An Intercomparison of Acoustic Current Meter Measurements in Low to Moderate Flow Regions

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ABSTRACT

Instrumented, subsurface moorings deployed in the Scotian shelf and slope regions of the North Atlantic provide data in low to moderate flows for a current meter intercomparison. The primary instruments being evaluated are two acoustic Doppler single-point current meters, the Aanderaa Seaguard (SG) and the Teledyne RD Instruments (RDI) Doppler volume sampler (DVS), which are compared against older-generation single-point current meters and acoustic Doppler current profilers. Analysis showed that the root-mean-square (RMS) of the speed difference between concurrent instrument combinations was in the range of 1.0–1.6 cm s^{-1}, which is about 3%–6% of the upper limit of speeds observed at these sites. Best agreement was between the DVS and the nearby Seaguard (RMS speed difference of 1.2 cm s^{-1}), during the shelf deployment, and between the Aanderaa recording current meter 11 (RCM11) and the nearby Seaguard (1.0 cm s^{-1}), during the slope deployment. Speed differences larger than 4 cm s^{-1} were uncommon, occurring less than 1.5% of the time. Slight overspeeding of one of the Seaguards is traced to an intentional alteration in the instruments' sampling strategy. The DVS compass had a slight meandering tendency that caused it to routinely disagree with other instruments by as much as 15° for hours at a time. The disagreement was random in direction and had no impact on most of the comparisons, but it did produce a 15% smaller magnitude of mean current. Subsequent to this field test, Teledyne RDI redesigned the DVS and replaced the compass with a new sensor.

1. Introduction

Over the last two decades, mechanical current meters have gradually ceded their dominance in the field of oceanography to newly developed acoustic instruments, most of which use Doppler-shifted acoustic backscatter to measure water velocity. Accurate long time series of currents are essential for quantifying, validating, and building our knowledge of the movement of water masses. It is therefore important to test the performance of the current meter recorders deployed in the field. This is particularly true when new instruments are to replace older, proven technologies. In addition, confidence in statistics derived from long-term time series depends on consistency between current meters when different technologies are combined.

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Acoustic current meters offer several significant advantages over mechanical ones. Because of the absence of mechanical parts, they are less sensitive to biological fouling and have lower maintenance requirements. They also have more flexibility in sampling strategies and are better suited to low-current environments, where mechanical rotor stalling can bias measurements. In addition, the older-generation current meters required significant effort to calibrate the compass that has been simplified for most modern instruments.

Acoustic current meters are typically point sensing or profiling. One acoustic profiler can provide current measurements over several hundred meters of the water column, thereby reducing the number of required point instruments to get water column coverage. It is now commonplace to deploy acoustic profilers to acquire full water column measurements on the continental shelf and in the near shore, and to obtain higher resolution of vertical structure in parts of the water column in the deep ocean. Most profilers measure water speed by analyzing the Doppler frequency shift of the acoustic backscatter. The current profile is deduced by subdividing the signal into uniform vertical depth bins (RD Instruments 1996). The part of the signal corresponding to each depth bin is determined by the travel time of the echo. The speed inside each depth bin is averaged in order to reduce errors. To provide the 3D velocity in each depth bin, the speed is measured simultaneously by multiple transducers that are typically angled several tens of degrees away from vertical. The true direction of the current is determined by combining the compass measurement with estimated current in each depth bin.

In the deep ocean, point-sensing current meters remain in common use; since they are sampling a smaller volume, they require less power and enable long-term deployments of several years. These instruments employ both the Doppler shift, as discussed above, and the travel-time difference method. The travel (or transit)-time method measures the transit time for an ultrasonic pulse traveling in a particular direction as well as the reverse direction. The velocity is deduced from the time difference (i.e., sound speed propagation changes with water speed). This method measures true point velocity (as opposed to the Doppler shift method, which averages over a volume) and is not hindered by the lack of scatters in the water column. As this study does not include instruments that use the transit-time method, further details are not included.

Several studies have been conducted to evaluate the performance of the new generation of acoustic current meters. Gilboy et al. (2000) carried out a 110-day field test at a site approximately 80 km southeast of Bermuda in which they compared the vector measuring current meter (VMCM) (Weller and Davis 1980) with an RD Instruments (RDI) acoustic Doppler current profiler (ADCP) and then a new Falmouth Scientific acoustic current meter (ACM). The VMCM is a biaxial mechanical instrument that employs two orthogonal propellers and a fluxgate compass. It has undergone extensive tests and calibrations, and was considered in this study to be a well-characterized current meter that had previously been used to benchmark other current meters. The ACM is a three-axis acoustic travel-time point sensor that at the time of the study had not been used extensively in the field. The correlation of velocity components from instrument pairs in this study was at least $r = 0.95$ in all cases. However, the analyses of measurements in the subtidal frequency band indicated that the mean ACM speed was 1.5 cm s^{-1} (2.5 cm s^{-1}) smaller than that of the VMCM (ADCP). This disagreement was linked to a directional error in the ACM compass reading that created offsets of 20°–30°. The systematic nature of this offset allowed for a postcalibration correction to be applied and better agreement was achieved. The study demonstrates the importance of reliable compass readings for obtaining the correct flow fields.

More recently, Hogg and Frye (2007) evaluated the performance of three acoustic Doppler current meters [Aanderaa recording current meter 11 (RCM11), Nortek Aquadopp, Sontek Argonaut] and two acoustic travel-time current meters [Nobska modular acoustic velocity sensor (MAVS), Falmouth Scientific ACM]. The results from the acoustic instruments were compared to two well-documented mechanical current meters, the VMCM and the vector averaging current meter (VACM; McCullough 1975). Two procedures were used to evaluate the performance of the instruments. First, the current meters were placed close to each other on deep-sea moorings southeast of Bermuda. Second, the instruments were mounted on a CTD system and lowered through the water column in an attempt to calibrate the current meters against the prescribed descent speed. The moored tests indicated that the RCM11 speeds have a systematic 10%–25% deficit in speed, relative to the VMCM and VACM. This pattern was consistent in records from two moorings, one of which was 2.2 yr long. Despite the reduced speed, the study finds the RCM11 to be the most reliable in terms of general data collection and consistency. The authors also stress the fact that the deep location near Bermuda is a challenging environment to both mechanical and acoustic instruments because of the low currents and low-scatterer concentrations. In addition, the low RCM11 speed issue was not apparent in the comparison of the CTD-lowered instruments for speeds of up to 25 cm s^{-1}. The ACM returned questionable data from two moorings that reported speeds 50% higher than the RCM11 and unreliable directions. However, the third mooring returned reliable speeds with a small bias in direction that is consistent with Gilboy et al. (2000). Both the first-generation Aquadopp and Argonaut current meters displayed biases due to low signal-to-noise ratios (SNR) in the deep subthermocline waters with low-scatterer concentrations. However, a subsequent version of the Aquadopp reduced this bias significantly. The travel-time instruments were hampered by technical issues but, when they were operating, they appeared to be capable of making measurements within 1–2 cm s^{-1} of the reference instruments.

In addition to these deep-ocean comparisons, Pettigrew et al. (2005) carried out field tests in a protected coastal embayment over a 30-day period. They compared a bottom-mounted Aanderaa recording Doppler current profiler 600 (RDCP600) to a string of seven moored Aanderaa RCM9 MKII single-point Doppler current meters, and an RDI 600-kHz Workhorse ADCP. Results of vector correlations and difference statistics showed good agreement among all of the instruments. Mean differences were generally less than 0.5 cm s^{-1} and the root-mean-square (RMS) differences were of the order of 2 cm s^{-1}.

The Bedford Institute of Oceanography (BIO) has deployed a number of moorings over the decades to assess the performance of various current meters (Devine and Scotney 2008; Loder et al. 1990; Woodward et al. 1990; Hamilton et al. 1997). The goal of this publication is to describe the results of two recent current meter intercomparison moorings deployed in 2008 on the Scotian shelf and slope. The main emphasis was placed on evaluating two new single-point acoustic current meters, the Aanderaa Seaguard recording current meter (Seaguard RCM) and the Teledyne RDI Doppler volume sampler (DVS). Other current meters used in these experiments were the Aanderaa RCM8 mechanical (paddle wheel rotor) current meter, the Aanderaa RCM11 acoustic current meter, and the 307-kHz Teledyne RDI ADCP, which have been the primary current meters used at BIO over the past three decades.

