Measuring currents in demanding environments with a Seaguard® RCM

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Abstract*— As a result of joint efforts spearheaded by leading oceanographic institutions, several Seaguard® current meters have participated in a number of inter comparison studies in different parts of the world, covering areas from coastal shallow waters to deep ocean basins. From all these deployments, datasets of high quality have been obtained, despite the environmental conditions being sometimes far from ideal. The ability of the SEAGUARD® current meters (Aanderaa Data Instruments) using ZPulse™ technology to collect high quality data under difficult dynamic conditions (high tilts and mooring line vibration/rotations) as well as different backscatter levels will be discussed and illustrated with data from these deployments.

Keywords- Doppler current sensor, current meter comparison; ZPulse technolog, Seaguard Current Meter

I. Introduction

AADI's Seaguard® platform is an advanced observatory for environmental measurements able to support up to 20 sensors using its AiCaP communication protocol. The plug-and-play flexibility of the platform allows the user to configure the instrument according to the particular needs of the mission. One of the most important applications of the platform is as a single-point current meter, when furnished with a ZPulse™ Doppler Current Sensor.

The theory behind the ZPulse™ technology is explained in Jacobsen et al. (2008). In a nutshell, it combines several frequencies into one single acoustic pulse in order to reduce the statistical noise of the measurement. This may be accomplished if the following conditions are met:

1- The spacing between adjacent frequencies must be wide enough to allow for a Doppler shift that won't encroach into the neighboring frequencies.

2- At the same time this spacing should be small enough so the resulting pulse stays within the bandwidth of the transducer.

3- The phase ambiguity of each frequency component, when embedded in one single ping, should stay uncorrelated.

This was accomplished and incorporated into the ZPulse™ Doppler current sensor available for the Seaguard RCM.

The ZPulse™ sensor has two transducers on each orthogonal axis X and Y. Two out of the four transducers ping simultaneously, one in each axis.

The sampling strategy on the sensor is highly customizable. The user has the option of using (or not) a tilt compensation algorithm. Tilt and heading corrections (if activated) are applied to the measured vectors at a rate of 1 Hz.

The ZPulse™ sensor pings horizontally. The sampling cell may start between 0.4m and 1m away from the transducer and the cell size may range between 0.75m and 2.5m. The acoustic beam is 2° wide.

The forward pinging algorithm, introduced with the RCM-9 and RCM-11, our previous generation of current meters, is also available and allows using information from only those transducers facing the upstream direction of the flow, thus avoiding measuring in the wake of the instrument or the mooring line.

While the multi frequency feature of the sensor is definitely the sensor's recommended operation mode, it is also optional, which means the user has the option of including just one frequency in the acoustic pulse. This option was left for the sake of comparison, since the single frequency regime one does not bring any practical advantage.

The main advantage of the ZPulse™ technology is the reduction of the statistical noise by a factor of $\sqrt{n}$, where n is the number of frequencies combined into the pulse. This can be used either to prolong the deployment time while preserving the data quality or to increase the data quality while preserving the deployment time, or a combination of both. So far the sensors are being built with a dual frequency capability.

AADI has actively participated in multiple comparison studies since the introduction of the sensor as part of our efforts to evaluate its performance and acquaint our customers with our new technology.

Four test deployments have been selected for discussion in this document. They cover a wide range of mooring designs and environmental conditions; from shallow waters with abundance of scatterers to deep areas with relatively clean background to highly dynamic current regimes with high levels of vibration and tilt.

II. DISCUSSION

A. Shallow mooring on the Scotian Shelf

A comparison mooring was deployed by Canada's Bedford Institute of Oceanography on May 8th, 2008 at a Scotian Shelf location with coordinates 44° 17.53'N; 63° 16.04'W. This mooring offered the opportunity to evaluate the instrument's performance on a relatively short mooring line (~ 100m) in an environment with abundant scatterers as shown by the signal strength record of the instruments (~ -35dB).

The site depth was around 155m. The instruments' depths and configuration options are shown in Table I. This comparison mooring included two Aanderaa Seaguards, one RDI Doppler Volume Sampler, one Aanderaa RCM-11 and one Aanderaa RCM8 (mechanical instrument with paddle-wheel rotor). Additionally, an RDI 300 KHz ADCP was placed under the single-point meters looking up, so each single-point instrument was in the immediate proximity of an ADCP acoustic bin.

