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On behalf of SOFAR Ocean (SOFAR), Integral Consulting Inc. (Integral) conducted a study to compare ocean current measurements from bottom-mounted ADCP and single-point velocity sensor integrated into the Spotter Smart-mooring system. The Integral team successfully deployed the two sensor systems that collected data concurrently for 24 days. This memorandum briefly outlines the field effort to deploy and recover the sensors, a summary of the data collected, and a comparison of measurements.

INSTRUMENT DEPLOYMENT AND RECOVERY

Integral and SOFAR deployed the two sensor packages on April 22nd off the coast of Santa Barbara in a space permitted for use by the University of California Santa Barbara (UCSB). Integral provided an RDI Sentinel Workhorse Acoustic Doppler Current Profiler (ADCP) which was secured to a stable platform and deployed to rest on the seafloor in an upward looking orientation. The instrument measured water column currents in 1-meter intervals every 20 minutes.

SOFAR provided a Spotter Wave Buoy with Smart Mooring system that included an Aanderaa ZPulse Doppler Current Sensor. The Aanderaa sensor was separated from the surface float by approximately 11 meters of smart mooring cable. The smart mooring system allows the ZPulse sensor to provide data in real-time into the SOFAR data dashboard and store 1-minute interval measurements onboard the sensor for download upon buoy retrieval.

The two sensors were successfully recovered with the help of scientific divers from UCSB. During recovery, the dive team attached a pressure sensor to the instrument to get one reading of depth. Pressure data was collected but not used in this analysis due to the workhorse ADCP battery running out of power on May 15th, prior to recovery.

SENSOR DATA PROCESSING AND COMPARISON

The current velocity magnitude and direction data collected by the Aanderaa ZPulse Doppler Current Sensor and the RDI Sentinel Workhorse were prepared for comparison with one another. Measurements from three RDI Workhorse 1-meter intervals, corresponding with 5, 6, and 7 meters from the sea bottom, were averaged for comparison with the Aanderaa ZPulse. These depths correspond with the approximate location of the Aanderaa ZPulse in the water column base on the instrument being 11 meters from the surface in an approximate depth of 17 meters. Specifically, North velocity and East velocity

measurements across the bins were averaged. The magnitude and direction of the resulting velocity vector were calculated from this average. An addition of +12 degrees was made to resulting direction calculations to account for magnetic declination.

The time series window for comparison selected, 20 April 2024 14:00 to 15 May 2024 15:40, was the period both sensors were active. The RDI Workhorse reports a measurement every 20 minutes that is an average of values measured continuously in the 20 minutes prior. The Aanderaa ZPulse reports a measurement every minute. The Aanderaa ZPulse measurements reported at the time closest to that of the RDI Workhorse were averaged with the prior 19 minutes to produce Aanderaa data averages centered at the same time as the RDI Workhorse. The same averaging method was used for the Aanderaa data as was used for the RDI Workhorse bins. The timeseries speed and direction curve smoothing via this averaging is depicted in Figure 1 and Figure 2 for a data day, 26 Apr 2024, with high standard deviation of both speed and direction averages. The 20-minute average curves were ultimately used for comparison with RDI Workhorse measurements.

