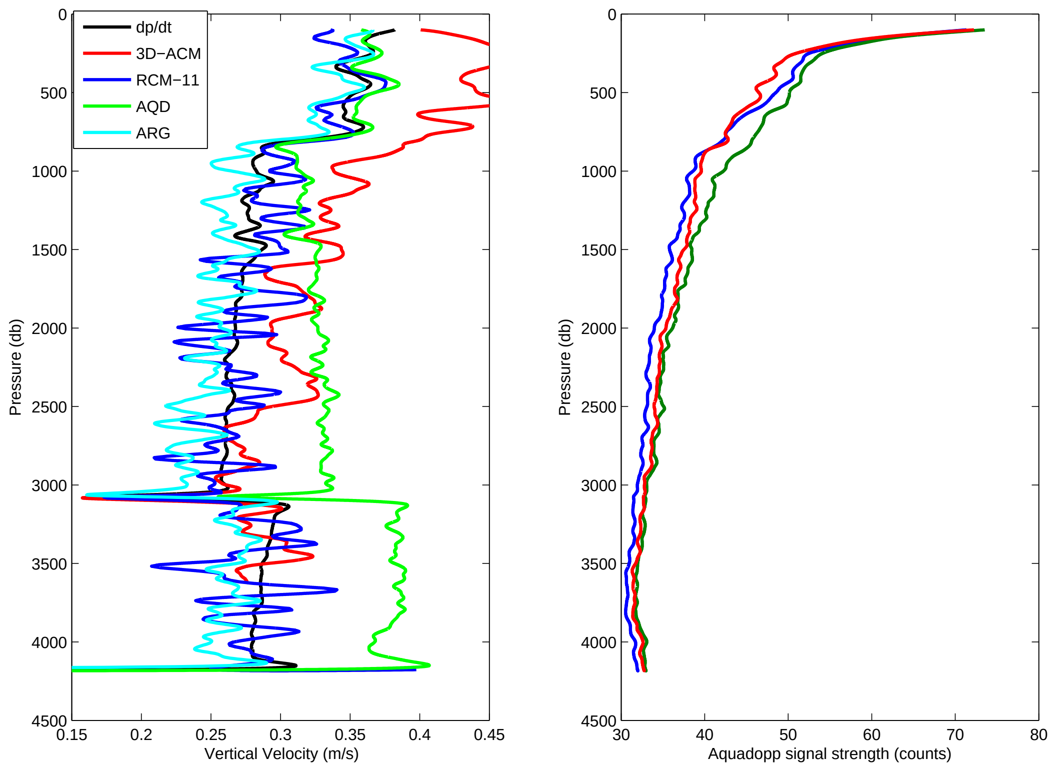

Figure 9: As in Fig. 8 but for the second lowering test cruise.