The following section will present the methods used for the intercomparison, including a deployment summary, discussion of the instruments utilized, and the returned data quality. The results of these deployments will be discussed in section 3, and the overall conclusions will be presented in section 4.

2. Methods

The intercomparison of current meters was carried out by placing closely spaced instruments on a taut subsurface mooring line. The advantage of this method is that it allows for analysis of simultaneously collected data in a realistic environment where these current meters would typically be deployed by our research programs as opposed to being placed in a simulated environment of the laboratory. The disadvantage is that the instruments do not sample the same volume even if placed within meters on the mooring line, which can introduce uncertainty if there is vertical shear in the water column. Acoustic data can also be affected by interference from other instruments or the mooring line itself. Finally, because we are not in a controlled environment, it is more difficult to state which instrument is more accurate when discrepancies occur and we are forced to discuss the level of agreement between instruments rather than actual instrument error. The temptation in this type of comparison is to use the older, well-used instruments as the standard, even though it is generally known that new instruments can offer higher accuracy as well as other advantages. The alternative would be to conduct tow tank experiments to calibrate the instruments; however, because of the large sampling volume required by acoustic instruments, this is often difficult. A potential compromise might be to use shipboard lowering, as suggested by Hogg and Frye (2007); but this methodology offers its own complications and is beyond the scope of the present study.

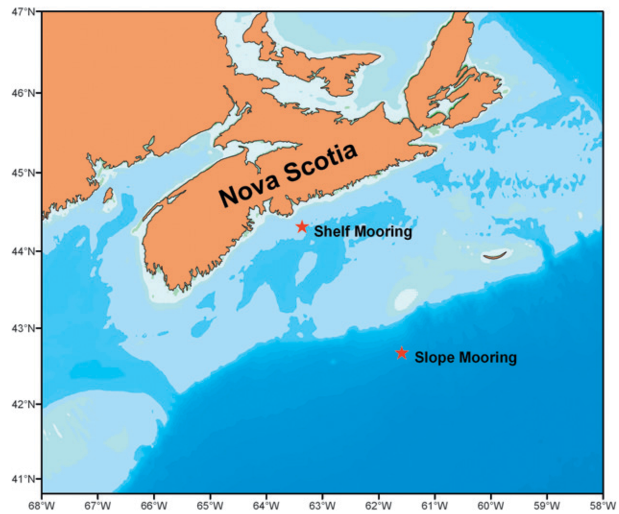

FIG. 1. Locations of the 2008–09 intercomparison moorings.

The instrumentation and deployment summary of this experiment are outlined below followed by a description of the quality of the returned data.

a. *Deployment summary*

The two moorings for the 2008–09 current meter intercomparison experiment were deployed on the Scotian shelf and slope (see map Fig. 1). The sites were chosen, in part, because the currents in the two locations have previously been investigated. In addition, the environment at these sites is typical of the eastern North American continental shelf and shelf slope, where most of our mooring work takes place.

The first mooring (shelf) was deployed in 155 m of water for the period of 8 May–3 June 2008 at 44°17.5′N, 63°16.0′W. Previous moored current measurements in this region (e.g., Lively 1988) indicate mean (maximum) speeds at middepths ranging from 15 (37) cm s^{-1} on the 100-m isobath to 24 (74) cm s^{-1} on the 170-m isobath. Current contributions come from weak mixed diurnal and semidiurnal tides with amplitudes up to 4 cm s^{-1} for individual constituents, local and larger-scale wind forcing, and the seasonally varying Nova Scotia Current (Anderson and Smith 1989).

The second mooring (slope) was deployed on the Scotian slope for the period of 3 October 2008–28 September 2009 in a water depth of 1700 m at 42°44.3′N, 61°34.6′W. This is a site at which some previous deep

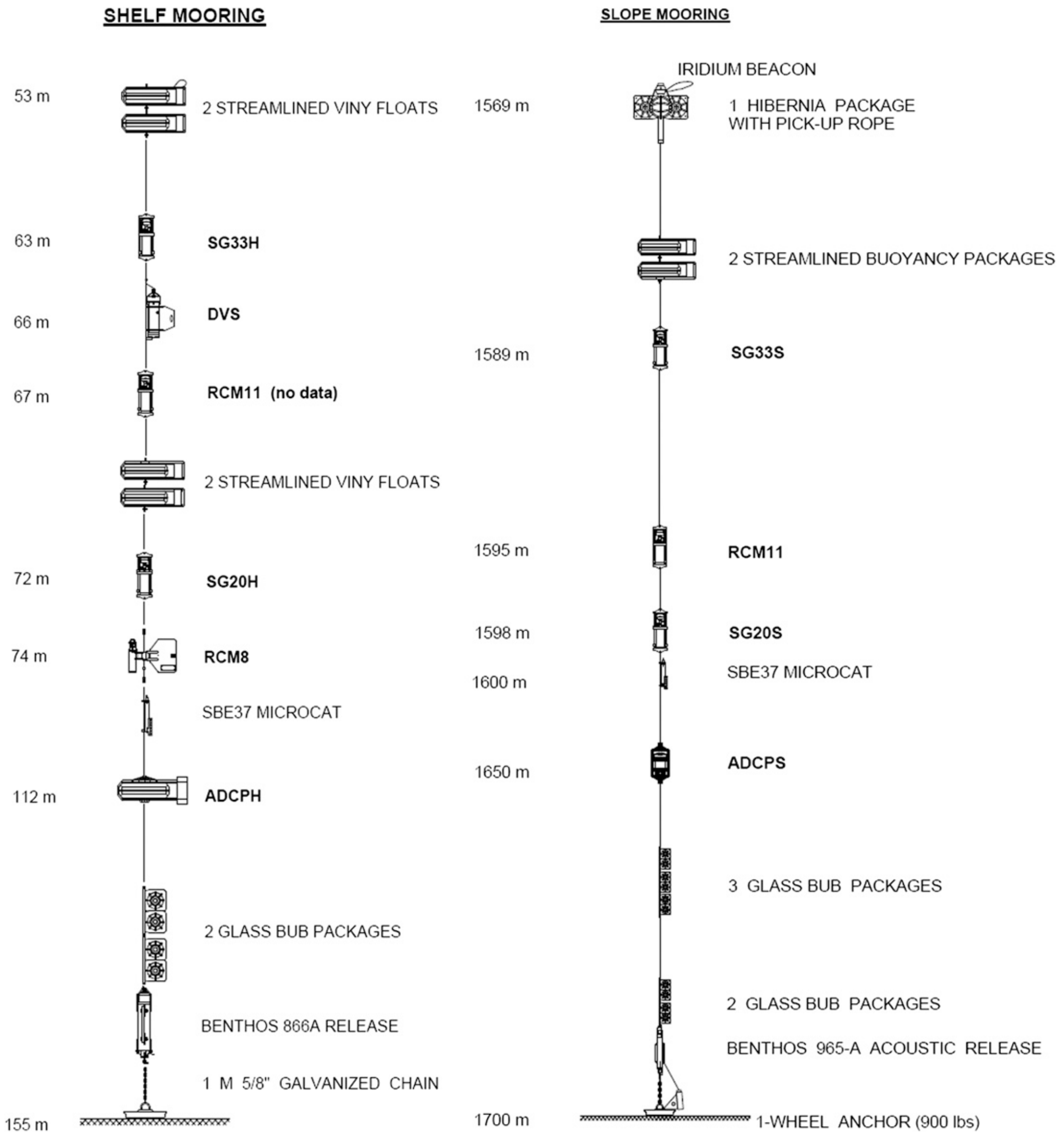

FIG. 2. Schematic of mooring layout used in the 2008–09 intercomparison experiment.

moorings have been deployed by BIO. Petrie and Smith (1977) examined records from the 1967/68 mooring program, which included three records from two moorings (980 and 1500 m) during the autumn 1968. These records varied in length from 33 to 78 days and demonstrated that low-frequency flow is oriented mainly along isobaths with some abrupt current reversals. Spectral analysis revealed peaks at the tidal and the inertial bands, and an increase in intensity toward lower frequencies. The correlation of the two near-bottom velocity components produced a regression axis that was rotated from the direction of the local isobaths by approximately 6°. Louis et al. (1982) examined current meter records from the 1976/77 Shelf Break Experiment and observed bursts of topographic Rossby wave energy in the region of the outer continental shelf and slope north of the Gulf Stream. Deep-water kinetic energy associated with these waves appears to be uniformly distributed over the upper portion of the Scotian Rise.

b. Instrumentation

The two intercomparisons described here were carried out by placing closely spaced current meters on a taut mooring line (Fig. 2). As previously stated, the main focus of this study was on evaluating two new single-point acoustic current meters against older, more commonly used ones. The new instruments were the Aanderaa Seaguard RCM (http://www.aadi.no/Aanderaa/Products/Seaguard/default.aspx) and the Teledyne RDI DVS (http://www.rdinstruments.com/dvs.aspx). The

TABLE 1. Instrument details.