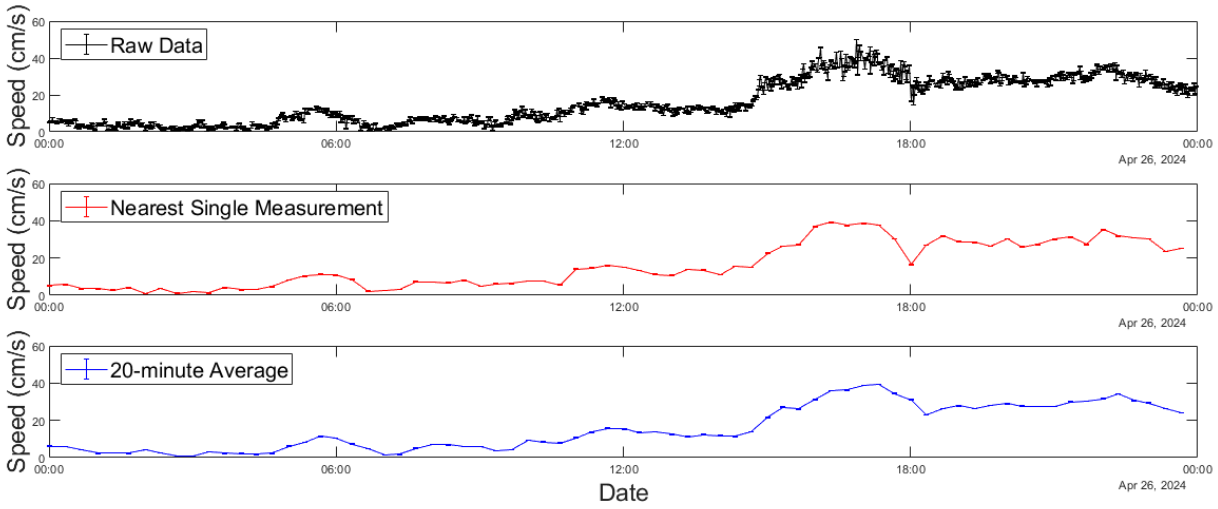

Figure 1. Comparison of raw Aanderaa ZPulse speed measurements with 20-minute sampling and 20-minute averaging on 26 April 2024.

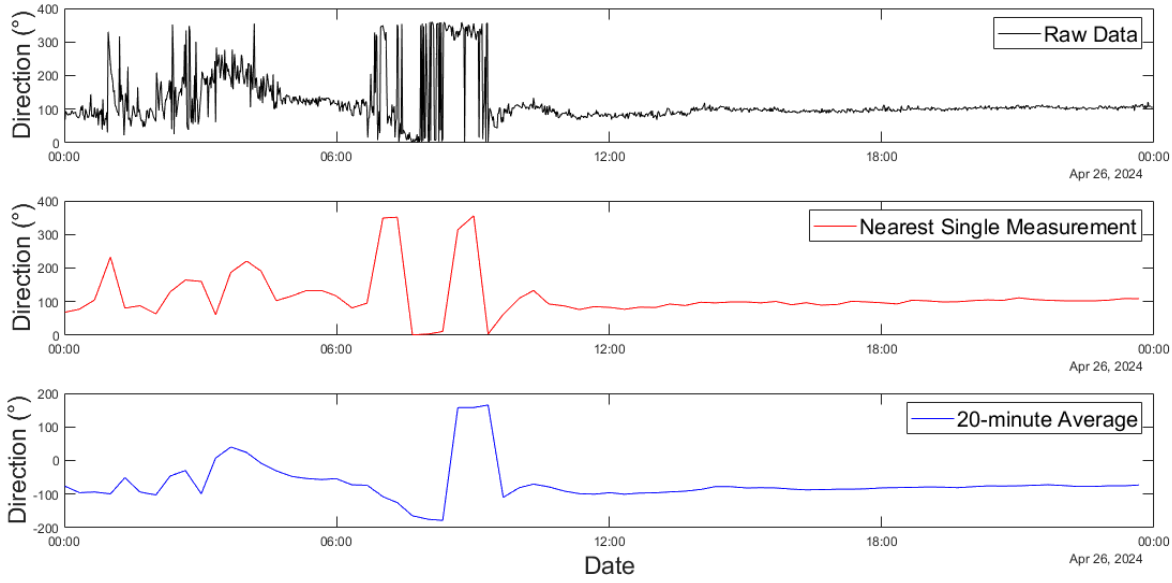

Figure 2. Comparison of raw Aanderaa ZPulse direction measurements with 20-minute sampling and 20-minute averaging on 26 April 2024.

The standard deviation of North and East velocity component measurement averages for both sensors are depicted below. (Figure 3 & Figure 4). North component velocity standard deviation values for both sensors are mostly below 3.5 cm/s. East component velocity standard deviation values are mostly below 6 cm/s.