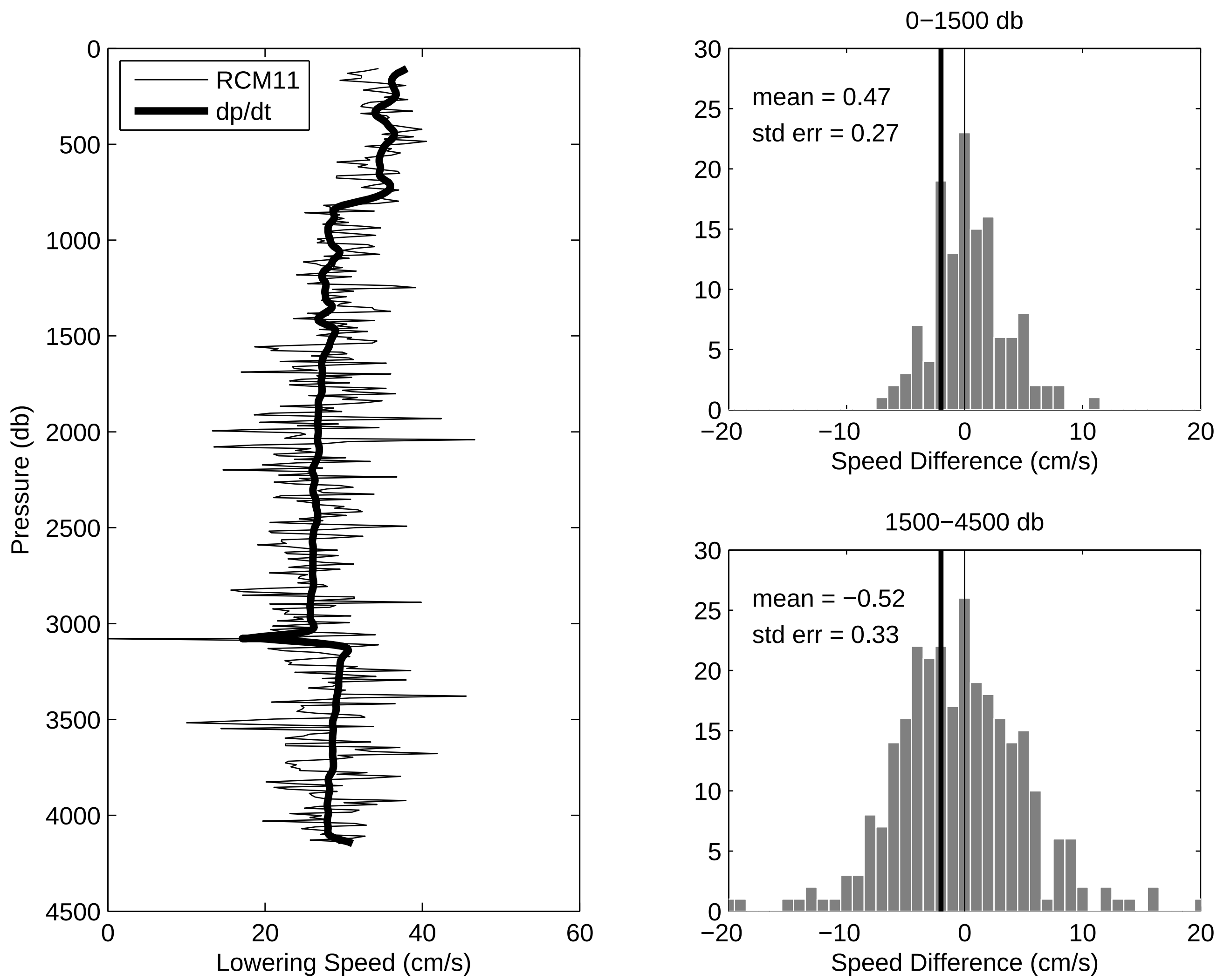

Figure 10: A comparison of the RCM11 vertical velocity with actual lowering speed for the second lowering test. The left panel shows the vertical component of the RCM11 velocity (thin noisy curve) and the lowpassed lowering speed (heavy smooth curve). The right hand panels contain histograms of the difference between the RCM11 vertical velocity and that calculated in two pressure intervals. The fine vertical line is at -2 cm/s; the heavy one is at the origin.