Instrument (name in text)	Area	Depth (m)	Sampling interval	No. of bins / Bin/cell size (m)	Sampling / Strategy
Seaguard (SG33H)	Shelf	63	10 min	1	Ping count: 300
				1.5	Burst mode: ZPulse
					Forward ping
DVS (DVS)	Shelf	66	10 min	5	Ping count: ~280
				1	Burst mode
Seaguard (SG20H)	Shelf	72	10 min	1	Ping count: 300
				1.5	Spread mode: ZPulse
					Forward ping: Yes
RCM8 (RCM8)	Shelf	74	10 min		Spread mode
Workhorse ADCP (ADCPH)	Shelf	112	10 min	30	Ping count: 80
				4	Burst mode (4 min)
Seaguard (SG33S)	Slope	1589	1 h	1	Ping count: 100
				1.5	Spread mode: Zpulse
					Forward ping
RCM11 (RCM11)	Slope	1595	1 h		Ping count: 600
					Spread mode
Seaguard (SG20S)	Slope	1598	1 h	1	Ping count: 300
				1.5	Spread mode: forward ping
Workhorse ADCP (ADCPS)	Slope	1650	1 h	30	Ping count: 100
				4	Spread mode (4 min)

Seaguard employs the Aanderaa ZPulse technology, which transmits an acoustic pulse of several distinct frequencies to improve the data quality of the Doppler current measurements without increasing the power drain, measurement time, or pulse length (Jakobsen et al. 2008). The DVS features a four-beam Janus configuration that provides five bins of velocity data with a range up to 5 m. A high-sample-rate compass/tilt sensor enables the user to estimate the relative importance of mooring vibrations.

Other current meters used in these experiments were the Aanderaa RCM8, RCM11, and the 307-kHz Teledyne RDI ADCP, which have been the primary current meters used at the BIO over the past three decades. The RCM8 is a mechanical instrument that uses a paddle wheel rotor to measure currents. After decades of use, the strengths and weaknesses of this current meter are well known. The primary issues with the use of the RCM8 at BIO have been the exact rate calibration formula, the tendency of the paddle wheel rotor to stall (or underspeed) at low flow speeds, and the underestimation of rate due to rotor shielding in the presence of mooring vibration in moderate to high flows (Hamilton et al. 1997; Loder and Hamilton 1991).

The Aanderaa RCM11 is a single-point acoustic current meter that has been utilized by BIO as a replacement for the RCM8. It uses a 2000-kHz narrowband Doppler current sensor using four horizontal beams to estimate the two horizontal components of velocity. Its performance has been evaluated by Hogg and Frye (2007), and it has been compared with the RCM8 in three previous BIO mooring deployments (see Drozdowski et al. 2010).

A 307-kHz Workhorse RDI ADCP was included in each mooring to provide an additional dataset for intercomparison, and to define the vertical velocity structure in the water column over the range of the mooring depth. The ADCP uses a four-beam Janus configuration to estimate the three components of velocity. Gilboy et al. (2000) demonstrated that the ADCP produced results similar to those achieved with the VMCM in terms of coherence and phase, and that there were only significant departures between the two instruments at frequencies greater than 0.01 cycles per hour.

The setup and specifications for each current meter are provided in Table 1. In both moorings, streamlined buoyancy packages were used along the mooring and for the ADCP mounting in order to eliminate potential errors from mooring-related vibrations (see Hamilton et al. 1997). A SeaBird 37M MicroCAT temperature and conductivity sensor was included on both moorings for other work not related to this experiment.

To avoid ambiguity when referring to same instruments from both moorings, the letter H (S) is attached to end of the instrument name for the shelf (slope) deployment. For the shelf mooring, SG33H was set up for burst mode sampling (300 pings in the last 60 s of a 10-min sampling interval), while the SG20H spread mode (300 pings evenly spaced over the sampling interval) was used to compare the performance of these methods on otherwise identical current meters. For the DVS, each ensemble collected during this deployment was composed of about 280 individual acoustic pings. The exact number of pings can vary slightly between ensembles, as it depends on how long it takes for the instrument to sample all its sensors.

For the slope mooring, both Seaguards sampled in spread mode. However, as part of the experiment, SG20S had the Zpulse mode turned off and instead sampled at a 3 times higher ping rate. The deployment of a DVS and RCM8 was also planned for this mooring, but it was not carried out because of technical limitations.

The DVS, ADCP, and RCM8 current meter compasses were calibrated before each deployment in order to decrease compass error introduced by nearby magnetic materials, such as new batteries and mounting frame. All calibrations are carried out in the ‘‘BIO Compass Hut,’’ a structure designed to minimize magnetic interference. The DVS and ADCPs are calibrated by rotating the instrument and mounting several times at constant tilt while internal software calculates the new calibration matrix. A calibration is deemed successful if the compass error is below 2°. The RCM8 compass was calibrated using a swing table aligned with true north. Two rotations are performed in 10° steps, while data are collected at each position to determine the compass offset from the true heading. A fan spins the rotor during the compass swing to reduce the effect of the rotor magnet on the compass swing results. User compass calibration of acoustic Aandaraa instruments (RCM11 and Seaguards) is not recommended by the manufacturer because of the complexity involved. Instead, the manufacturer recommends the use nonmagnetic lithium batteries and frames, and that the instruments are sent back for a calibration check every few years, or sooner if the compass is suspect.

c. *Returned data quality*

All instruments were successfully recovered from both mooring deployments. There were no visible signs of physical damage or biofouling of the instruments. Below is a discussion of the returned data quality parameters for each deployment.

1) SHELF MOORING

Pressure records from instruments indicated that current meters located in the upper group (SG33H, DVS, RCM11; see Fig. 2) had a possible issue of wire entanglement for the period of 8–12 May. It appears that the streamlined buoyancy float, which was designed to be at the top of the mooring, was somehow caught in the DVS structure; this would most likely have happened while the mooring was deployed, as our standard procedure involves laying out the mooring on the surface prior to the release of the anchor. The float freed itself on 12 May 2008 and ascended to its designed depth. For this reason, analysis of data from this mooring only used data from 12 May onward.

All instruments on the mooring returned complete data records for the entire period of the mooring deployment. During the initial processing of the RCM11 data, it was noted that its speed and direction values were significantly different from those of nearby instruments. The heading remained within a few tens of degrees of true north throughout the deployment. This instrument was returned to Aanderaa for investigation, but nothing conclusive was found to explain the malfunction. The instrument was excluded from the analysis.

All other instruments from this deployment returned reliable data. Quality control parameters for the ADCP, Seaguards, and DVS are summarized below. ADCPH reported mean percent good pings of 99.91% and 1.36% standard deviation (STD) for the 21 bins below 20 m. SG33H reported a mean signal strength of −35.8 dB with an STD of 3.35 dB. SG20H had similar values of −35.7 and 3.0 dB, respectively. The instrument manufacturer reports a noise floor of about −71 dB, which suggests a high SNR for both datasets. The DVS provided good quality data from the lower three bins. The best bin (at 1 m above the transducer head), reported a mean of 100% good pings with 0% STD. However, it should be noted that RDI's standard for differentiating signal from noise is to declare a good ping if more than 64 counts are recorded on the analog-to-digital (A/D) converter. The second bin (2 m) reported 85.6% good pings with an STD of 29.6%. The overlapping good data from both bins were compared and found to correlate highly (99% correlation and $R^2 = 0.99$) for both speed and direction. The third bin (3 m) returned only 3.3% good pings. The likely cause of this low data return is interference with SG33H directly above. Only the data from the 1-m bin were used in this investigation.

2) SLOPE MOORING

SG33S reported a mean signal strength of −52.5 dB with an STD of 1.8 dB. SG20S had similar values of −52.9 and 1.6 dB, respectively. ADCPS stopped functioning on 30 June 2009 as a result of a battery failure. The presentation and analysis of data from this site were limited to the period of valid ADCPS data. During its operation, this instrument recorded percent good pings of above 95% with a standard deviation of 5%–10% for bins 1–15. The good pings degraded rapidly for the

TABLE 2. Current meter data summary statistics (speeds in cm s^{-1}).