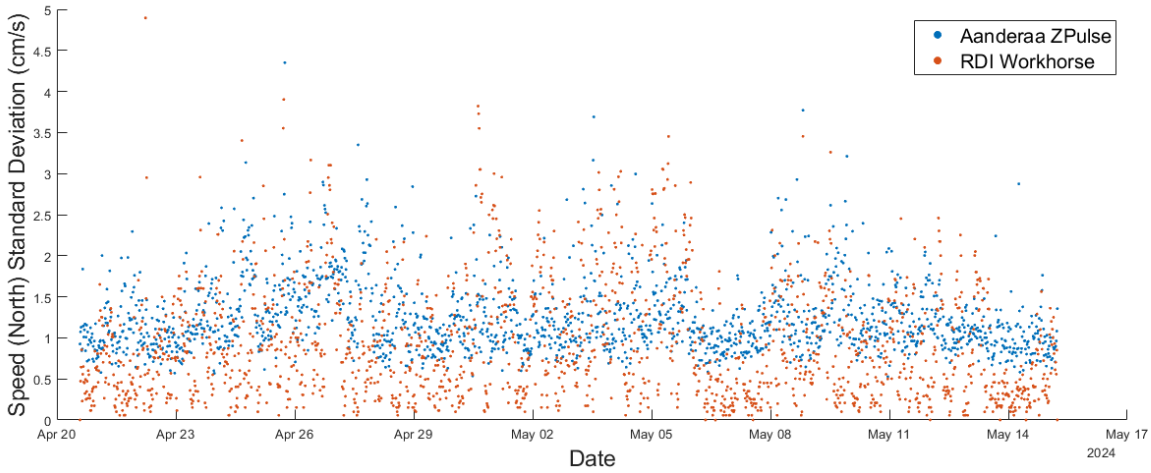

Figure 3. Aanderaa ZPulse Averaged Velocity (North) Standard Deviation (cm/s).

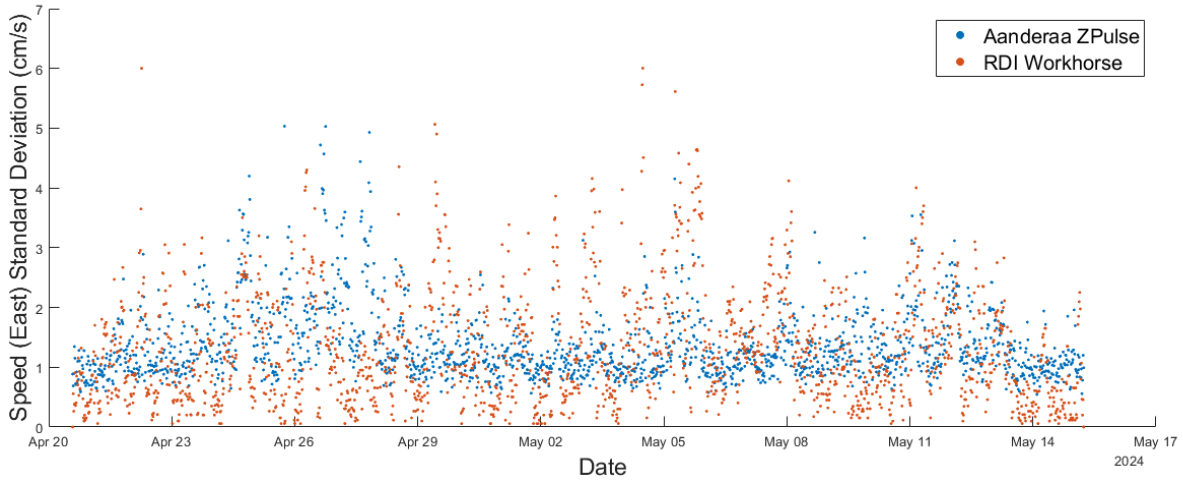

Figure 4. Aanderaa ZPulse averaged velocity (East) standard deviation (cm/s).