Drozdowski at al. (2008) arrived to the conclusion that, in this mooring, the vertical shear of the currents was a significant source of variability in the flow. Therefore, for the purpose of their analysis, the authors divided the instruments in two groups according to their vertical position. The instruments compared in Group I were:

- Seaguard SN 33 at 63m – DVS SN 8928 at 66m
- DVS SN 8928 at 66m – ADCP 66m bin
- Seaguard SN 33 at 63m – ADCP 63m bin
- ADCP 63m bin – ADCP 66m bin

The analysis of Group II included the comparison of the following time series pairs:

- Seaguard SN 20 at 72m – Aanderaa RCM8 at 74m
- Aanderaa RCM8 at 74m – ADCP 74m bin
- Seaguard SN 20 at 72m – ADCP 72m bin
- ADCP 72m bin – ADCP 74m bin

The ADCP to ADCP pairs involve a comparison of adjacent bins, included to estimate the magnitude of an eventual vertical shear within each group.

Table II shows a statistical summary of the time series collected by the instruments in the two groups. The spread of the average speeds was 10 % of the maximum averages for group I and 10.1% for Group II. In the case of current directions, the average values ranged within 235° and 241°, however, all instruments showed high directional differences at low speeds (< 10 cm/sec), with the Aanderaa RCM8 standing out in this category.

The scatter plots for speed and direction and best fit lines for the two groups are shown in Fig. 1. Even though there were small differences between pairs, the agreement within each group is reasonably good.

TABLE I. INSTRUMENT CONFIGURATION ON THE SHORT MOORING ON THE SCOTIAN SHELF

	SG33	RDI DVS	RCM11 (*)	SG20	RCM8	ADCP
INTERVAL (min)	10	10	10	10	10	10
DEPTH (m)	63	66	67	72	74	112
MODE	Burst	Burst	Burst	Spread	Spread	Burst
TILT COMP.	Yes	N/A	Yes	Yes	N/A	?
ZPulse	Yes	N/A	N/A	Yes	N/A	N/A
FWRD. PING	Yes	N/A	Yes	Yes	N/A	N/A
PING COUNT	300	280	600	300	N/A	80

(*) The data from the RCM11 was unusable due to compass problems

The regression statistics for the pairs of datasets (Table III) show that the correlation between them was always above 0.9. The best agreement (0.99) was found between the Seaguard at 63m and the DVS at 66m. The lowest correlation was found between the RCM8 and the corresponding ADCP bin for both speed and direction. This difference may be explained by the different principles of operation employed by the two instruments.

In short, all the instruments are considered to have adequately measured the variability of the currents in the environment. The presence of vertical gradients in the current structure somewhat impeded a completely accurate comparison of the instruments' performance. However the consequential effect is expected to be rather small, therefore resulting in the aforementioned statement to remain valid.

B. Deep mooring on the Scotian Slope

This mooring was deployed on October 3rd, 2008, also by the Bedford Institute of Oceanography, at a location with coordinates 42° 44.34'N; 61° 34.50'W, on the upper Scotian Slope. The depth of the ocean floor in the area was 1,700m.

In this case a Seaguard (SN 33) was placed at 1,589m, an Aanderaa RCM11 at 1,596m and a second Seaguard (SN 20) at 1,598m. At a depth of 1,650m an RDI 300KHz Workhorse ADCP was deployed looking up.

During the analysis of this data it was found that the speeds for those ADCP bins matching the depths of the single point current meters showed conspicuously lower than expected average current speeds. At the moment of this writing the nature of this phenomenon has not been fully investigated and therefore this document will not refer to the ADCP data. Instead, the data sets from the single point meters will be evaluated against each other. Given the intermediate location of the RCM11, its data will be compared to those from both Seaguard meters.

Tables IV and V show the configuration settings used by the instruments and the statistical summary for the collected data, respectively.

TABLE II. STATISTICAL SUMMARY OF CURRENT SPEED AND DIRECTION FOR THE SHALLOW MOORING ON THE SCOTIAN SHELF

	SG 33@ 63M	ADCP @ 63M	DVS @ 66M	ADCP @ 66M	SG 20 @ 72M	ADCP @ 72M	RCM8 @ 74M	ADCP @ 74M
	Group I				Group II			
MEAN SPEED (cm/sec)	12.69	12.34	11.10	11.99	12.74	11.58	11.94	11.45
MIN SPEED (cm/sec)	0.43	0.45	0.20	0.24	0.22	0.39	1.10	0.25
MAX SPEED (cm/sec)	36.44	35.29	35.70	34.94	38.86	38.56	39.46	40.19
SPEED STD (cm/sec)	6.7	6.74	6.18	6.72	6.31	6.23	6.65	6.14
MEAN DIR (deg)	238.49	237.09	240.61	237.58	237.99	237.30	235.04	238.92
DIR STD (deg)	70.93	59.84	70.81	64.23	71.79	63.53	68.55	66.15
SPstd (cm/sec)	3.46	N/A	N/A	N/A	3.45	N/A	N/A	N/A
SIGNAL STRENGTH (dB)	-35.82	N/A	N/A	N/A	-35.68	N/A	N/A	N/A

TABLE III. REGRESSION STATISTICS FOR THE INSTRUMENT PAIRS ON THE SHALLOW MOORING ON THE SCOTIAN SHELF (FROM DROZDOWSKI ET AL, 2008)