Statistic	SG33H	ADCPH Bin 10 at 65.7 m	DVS	ADCPH Bin9 at 69.7 m	SG20H	ADCPH Bin8 at 73.7 m	RCM8	SG33S	RCM11	SG20S	ADCPS Bin 9 at 1612 m
Mag. mean vel.	8.5	8.3	7.1	8.0	8.3	7.6	8.1	2.9	3.2	3.0	3.0
Dir. mean. vel. (°T)	238	238	240	238	238	239	235	241	246	246	244
STD (u, v)	10.4	10.5	10.5	10.3	10.6	10.2	10.2	8.3	7.9	9.1	8.1
Mean speed	11.9	11.7	11.1	11.5	12.1	11.2	11.5	7.8	7.4	8.5	7.6
Min speed	0.43	0	0.2	0.1	0.2	0.1	1.1	0.07	0	0.12	0.1
Max speed	34.8	37.5	35.7	40.2	38.9	40.4	39.5	26.0	25.2	26.0	26.0
STD speed	6.3	6.5	6.2	6.2	6.0	5.9	6.24	4.1	4.2	4.4	4.2
Sample size	3164	3155	3163	3155	3164	3155	3163	6462	6462	6462	6462

higher bins, with bin 20 reporting 50% good pings with a 30% STD. This is not unexpected, since the number of scatterers in the water column is likely limited at this location and depth, and this has been observed in other recent ADCP deployments in this location. In addition, there was a 10%–25% decrease in RMS speed in bins 10–19, which happen to cover the vertical range of the single-point instruments. For a more detailed discussion of these ADCPS data quality issues, see Drozdowski and Greenan (2012). Bin 9, the closest to the single-point instruments but below the signal contamination, was chosen for the present intercomparison.

A compass offset for magnetic declination (−18.27°) was applied to all instruments to obtain directions relative to true north.

3. Results

Table 2 summarizes the current statistics for each instrument. For the ADCPH, only the results from bins 8 to 10, which are nearest to the single-point current meters, are presented. On the shelf, the mean current magnitude (direction) is in the range 7.1–8.5 cm s^{-1} (235°–240°T), consistent with the climatology of the Nova Scotia Current in this region (Anderson and Smith 1989). The range of the magnitudes (1.4 cm s^{-1}) is quite large for instruments so close together. Some of the variation can be attributed to shear in the water column, as observed with the ADCP profiler (bins 8–10), but it can only account for approximately 0.7 cm s^{-1} over 8 m. The presence of shear is further illustrated in Fig. 3,

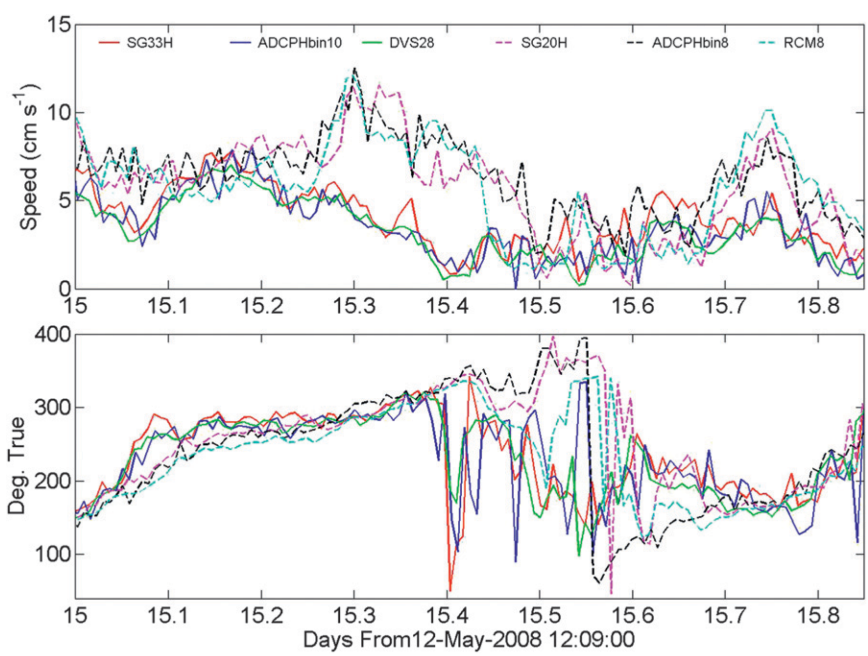

FIG. 3. Example of large current differences due to vertical shear at the shelf deployment: (top) speed and (bottom) direction. Top and bottom instrument groups are distinguished by the solid and dashed line types.

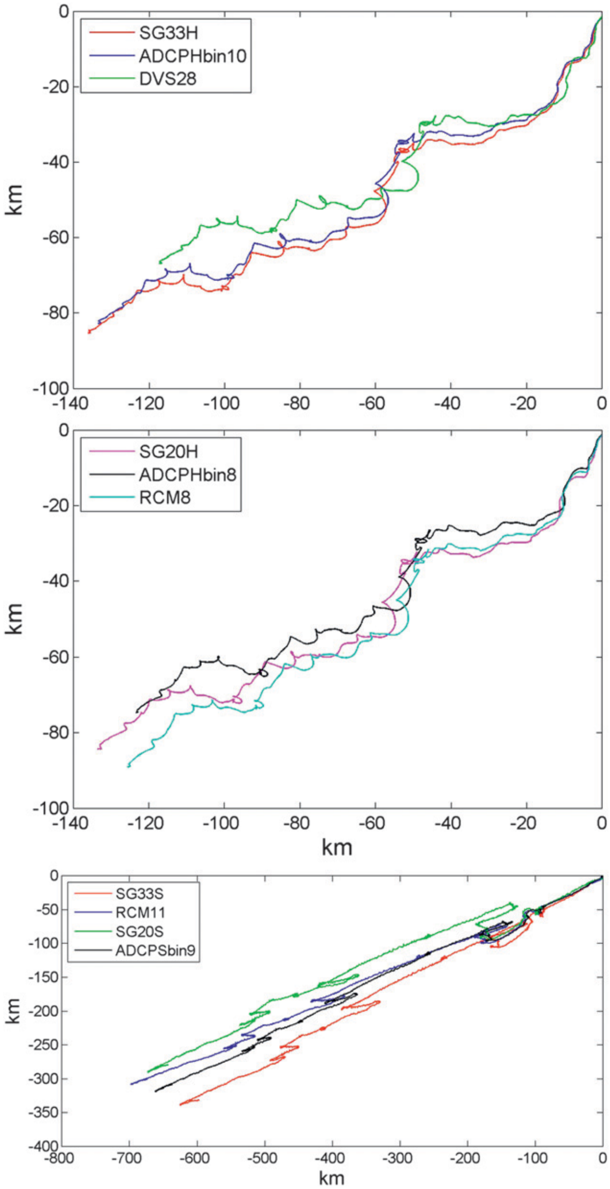

FIG. 4. The PVDs for (top),(middle) shelf and (bottom) slope mooring.

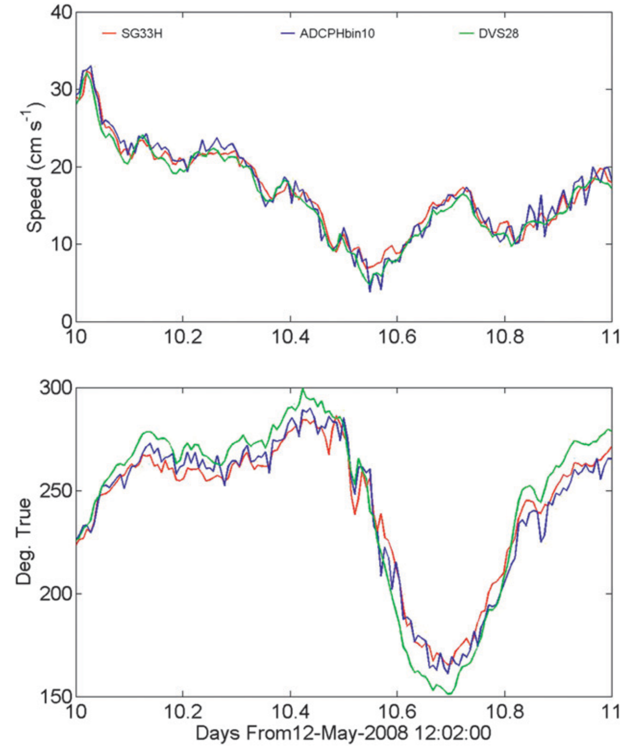

FIG. 5. Example of small but persistent DVS compass deviations: (top) speed and (bottom) direction.

where the top (SG33H, DVS, ADCPHbin10) instruments deviate from the bottom (SG20H, RCM8, ADCPHbin8) by as much as 5 cm s^{-1} for a few hours. Prompted by this finding, we do not compare measurements from instruments in the upper pair (at 63 and 66 m) with those in the lower pair (at 72 and 74 m). The STD of the current velocity is between 10.2 and 10.6 cm s^{-1}, which is indicative of the large flow variability and commonly observed current reversals in this region (Anderson and Smith 1989). The speeds peak at 34–40 cm s^{-1}.