The current velocity magnitude and direction measurements made by both sensors were qualitatively compared with one another. Examination of the speed and direction measurements by both sensors across the entire comparison period indicates a reasonable selection of Aanderaa ZPulse measurement averages and RDI Workhorse 1-meter bins (Figure 5). In Figure 6, the same comparison is made, but for only the first week of the selected period. Error bars reflecting the specified velocity measurement accuracy range for each sensor are included as well. This comparison reflects more realistic misalignment between the two sensors' measurements than a viewing of the entire timeseries.

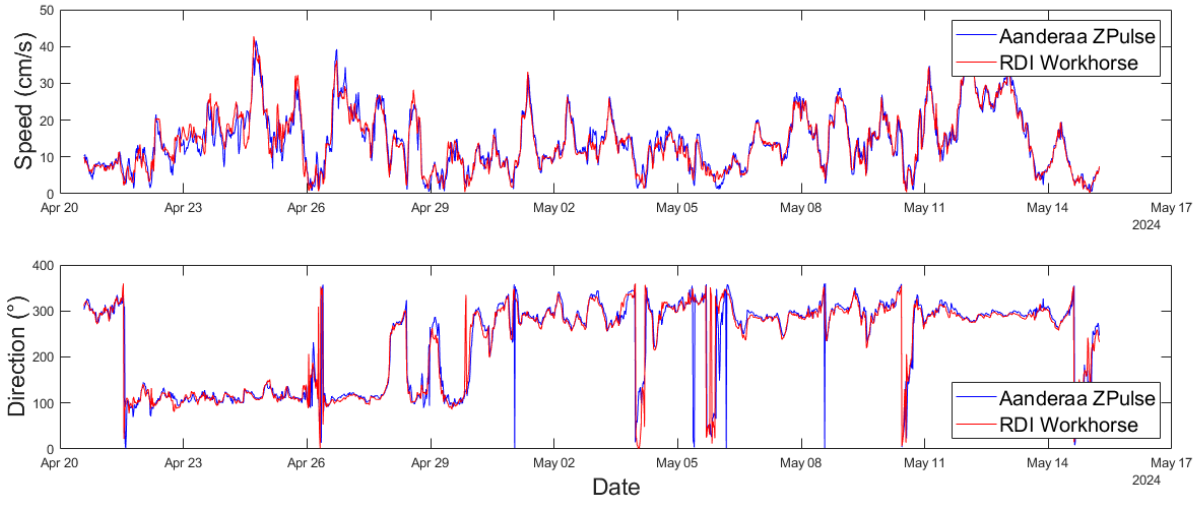

Figure 5. Speed and direction measurements across both sensors for the entire comparison.