PAIR	SLOPE	Y INTRCPT.	CORR.	RMS
GROUP I SPEED				
SG33-DVS28	1.005	0.756	0.990	1.2
ADCP66m-DVS28	1.028	0.269	0.984	1.3
SG33-ADCP63m	0.924	0.961	0.975	1.5
ADCP63M-ADCP66M	1.002	0.152	0.977	1.4
GROUP I DIRECTION				
SG33-DVS28	0.931	16.189	0.976	13.7
ADCP66m-DVS28	0.952	9.446	0.969	15.3
SG33-ADCP63m	0.965	11.089	0.966	17.0
ADCP63M-ADCP66M	0.992	0.859	0.980	13.2
GROUP II SPEED				
SG20-RCM8	0.931	1.452	0.974	1.6
ADCP74M-RCM8	0.916	0.720	0.967	1.6
SG20-ADCP72M	0.972	1.177	0.972	1.6
ADCP72M-ADCP74M	0.996	0.093	0.987	1.0
GROUP II DIRECTION				
SG20-RCM8	1.005	4.236	0.975	15.1
ADCP74M-RCM8	1.058	-7.680	0.962	19.6
SG20-ADCP72M	0.969	7.036	0.977	14.2
ADCP72M-ADCP74M	0.986	2.441	0.991	9.1