On the slope, the flow is significantly weaker. The magnitude (direction) of the mean current is 2.9–3.2 cm s^{-1} (241°–246°). The standard deviation of the current velocity ranged from 7.9 to 9.1 cm s^{-1}, which is 3 times higher than the mean and indicates a presence of current reversals as mentioned earlier. Maximum speeds recorded were approximately 26 cm s^{-1}.

The flow field from each current meter is summarized with a progressive vector diagram (PVD) in Fig. 4. For the shelf deployment, the integration path of the DVS is shorter than observed by the other instruments. This can also be seen in Table 2 as a 1.3 cm s^{-1} (or 15%) lower mean magnitude compared to the two other instruments in the top group. Despite the underestimation of the mean, the STD and other statistics for the DVS are consistent with the rest of the group. The issue was investigated further (Drozdowski et al. 2010), and the conclusion was that it was caused by the compass routinely disagreeing with other instruments by as much as 15° for several hours at a time. An example is illustrated in Fig. 5. Note the deviation is not of a systematic nature that can be removed with postcalibration; the compass records 5°–10° clockwise error for a few hours followed by a few hours of counterclockwise error and then reversing again. Also note that the speed stays consistent with the other instruments during this period. However, the vector displacement, as noted above for Fig. 4, is

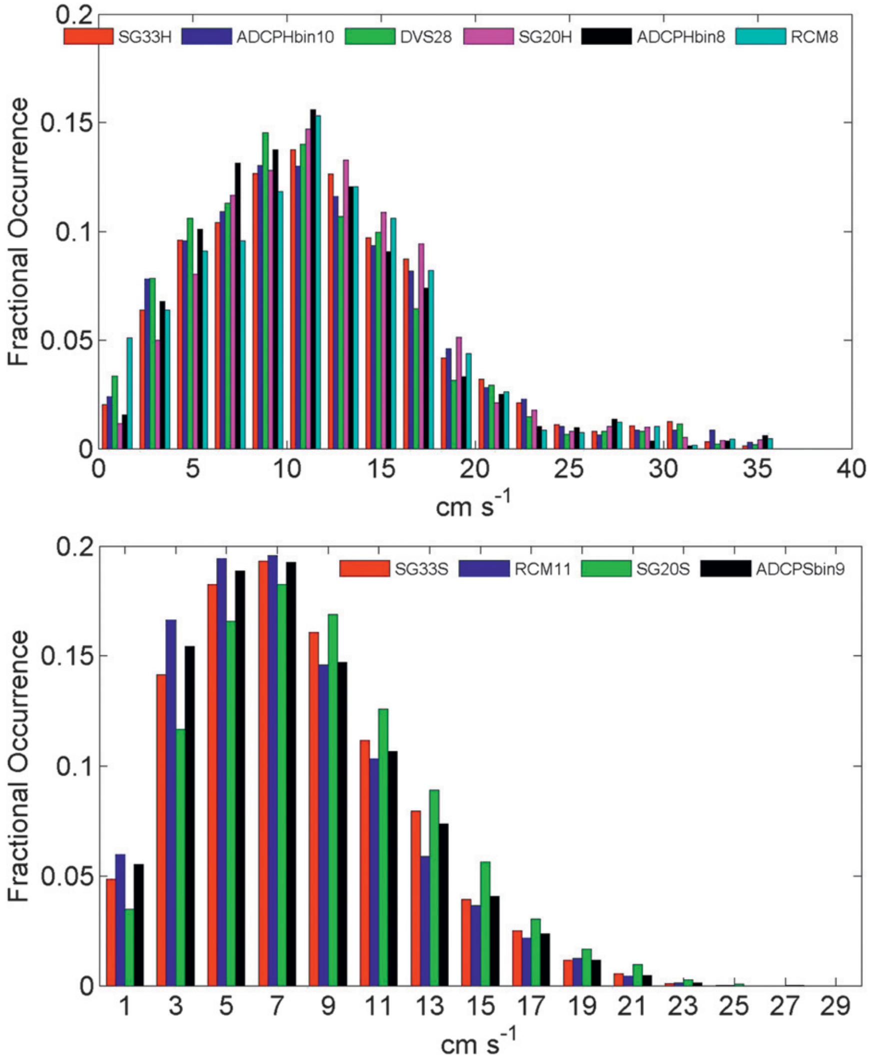

FIG. 6. Current speed distribution for the (top) shelf and (bottom) slope moorings. Data are binned in $2\,cm\,s^{-1}$ intervals.

reduced by the meandering of the compass. As mention, the disagreement was random in direction and hence there is no bias in the mean direction for this instrument.

The PVD lines in all three comparison groups gradually diverge over the period of the deployment, but some of the divergence occurs in short-term events that create offsets. For example, the slope mooring shows a northward shift in the track of SG20S (at around −180 km on the *x* axis) relative to the other instruments early in the time series, and this puts it on a slightly different trajectory for the remainder of the integration.

Figure 6 shows the distribution of the measured speeds binned in $2\,cm\,s^{-1}$ intervals. For the shelf deployment, all instruments provide comparable results. Overall, approximately 70% of the data samples were observed to be in the 4–18 $cm\,s^{-1}$ range and about 10% of measurements are below $4\,cm\,s^{-1}$. Moderate current speeds ($>18\,cm\,s^{-1}$) occurred 20% of the time. The RCM8 had twice as many observations in the 0–2 $cm\,s^{-1}$ range, indicating possible stalling (or underspeeding) in this speed range. In addition the RCM8 recorded a minimum speed of $1.1\,cm\,s^{-1}$, which is the defined lower threshold of $1.1\,cm\,s^{-1}$ assigned to zero rotor counts in the manufacturer's original calibration formula (Aanderaa Instruments 1993). However, speeds in this range were found to occur only about 2%–5% of time and have little impact on the overall performance of this instrument in the comparison.

For the slope deployment, the majority of data (approximately 75% of the data samples) were between 4 and $12\,cm\,s^{-1}$; 5% were below $2\,cm\,s^{-1}$, while 20% exceeded $12\,cm\,s^{-1}$. Observations over $20\,cm\,s^{-1}$ were

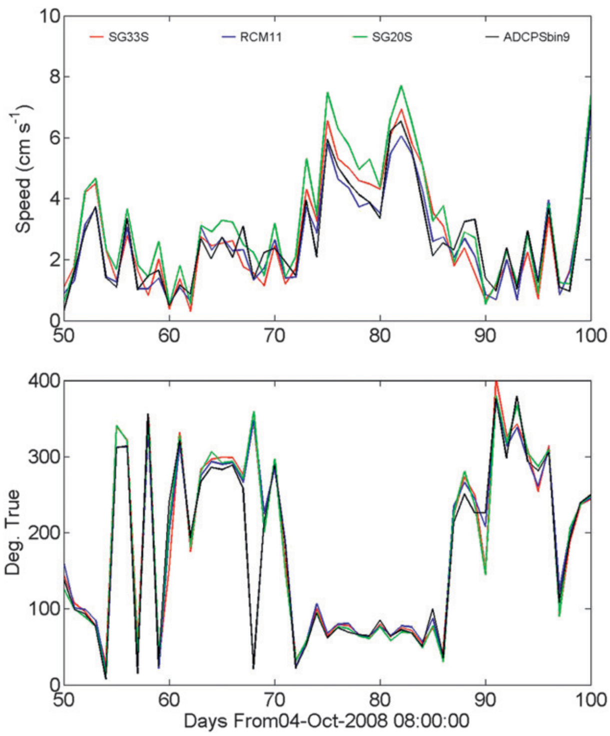

FIG. 7. Example of small but persistent SG20S overspeeding error: (top) speed and (bottom) direction.