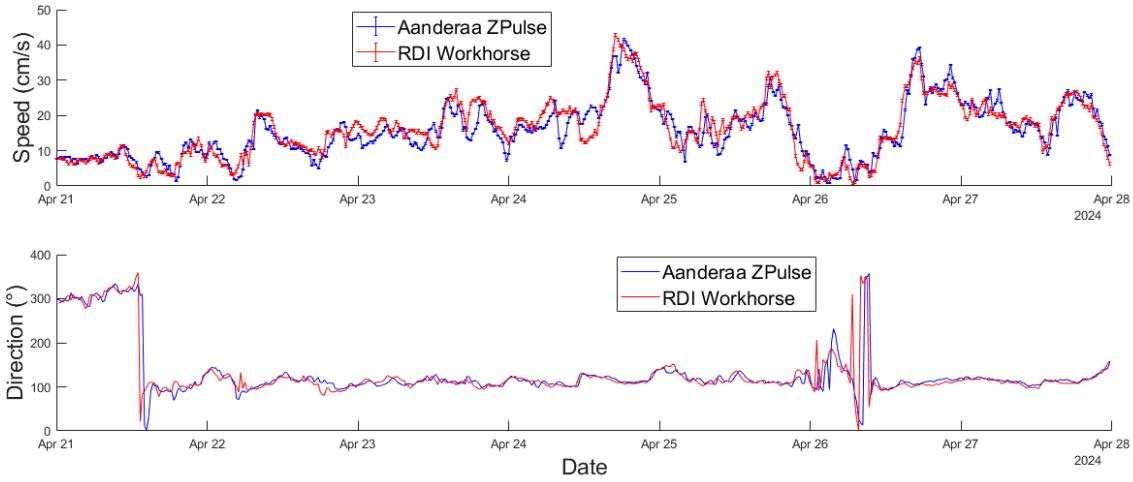

Figure 6. Speed and direction measurements across both sensors for the first week of the comparison period.

To determine how often Aanderaa ZPulse speed measurements fell within the accuracy range of RDI Workhorse speed measurements (+/- 0.3% of the measured speed + 0.3 cm/s) and vice-versa, the difference between these values was compared to the sum of the accuracy range values for each sensor. Speed measurements were in range for 21.06% of observations (Figure 7).

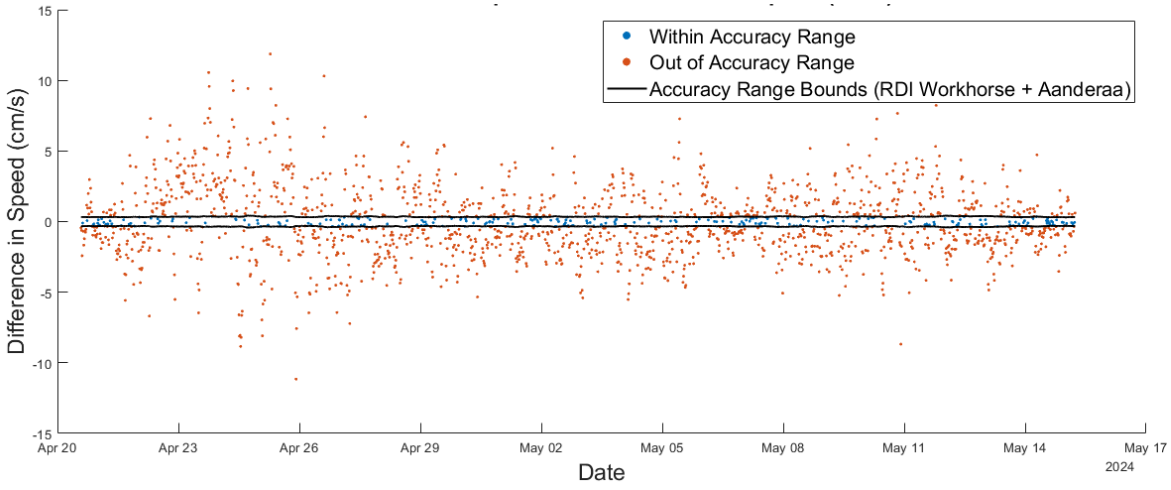

Figure 7. Difference in speed measurements as compared to specified RDI Workhorse accuracy range bounds.

The rose plots below indicate two current velocity directional clusters separated by ~180° and a very similar orientation of these clusters across both sensors.

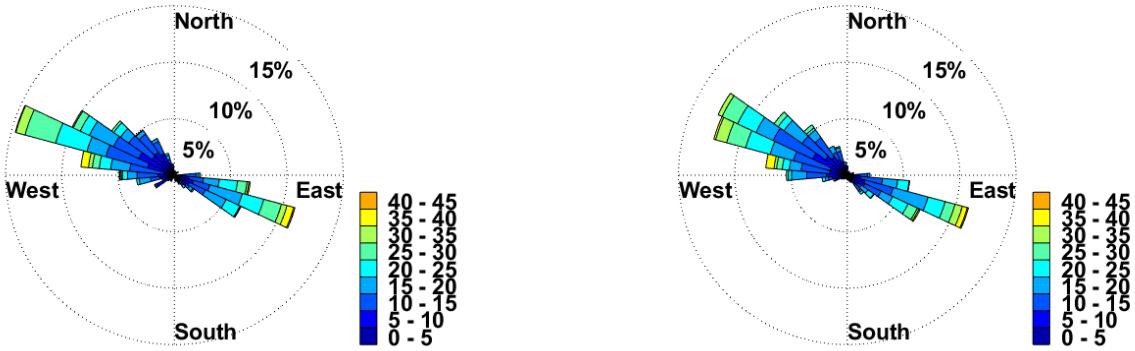

Figure 8. RDI Workhorse (left) and Aanderaa ZPulse (right) current velocity rose plots.