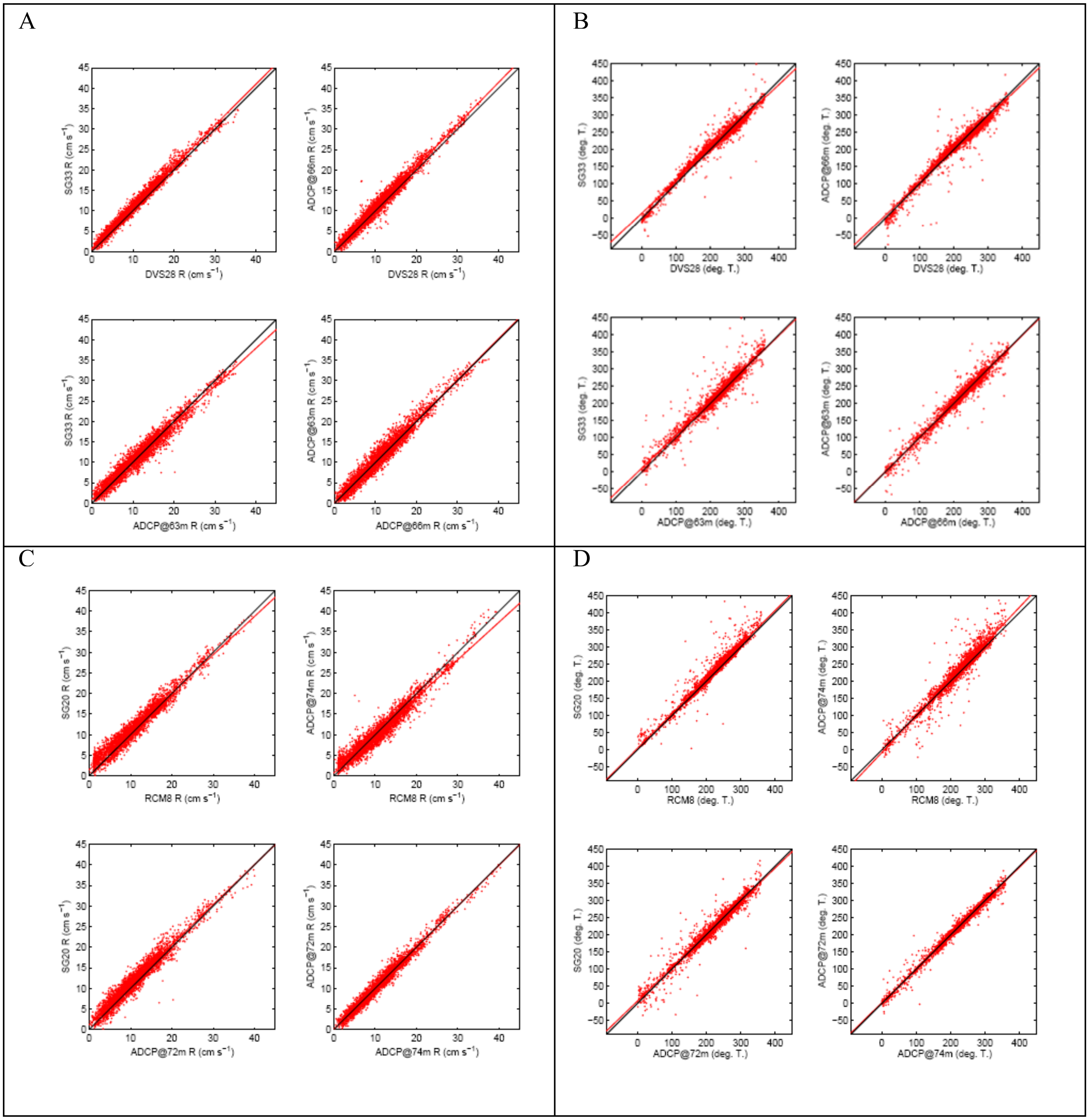

Figure 1. Scatter plots of speeds and directions for the shallow mooring on the Scotian Shelf
(from Drozdowski et al., 2008)
A scatter speed analysis for group I
B scatter direction analysis for group I
C scatter speed analysis for group II
D scatter direction analysis for group II

TABLE IV. INSTRUMENT CONFIGURATION ON THE DEEP MOORING ON THE SCOTIAN SLOPE

	SG33	RCM11	SG20
INTERVAL (min)	60 min	60 min	60 min
DEPTH (m)	1,589	1,596	1,598
MODE	Spread	Spread	Spread
TILT COMP.	Yes	Yes	Yes
ZPulse	Yes	N/A	NO
FWRD PING	Yes	Yes	Yes
PING COUNT	100	600	300

TABLE V. STATISTICAL SUMMARY OF CURRENT SPEED AND DIRECTION FOR THE DEEP MOORING ON THE SCOTIAN SLOPE

	SG 33@ 1589m	RCM11@ 1596m	SG 20@ 1598m
MEAN SPEED (cm/sec)	7.67	7.23	8.29
MIN SPEED (cm/sec)	0.04	0.00	0.03
MAX SPEED (cm/sec)	25.99	25.22	26.04
SPEED STD (cm/sec)	4.10	4.13	4.31
MEAN DIR (deg)	251.25	245.13	246.01
DIR STD (deg)	92.12	89.87	90.21
SP std (cm/sec)	2.74	N/A	4.16
SIGNAL STRENGTH (dB)	-52.45	N/A	-53.18

Speed correlation between the two pairs of instruments was 0.98 for SG33-RCM11 and 0.97 for SG20-RCM11, with relatively good fits to the linear regression equation (Table VI). Direction correlation was around 0.97 for both pairs. Fig. 2 shows the scatter plots of current speed and direction for the corresponding instrument pairs.

The second to last row in Table V is the average Single Ping Standard Deviation (SPstd), a measure of the statistical noise of the data, recorded by the Seaguards, and defined in a ZPulse™ sensor as the standard deviation of all speed measurements (pings) within an ensemble.

With the goal to evaluate the potential benefit of the new technology, SG33 was configured to use 100 pings per measurement and the dual (ZPulse™) frequency activated. SG20, in contrast, was setup with 300 pings per record and used only one frequency (ZPulse™ off). Table V shows that while working with one third of the pings, SG33 was able to collect data with a significantly lower statistical noise compared to SG20, due to the fact that the former took advantage of the dual frequency technology. Besides, SG20 shows mean speeds that are close to 10% higher than its closest counterpart. In this case SG20 is most likely over estimating the speeds due to being close to its sensitivity limit in a low scatter environment and working in single frequency mode. SG33 on the other hand, performed flawlessly while using one third of the power.

C. *Buoy suspended mooring in the Equatorial Atlantic*

A Seaguard RCM was installed by NOAA's Pacific Marine Environmental Laboratory staff on PIRATA mooring PM784 at a location with coordinates 11.5°N; 23°W between October 23, 2008 and July 24, 2009. The ocean depth at this location was 5,119m.

The Seaguard was deployed at an effective depth of 7.5m.

Below the Seaguard, a Sontek Argonaut was deployed at 12m. The Argonaut was deployed looking upward but the vertical distance between the two instruments allowed for no overlapping of the sampling volumes. The effective depth of the Sontek was 10m.

The PIRATA mooring uses a real time data transfer solution, which requires a continuous cable between the surface and the deepest instrument, to allow for the use of inductive modems. In order to comply with this requirement, the Seaguard RCM was attached to the wire with *ad hoc* clamps rather than using the standard Aanderaa solution that would require terminating the mooring cable above and below the instrument.

The heading record of the Seaguard shows a rather noisy picture (Fig. 3). So does the tilt (not shown). The firmware on the Seaguard at the moment of this experiment outputted among its quality assurance parameters, the last tilt and headings values of each sampling interval (the latest firmware version offers additional statistics). This certainly contributed to the noisy look of the data. Since the mooring was suspended from a surface float subjected to the action of wind and waves, in our opinion, a good part of this high frequency heading variability may be caused by the effect of wind and waves on the surface buoy, which in turn, propagated down the mooring line.