FIG. 8. Speed difference statistics for various pair configurations.

uncommon, occurring ~1% of the time (i.e., 3–4 days per year). From the distribution we see that SG20S speeds are slightly skewed toward higher speeds. This instrument also had the largest STD (Table 2)—10% higher than the next highest, SG33S, which is significant because there is only a 6% difference between the second highest (SG33S) and lowest (RMC11). The mean and maximum speeds for SG20S are also the highest. Figure 7 shows an example where this instrument recorded 0.5–1 cm s^{-1} higher speeds for a period of about 40 days. However, the magnitude of the mean flow for this instrument is in the middle of the group, indicating that the tendency cancels out when long-term vector averaging is used (i.e., the overspeeding is as likely to be toward one direction as another and hence cancels when averaged). The disagreement is not likely to be caused by the vertical offset because of the depth of the instruments at this site. In addition, ADCPS showed no shear in the good bins below the point instruments. Based on these findings, the issue was attributed to this Seaguard having had the Zpulse sensor intentionally turned off as a part of the experiment, and is consistent with the Aanderaa finding that Zpulse reduces variance (Jakobsen et al. 2008). An overestimation of the variance mathematically leads to larger speeds because of the additional error from combining the flow velocity components.

Scatterplots and regression fits showed a very good general agreement and are not included in this paper (see Drozdowski and Greenan 2012; Drozdowski et al. 2010). A more detailed intercomparison involves analyzing differences between specific instrument pairs. For each deployment instruments were paired with other single-point instruments and then with the ADCP. Figure 8 shows the various pairings and basic statistics. Drozdowski and Greenan (2012) showed that the distribution of speed differences closely resembles a Gaussian distribution and can therefore be characterized by a mean and standard deviation. The physical interpretation of these statistics is as follows. The mean represents systematic biases between instruments that might arise from instrument design or calibration differences. This statistic is mathematically equivalent to the differences in the mean speeds from Table 2. The STD for a pair gives a measure of variability in the speed difference and is nonsystematic (i.e., random). Hence, if a pair includes a noisy instrument, then we would expect a larger value here. In addition, more averaging by the instrument during measurement (i.e., higher ping count, spread mode, or longer sampling period) or in postprocessing would reduce the STD. The mean differences for the pairs studied here are in the range −0.6–1.1 cm s^{-1}, with an average of 0.4 cm s^{-1} for all the pairs. The SG20S–RCM11 pair had the highest mean difference (1.1 cm s^{-1}). The STD of the pair differences varied from 0.9 to 1.6 cm s^{-1} with an average of 1.2 cm s^{-1}. Pairs involving ADCP and RCM8 had the higher range of values, 1.2–1.6 cm s^{-1}, as is expected because these instruments have a higher noise floor

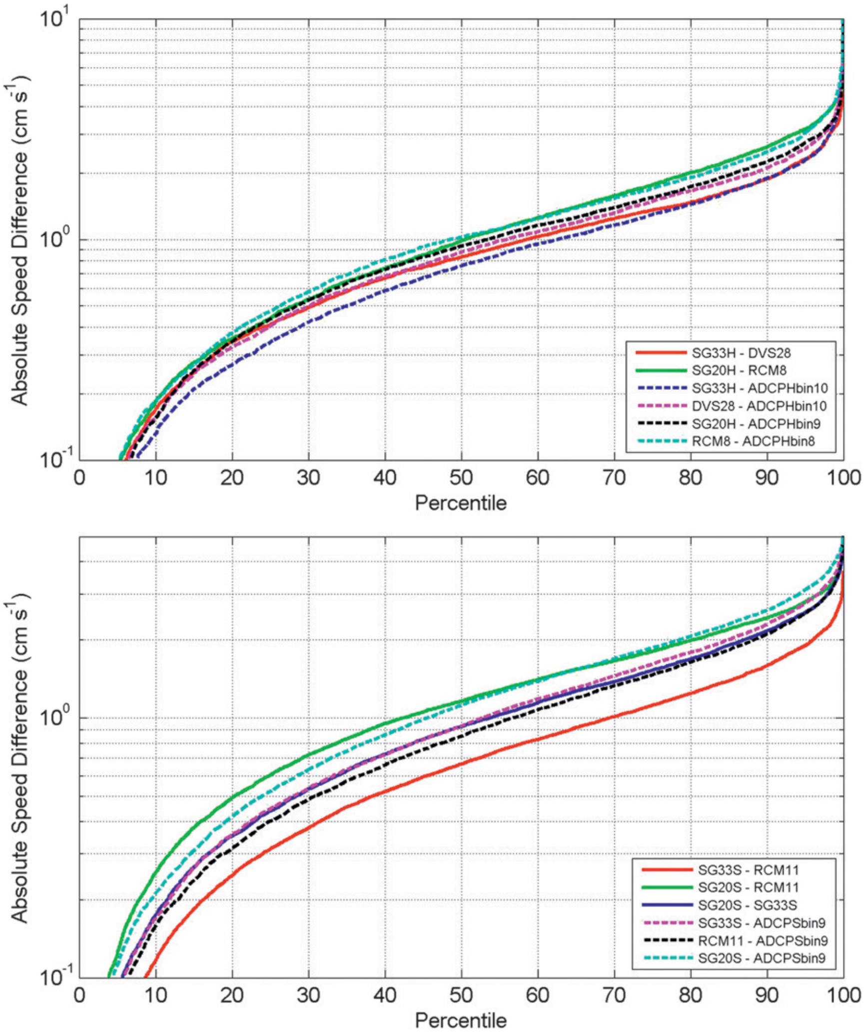

FIG. 9. Percentiles of instrument speed differences for (top) shelf and (bottom) slope deployment.

when compared to acoustic point current meters [see manufacturer-reported uncertainties in Drozdowski et al. (2010)]. The RMS of the difference is the combination of the mean and STD contribution, and gives the overall agreement for the pair. Values were in the range 1.0–1.6 cm s^{-1}, with 1.4 cm s^{-1} as the average over all the pairs. Best agreement was between SG33H and DVS (1.2 cm s^{-1}) on the shelf deployment and between SG33S and RMC11 (1.0 cm s^{-1}) on the slope deployment.

The next step involves a closer look at the speed difference distribution. Figure 9 shows the instrument speed differences from the various instrument pairs as a function of percentile values. The distributions are cumulative, and a point (p, u) on the curves has the following interpretation: the ‘‘pth’’ percentile of u cm s^{-1} means that p% of the differences are less than u, while 100-p% are greater. These figures demonstrate that for both the shelf and slope moorings, the 50th percentile for the instrument speed difference is less than or equal to about 1 cm s^{-1}. In both deployments, the 90th percentile is less than 3 cm s^{-1} and the plots indicate that there are relatively few outliers in these instrument pairings.

Figures 10 and 11 are the result of computing the average instrument speed anomaly inside 25% percentile bins spanning the entire absolute speed difference distributions (Fig. 9) for the shelf and slope mooring deployments, respectively. Each of the six panels represents analysis based on a particular speed difference pairing. For example, in the middle-left panel of Fig. 10, the ADCPHbin10 anomaly of −1.5 cm s^{-1} for the 0%–25% percentile bin is the difference between the average ADCPHbin10 speed at times in the deployment when its agreement with the DVS was within the 0–25th percentile, which corresponds to an actual speed difference