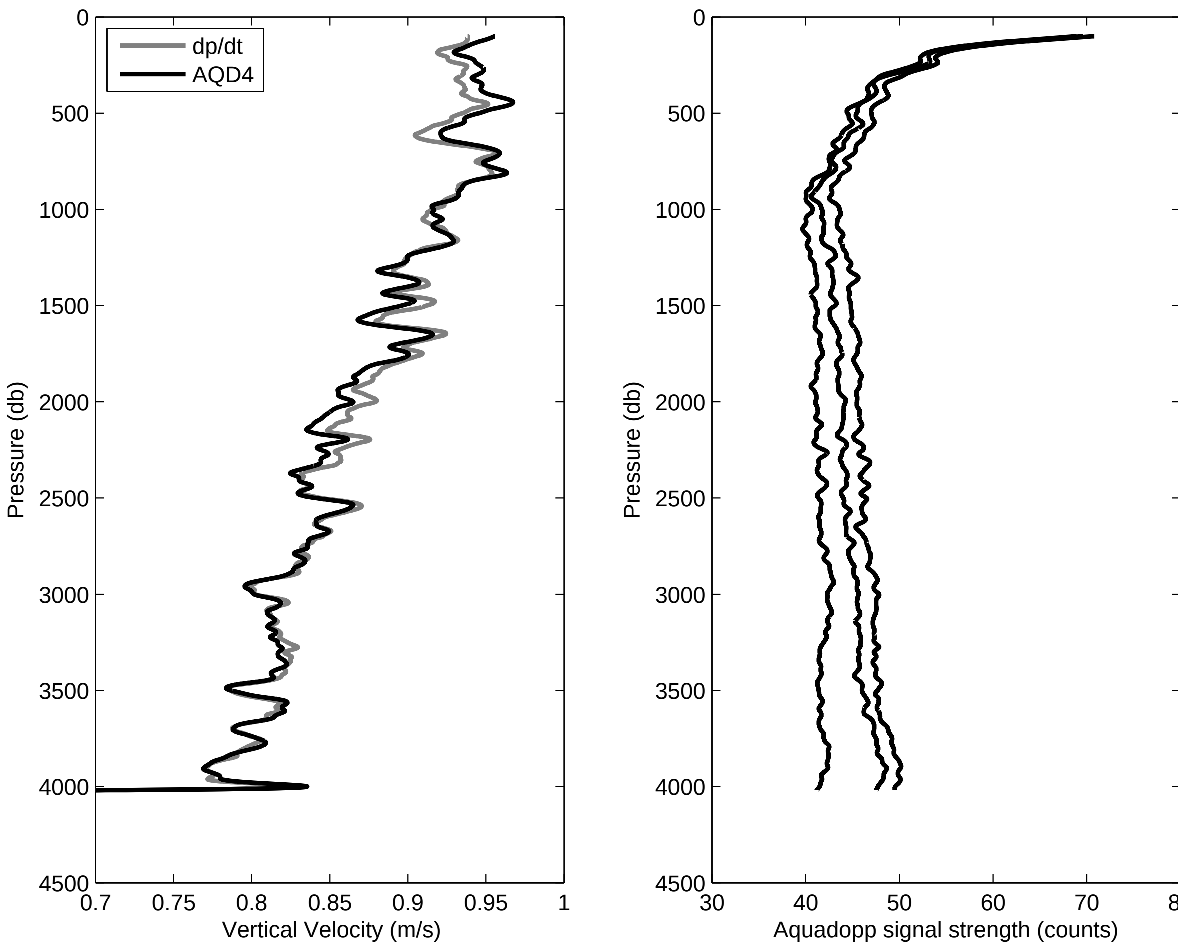

Figure 11: As in Fig. 8 but for the third lowering. Here just one instrument, a 4th generation Aquadopp was tested.