TABLE VI. REGRESSION STATISTICS FOR THE INSTRUMENT PAIRS ON THE ON THE DEEP MOORING ON THE SCOTIAN SLOPE

PAIR	SLOPE	Y INTRCPT.	CORR.	RMS
SPEED				
SG33-RCM11	0.970	0.655	0.980	1.0
SG20-RCM11	1.011	0.981	0.970	1.5
DIRECTION				
SG33-RCM11	0.989	0.838	0.973	18.5
SG20-RCM11	1.004	-7.656	0.966	22.1

In this case the solid state tilt/heading sensor in the sensor, combined with the heading/tilt compensation algorithms embedded in the digital signal processor does a reasonably good job of filtering out all the undesirable mooring vibrations and inclinations. The result is a smooth data set that compares reasonably well with the data from the instrument near by.

The Seaguard worked for the entire length of the deployment (October 23, 2008 – July 24, 2009). The configuration settings are in Table VII. The Argonaut worked until January 12, 2009. The difference in dataset durations hindered to some extent the comparison of the two instruments. However some preliminary estimated have been done based on the less than three months of concurrent data.

This Seaguard had been preconfigured with a fixed sound speed value of 1,500m/sec. Upon recovery of the instruments it was found that the actual speed of sound had an average value of 1,545cm/sec. The speed data from the Seaguard was post processed to account for this difference.

Table VIII contains the statistical summary for the two datasets. The mean speeds for the two instruments, based on the 20-minute data differed by 0.98 cm/sec and directions by 3°, although the measured currents were relatively low.

TABLE VII. INSTRUMENT CONFIGURATION ON THE PIRATA MOORING

	SG56	Sontek
INTERVAL (min)	20 min	20 min
DEPTH (m)	7.5	10
MODE	1min burst	2min burst
TILT COMP.	Yes	Yes
ZPulse	Yes	N/A
FWRD PING	Yes	N/A
PING COUNT	300	120

TABLE VIII. STATISTICAL SUMMARY OF CURRENT SPEED AND DIRECTION FOR THE PIRATA MOORING

	SG 56@ 7.5m	Sontek@ 10m
MEAN SPEED (cm/sec)	18.25	19.23
MIN SPEED (cm/sec)	0.31	0.10
MAX SPEED (cm/sec)	58.44	60.70
SPEED STD (cm/sec)	10.02	10.37
MEAN DIR (deg)	311.11	308.12
DIR STD (deg)	111.35	112.98
SP std (cm/sec)	31.17	N/A
SIGNAL STRENGTH (dB)	-38.51	N/A

Linear regressions obtained by Freitag et al. (unpublished, Table IX) suggest that the magnitude of the speed difference would be larger for higher speeds. The 20-minute data shows a correlation between the two datasets of 0.75 for speed and 0.91 for direction. However these numbers increase to 0.99, respectively, if daily averages are considered, which is consistent with the likelihood of high frequency pulsations in the flow, probably wind driven, which would be filtered out as a result of the averaging process. Fig. 4 shows the scatter plots for the 20-minute and the daily average data.

D. Short mooring in a highly tidal flow

Seaguard RCM SN 235 was deployed from June 25th to July 23rd, 2009 in the Dollart Bay, near the mouth of the Ems River in northern Germany. This deployment was part of an instrument inter-comparison study carried out by a customer prior to implementing a multi platform observation network in the lower parts of Ems and Elbe rivers, serving for navigational safety and environmental monitoring. The study aimed at exploring the ability of the instrument to perform under different challenging conditions, as well as comparing its performance with that of other instruments.

After the study was finished, only the data from the Aanderaa Seaguard was made available to us, therefore a comparison with other instruments is not included in this document. This section will instead deal with the response of the current meter to environmental scenarios, in particular an intense tidal regime which caused significant tilts of the mooring line.

The mooring consisted of a dead weight, a 1m chain to the instrument and then a ~2.5m wire rope to a relatively large subsurface float, which served as a drag element. The depth, as registered by the pressure sensor on the meter varied between 5 and 10m. This variability includes both real sea level changes and vertical movements of the instrument up and down the water column as the mooring is dragged by the currents. The configuration options are shown in Table X.

As stated above, the principal feature of the current record was a strong tidal signal. A preliminary harmonic analysis of the series showed that the predominant tidal constituent is the lunar semidiurnal constituent M_2, whose ellipse had a major axis over 400 times larger than its minor axis and was almost 5 times larger than major ellipse of the second most important constituent, namely N_2.