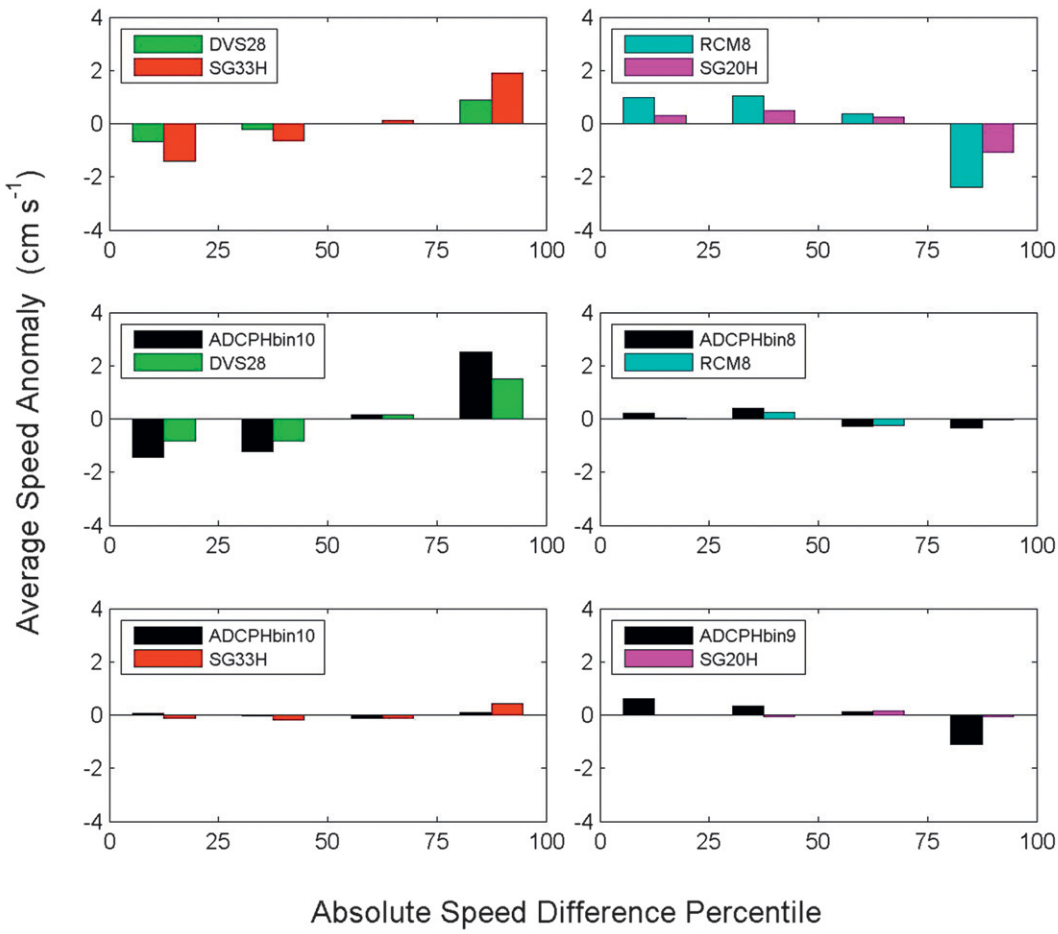

FIG. 10. Average instrument speed anomaly for the shelf deployment for instrument pairs indicated computed in 25% percentile speed difference bins. Percentiles based on pair indicated in legend. Anomaly is based on the overall average speed for each instrument.

of $<0.4\,\mathrm{cm\,s^{-1}}$ from Fig. 9, and the average ADCPHbin10 speed for the whole deployment. In the bottom-left panel of Fig. 10, the ADCPHbin10 is paired with SG33H and the anomaly is $\sim 0\,\mathrm{cm\,s^{-1}}$ for the same bin, which implies that for the 0–25th percentile level of agreement, the ADCPHbin10 speed was closer to its deployment average value for the SG33H pairing than the DVS28 pairing.

Percentiles were used in place of actual speed differences due to the large skew of the distribution toward low differences. In addition, using percentile bins ensures that all bins have the same sample size. The purpose of this analysis is to determine whether there are differences in the agreement levels of instrument pairings, at different speeds. In cases where the anomalies are close for all four bins in a given instrument pair, there is little speed dependence of the errors. The largest speed dependence of instrument differences occurs in pairs involving the DVS (shelf mooring,) and SG20S (slope mooring, Fig. 11). The DVS anomaly has an increasing trend of approximately $3\,\mathrm{cm\,s^{-1}}$ over the entire percentile range, indicating more disagreement at higher speeds. The pattern appears in its pairing with both SG33H and ADCPH, while in the pairing of ADCPH and SG33H, the anomalies are close to zero. The RCM8 anomaly on the shelf mooring shows a negative trend for the comparison with SG20H (indicating a tendency to higher disagreement at lower speeds) but not with ADCPH (where the anomalies are close to zero) and hence there is no clear conclusion. On the slope mooring, SG20S has a positive $2\,\mathrm{cm\,s^{-1}}$ trend over the percentile range that shows up consistently in its comparison with all other instruments, and is consistent with the previous findings of this instrument overspeeding.

A final look at the instrument pair differences involved computing exceedance probabilities (Fig. 12). This statistic is a measure of the fraction of total time that the instruments in a pair disagreed by more than

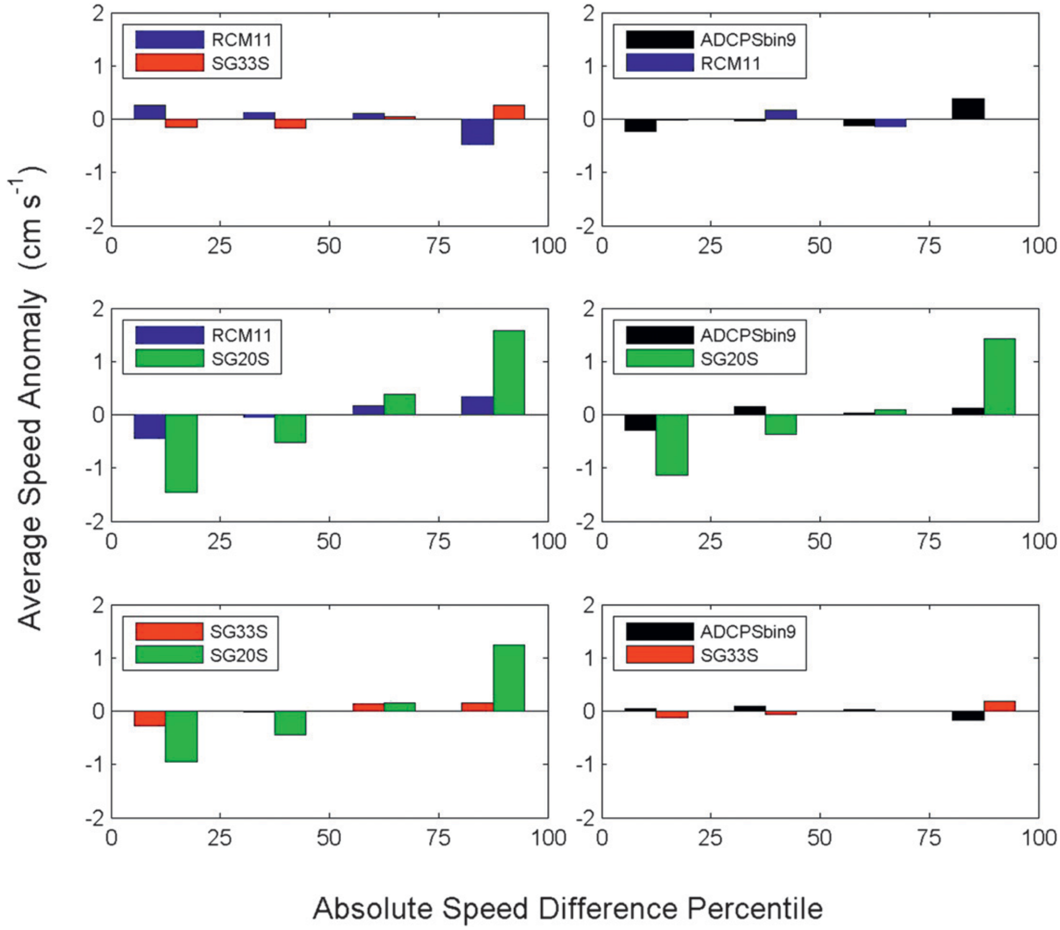

FIG. 11. As in Fig. 10, but for the slope deployment.

a certain value. Also shown on the graphs are two analytical Gaussian speed difference distribution plots computed for a best-case (mean = 0.2, STD = 0.8 cm s^{-1}) and worst-case (mean = 0.8, STD = 1.6 cm s^{-1}) scenario (see Fig. 8). The distributions are well contained inside the Gaussian envelope, except for comparisons involving the ADCP in the shelf deployment, where there is an indication of very infrequent occurrences of very high (>10 cm s^{-1}) errors. Two examples of such errors are seen in the middle of the time series and shown in Fig. 13. The source of these errors is unknown, but they are not common enough to be a concern with respect to the overall performance of the instrument.

Large errors (or disagreements) are defined here as those differences exceeding 4 cm s^{-1}, which is about 3 times larger than the typical standard deviation (Fig. 8) and should never occur for the best-case Gaussian (as defined above) and only ~2% of the time for the worst-case Gaussian. For the shelf deployment, large errors occur between 0.3% and 1.5% of the time, the 0.3% case being for the DVS–SG33H pair on the shelf deployment. In the slope deployment, the SG33S–RCM11 comparison stands out as having no large errors. For the other instruments, large errors occur only 0.2%–1% of the time. It appears that the slope deployment produced fewer (~50% less) large errors than the shelf deployment, although there is no notable overall performance difference (see RMS of the differences, Fig. 8).