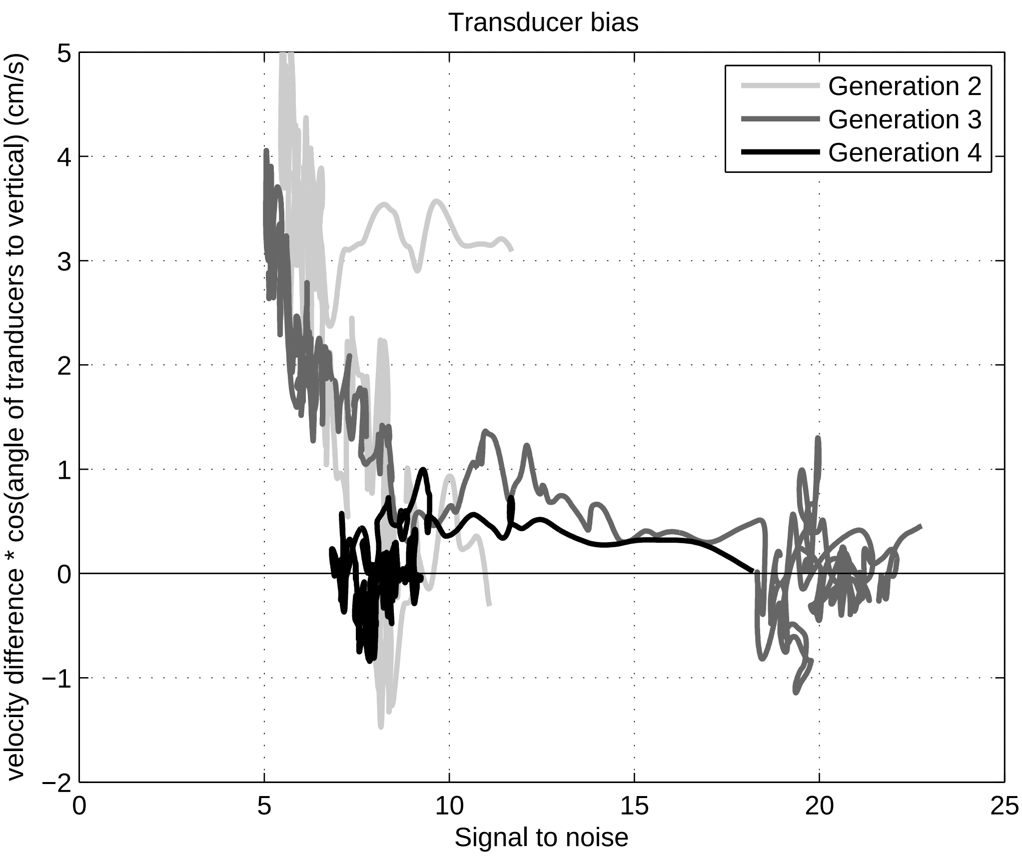

Figure 12: Transducer bias versus signal-to-noise for three generations of the AQD. The bias is calculated as the difference between the measured vertical velocity and the lowering rate projected into the relevant beam coordinate. The signal-to-noise is calculated as 0.4*(signal strength - signal strength just after instrument recovery) according to the manufacturer's instructions (Atle Lohmann, pers. comm.).

Table 1: Instruments used on the test moorings and lowerings. An empty box signifies that an instrument was not used while the other notations indicate a generation or configuration. VACM = Vector Averaging Current Meter. VMCM = Vector Measuring Current Meter. RCM11 = Recording Current Meter - 11. AQD = Aquadopp. ARG = Argonaut. MAVS = Modular Acoustic Velocity Sensor. ACM = Acoustic Current Meter.

Instrument	Type	Manufacturer	Ultramoor-1	Ultramoor-2	Minimoor	Lowering 1	Lowering 2	Lowering 3
VACM	mechanical, Savonius rotor	EG&G	X	X				
VMCM	mechanical, propeller	EG&G			X			
RCM11	acoustic, Doppler	Aanderaa	X	X	X	X	X	
AQD (4 generations)	acoustic, Doppler	Nortek	1	2		2	3	4
ARG	acoustic, Doppler	Sontek					X	
MAVS (2nd and 3rd generation)	acoustic, travel-time	Nobska	2		3		3	
ACM (2D and 3D)	acoustic, travel-time	Falmouth Scientific	2D	3D	3D	3D	3D	

Table 2: The six opportunities associated with the Ultramoor development program in which acoustically based instruments have been compared either with more traditional instruments based on mechanical speed and direction sensors or with the lowering rate of the instrument. Numerals after the MAVS and AQD signify the generation of instrument. The ACM was manufactured either as a 2D (2 horizontal axes) or 3D instrument as indicated. cont. = continuous. inst. = instantaneous.

Experiment	Type	Water Depth m	Start	End	Instruments	Depth m	Duration days	Sampling rate Hz	Avg. Int. min	Sampling interval min
Ultramoor 1	Subsurface Mooring tall	4552	7-30-2000	11-11-2000	VACM	1967	102	cont.	3.75	3.75
					2D-ACM	1974	57	2	variable	variable
					AQD1	1980	—	—	—	—
					MAVS2	1986	69	2	5	5
					RCM11	1993	102	0.5	5	5
					VACM	2000	102	cont.	3.75	3.75
Ultramoor 2	Subsurface Mooring tall	4370	11-20-2001	2-5-2004	RCM11	2002	806	.042	60	60
					VACM	2013	347	cont.	30	30
					AQD2	2025	806	23	2	60
					3D-ACM	4042	806	2	5	60
					RCM11	4055	806	.042	60	60
Minimoor	Subsurface Mooring short	4300	4-3-2002	5-29-2002	3D-ACM	3988	54	2	10	10
					RCM11	3991	56	0.5	5	5
					RCM11	3997	56	0.5	burst	5
					VMCM	4000	56	cont.	3.75	3.75
					MAVS3	4003	56	2	.33	.33
Lowering 1	Lowering beneath CTD	~4300	9-24-2002	9-25-2002	3D-ACM	—	—	2	inst	.25
					RCM11	—	—	5	.3	.3
					AQD2	—	—	23	.017	.017
Lowering 2	Lowering from ship	~4300	8-20-2003	8-21-2003	3D-ACM	—	—	2	.5s	.5s
					RCM11	—	—	5	.57	.57
					AQD3	—	—	23	.017	.017
					ARG	—	—	1	.167	.167
Lowering 3	as above	~4300	6-15-2005	6-16-2005	AQD4	—	—	23	.017	.017