TABLE IX. REGRESSION STATISTICS FOR THE THE PIRATA MOORING

	SLOPE	Y INTRCPT.	CORR.	RMS
20 MINUTE DATA				
SPEED	0.96	-0.10	0.749	7.3
DIRECTION	1.05	-12.25	0.913	47.0
DAILY AVERAGED DATA				
SPEED	0.96	-0.02	0.987	1.4
DIRECTION	1.05	-12.33	0.993	14.2

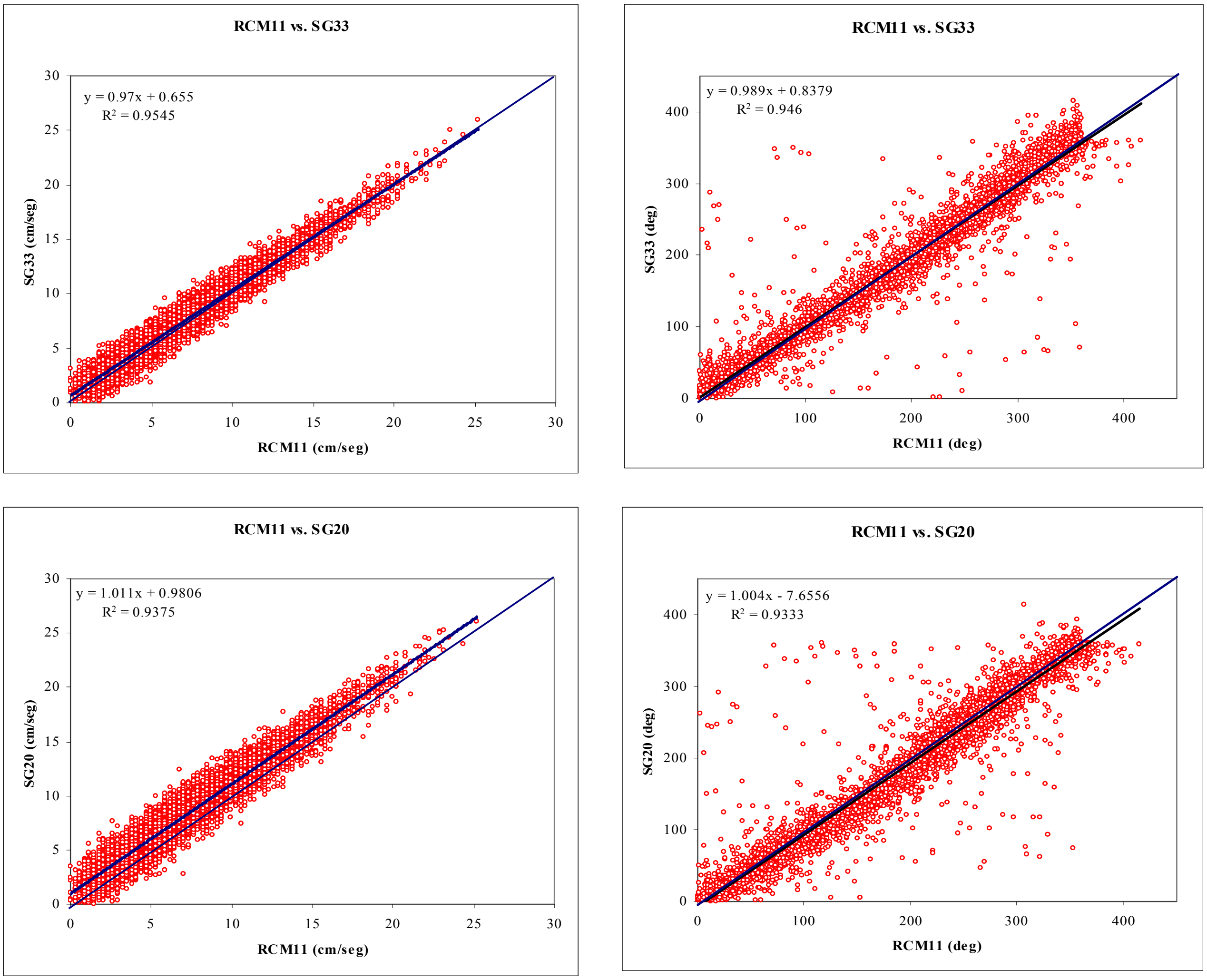

Figure 2. Scatter plots of current speed (left) and direction (right) for the upper (up) and lower (down) current meter pairs on the deep mooring on the Scotian Slope.