4. Conclusions

Results of the 2008–09 intercomparison of nine current meters from two moorings demonstrate very good performance from newer Doppler point instruments as well as from older current meter technologies. The RMS of speed differences ranged between 1.0 and 1.6 cm s^{-1} for all compared instrument pairs. The best agreement was between a Seaguard from the shelf mooring and the DVS (1.2 cm s^{-1}), and between a Seaguard and a RCM11 (1.0 cm s^{-1}) on the slope mooring. Overall, it was found that inconsistencies larger than 4 cm s^{-1}

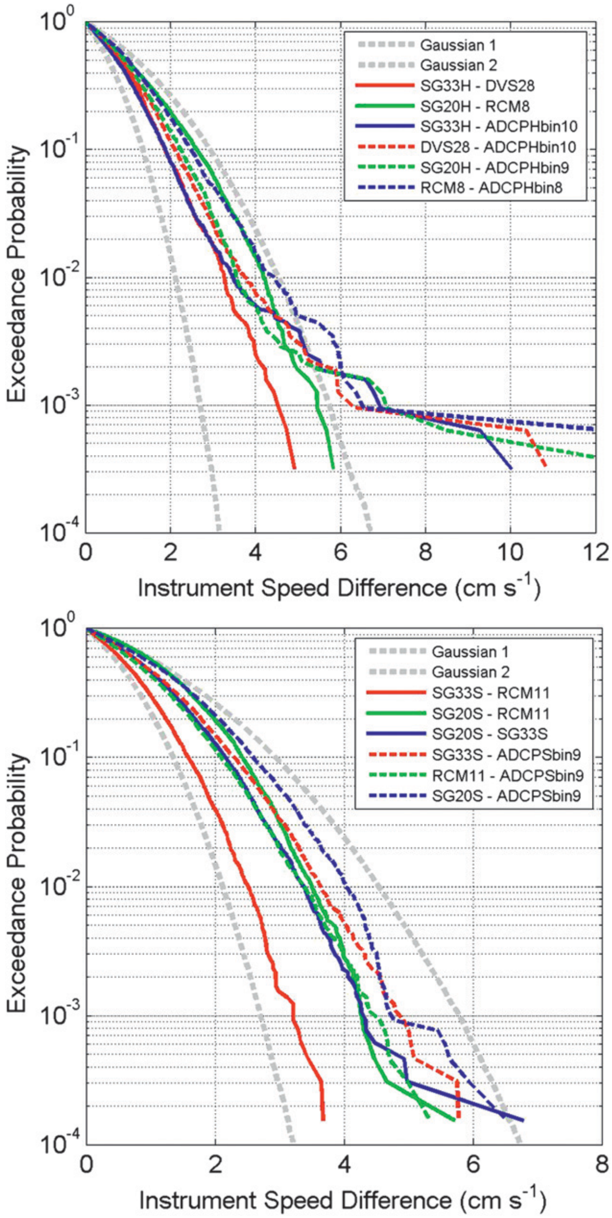

FIG. 12. Exceedance probabilities for pair absolute differences for (top) shelf and (bottom) slope deployment (Gaussian1: mean = 0.2, STD = 0.8 cm s^{-1}; Gaussian2: mean = 0.8, STD = 1.6 cm s^{-1}).

between instrument speeds are uncommon, occurring less than 1.5% of the time. Moreover, the speed difference distributions are generally consistent with the Gaussian distribution. This is encouraging, given the wide variety of instrument technologies used in this intercomparison, and is critical for oceanographers attempting to integrate historical datasets with modern ones.

There was no evidence of RCM11 significantly underspeeding, as reported by Hogg and Frye (2007). Current statistics such as mean, maximum, minimum, and standard deviation for this instrument were within the range of the other instruments. Moreover, the RMS speed difference of this instrument with one of the Seaguards was the lowest of all the studied pairs (as reported above). It should be noted, however, that the RCM11 comparison presented here is from a single deployment and includes only validations with other acoustic current meters. Hogg and Frye (2007) base their findings on extensive testing with mechanical instruments VMCM and VACM, which they consider their long-standing benchmark current meters. The equivalent for us (BIO) is the RCM8. Unfortunately, we were not able to carry out a RCM8-versus-RCM11 intercomparison on the shelf mooring because of technical reasons. However, two sets of earlier intercomparisons (see Drozdowski et al. 2010) between the RCM8 and RCM11 reveal high agreement (speed correlations above 0.98).

A few notable performance issues are discussed below. The DVS reported a 15% lower mean magnitude compared to the nearby Seaguard and ADCP bin. Despite the underestimation of the mean, the standard deviation and other statistics of the DVS velocity were not different from the rest of the group. In addition, as noted above the RMS speed difference of this instrument with the Seaguard was the best for the deployment. The conclusion was that it was connected to the compass meandering slightly, routinely disagreeing with other instruments by as much as 15° for several hours at a time. The disagreement was random in direction and hence there is no bias in the mean direction for this instrument. Subsequent to this deployment, Teledyne RDI redesigned the DVS and replaced the compass with a new sensor.

Another issue with the DVS was that pairs involving this instrument showed a slight tendency for more disagreement at higher speeds. In fact, the top 25% of speed differences occurred when DVS speeds were on average 3 cm s^{-1} (or ~30%) higher than for the bottom 25%. This is not a large discrepancy in itself, but if combined with the meandering compass (as noted above) could amplify the consequences of the latter.

It was found that one of the Seaguards from slope deployment had a speed distribution that was slightly skewed toward higher speeds. The mean and standard deviation of the speed for this instrument was the highest, 6% higher for mean and 12% higher for the standard deviation compared to the average of the remaining three instruments. Moreover, pairs involving this instrument showed a slight tendency for more disagreement at higher speeds; the top 25% of speed differences occurred when Seaguard speeds were on average 2 cm s^{-1} (or ~25%) higher than for the bottom

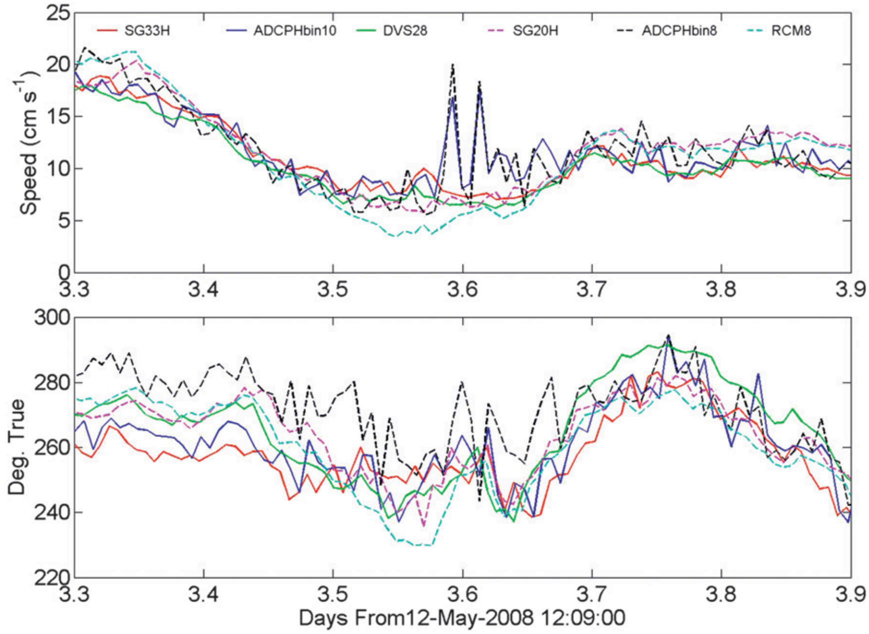

FIG. 13. Example of occasional large ADCP error in shelf deployment: (top) speed and (bottom) direction.

25%. However, the magnitude and direction of the mean flow for this instrument is consistent with the other instruments, indicating the overspeeding cancels out when long-term vector averaging is used. The conclusion was that the issue is related to this Seaguard having had the Zpulse sensor intentionally turned off as a part of the experiment. This finding also suggests that increasing the ping rate (this Seaguard was set up with a ping rate 3 times higher than the other Seaguard on this mooring) does not compensate the loss of performance from turning off the Zpulse. This is a positive finding, which suggests that using the Zpulse technology leads to better data quality and less power consumption.

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