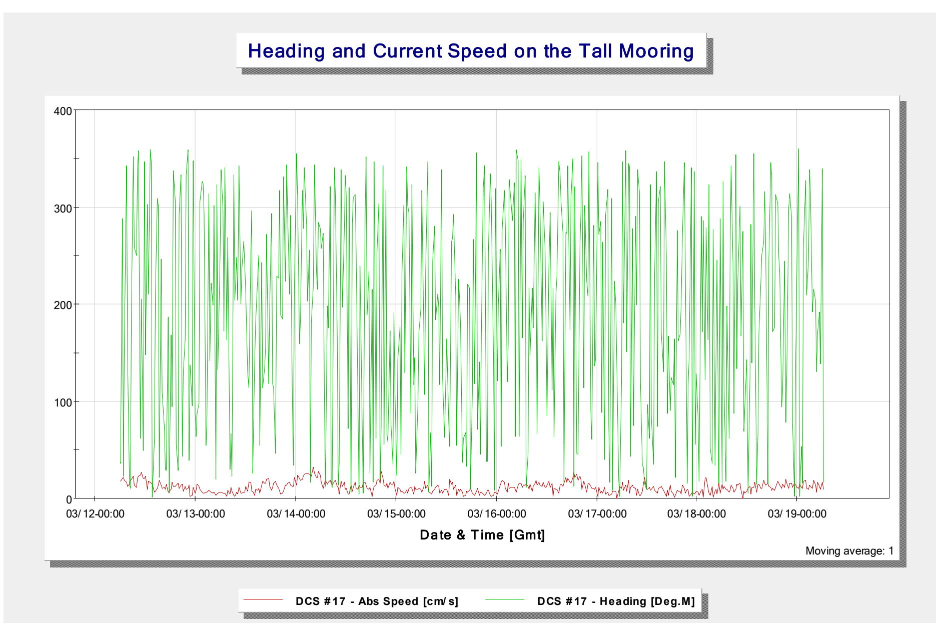

Figure 3. Arbitrary subset of the current speed and heading record from the PIRATA mooring

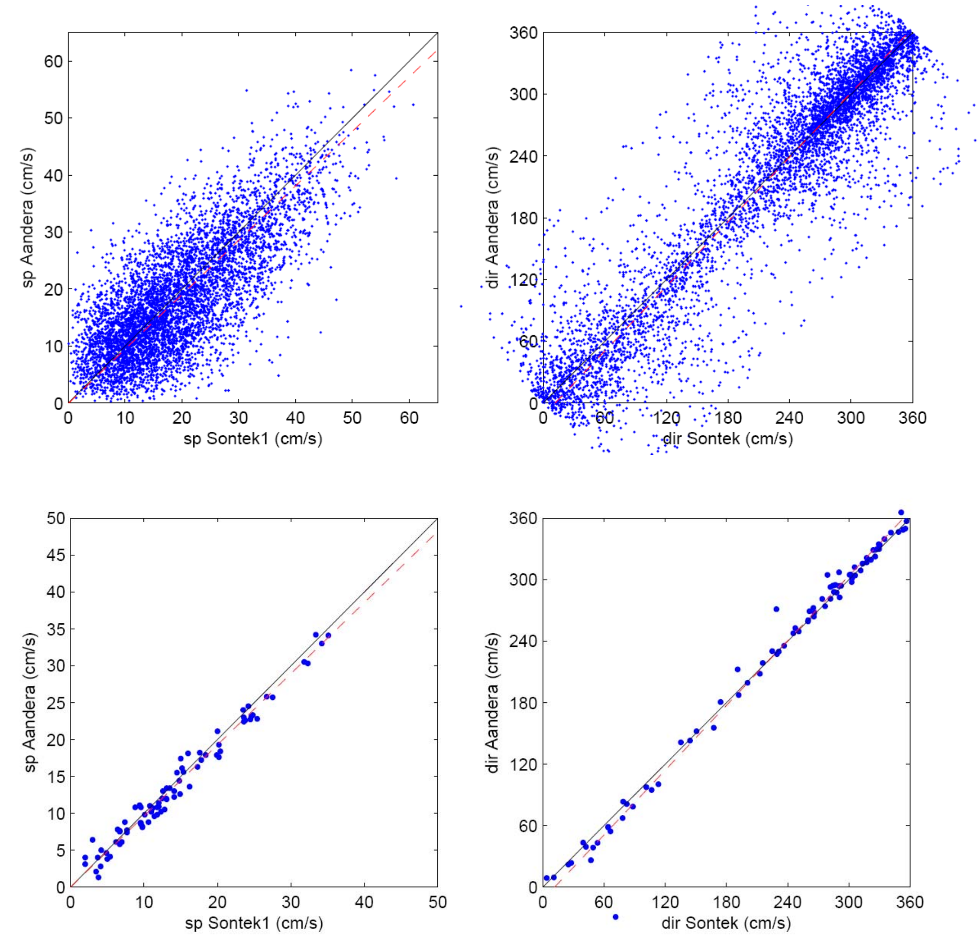

Figure 4. Scatter plots of current speeds and directions for the 20-minute (up) and daily averaged data from the PIRATA mooring. From Freitag et al. (unpublished)

Overall, tides accounted for over 90% of the current variability.

The design of the mooring combined with this strongly tidal current regime, resulted in the array tilting in alternating directions as currents cycled over the tidal periods.

Currents speeds were above 80cm/sec and absolute tilts exceeded 30° in every tidal cycle. Tilt reached its maximum value of 51.7° on July 11th. Figure 5 shows a segment of the current speed and absolute tilt record centered on the maximum tilt episode. It can be observed that the current speeds recorded by the instrument do not seem to be affected by the extreme inclination of the instrument.

In lieu of a better way to evaluate the quality of the data recorded by the Seaguard, the single ping standard deviation (SPstd) was assessed against the tilt record. Fig. 6 shows that as the instrument's tilt increases, the data collected becomes noisier. Eventually, as the regression curve indicates, the statistical uncertainty would be too large and the data would be of no value. However within the confines of the observed values, the instrument remained delivering good data. The SPstd stayed below 15cm/sec while the highest speeds, concurring with the largest tilt events, surpassed 100cm/sec.

III. SUMMARY

The Aanderaa ZPulse™, a new generation of Doppler current sensor, has proved to be a reliable instrument even in very difficult conditions. The current speed and direction time series collected during these test moorings has, at least, similar quality to that from other instruments.

The dual frequency mode available for the sensor allows for clean, accurate data in environments with low levels of scatterers, as the information available to the DSP to estimate the correct Doppler shift is doubled. This comes with the additional benefit of an extended battery life.

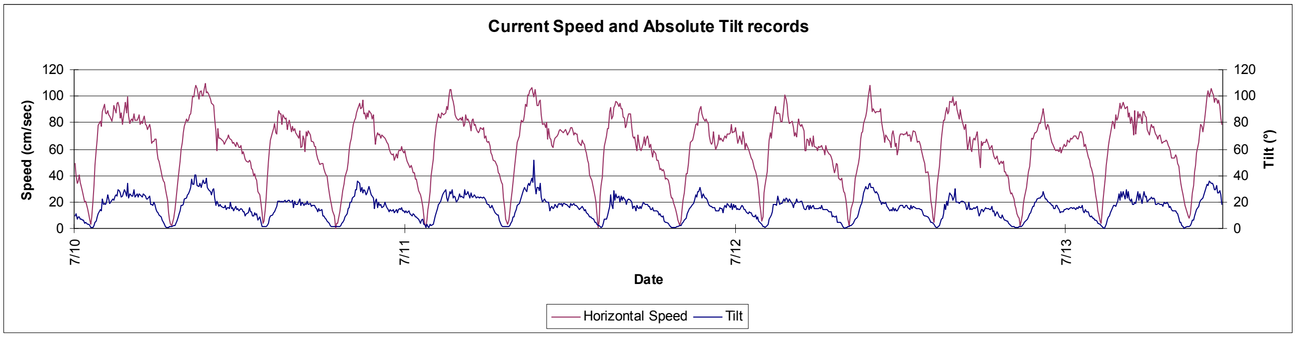

Figure 5. Current speeds and absolute tilts records from the short mooring in the Dollart on and around July 11th, when the maximum tilt was registered

TABLE X INSTRUMENT CONFIGURATION FOR THE MOORING AT THE DOLLART

	SG235
INTERVAL (min)	5 min
DEPTH (m)	5-10
MODE	Spread
TILT COMP.	Yes
ZPulse	Yes
FWRD PING	Yes
PING COUNT	300

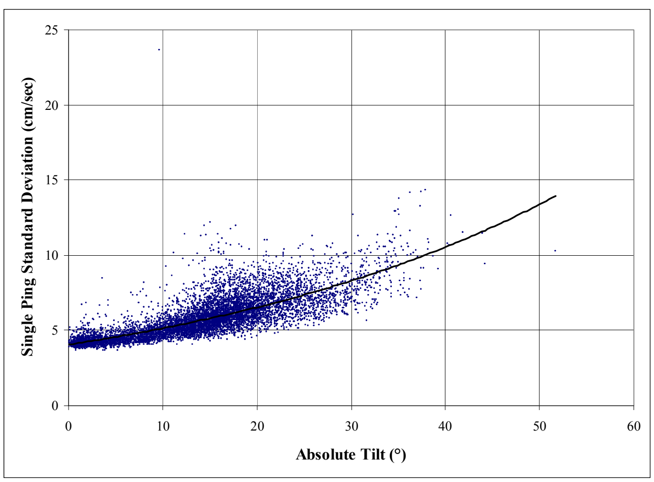

Figure 6. Single ping standard deviation as a function of the absolute tilt in the data from the Dollart deployment

The ZPulse™ Doppler sensor uses onboard compensation techniques, which are able to correctly resolve the current vectors in case of high frequency heading variability and severe mooring inclinations (at least up to 50°), well beyond the instruments stated specifications.

The robust solid-state compass and tilt sensor have proved to be a key element in the collection of clean and correct current data under difficult environmental conditions. The horizontally directed acoustic beams of the Seaguard allow for a significantly larger operational range of tilts due to the practical impossibility for the beams to adopt a vertical position, which would result in a zero Doppler shift from horizontal currents, like may be the case with other Doppler-based instrument with vertically arranged beams.

ACKNOWLEDGMENTS

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