Descriptive statistics were calculated to compare the RDI Sentinel Workhorse and Aanderaa ZPulse current velocity magnitude and direction measurements. Some, including the mean, maximum, minimum, and range of each measurement-sensor combination are summarized in the table below (Table 1). The difference of speed means is 0.049 cm/s. The difference of northern-component velocity means is 0.386 cm/s. The difference of eastern-component velocity means is 0.156 cm/s. The RDI Workhorse reported a greater range of current velocity magnitude and direction measurements.

Table 1. Summarizing statistics of current velocity magnitude and direction across the two sensors.

	Mean	Max	Min	Range	Standard Deviation
Aanderaa Speed (cm/s)	14.212	41.585	0.5304	41.054	7.9494
Aanderaa Speed (North cm/s)	1.1188	17.868	-13.923	31.791	5.072
Aanderaa Speed (East cm/s)	-3.6501	40.97	-39.709	80.679	14.999
Workhorse Speed (cm/s)	14.163	42.753	0.31447	42.439	7.9533
Workhorse Speed (North cm/s)	0.73251	18.333	-14.867	33.2	4.5276
Workhorse Speed (East cm/s)	-3.4939	42.267	-37.333	79.6	15.189
Aanderaa Direction (°)	228.78	359.71	1.7162	357.99	92.72
Workhorse Direction (°)	228.18	359.68	0.76306	358.92	90.727

Box plots of both sensors' speed and direction measurements are shown below (Figure 9). The red line inside of each box represents the median value, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and outliers are plotted as red points outside the whiskers.

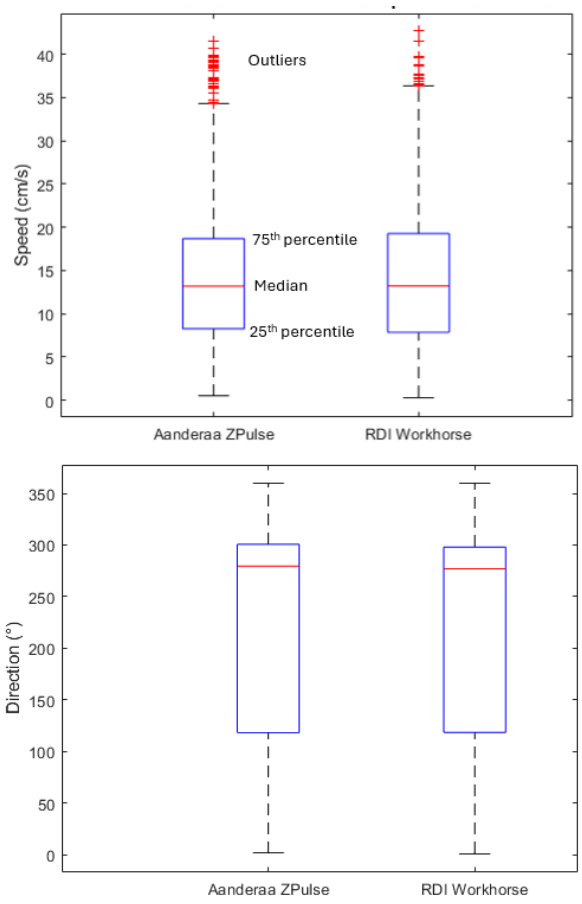

Figure 9a (left). Box plot of speed measurements made by RDI Workhorse and Aanderaa ZPulse. Figure 9b (right) Box plot of direction measurements made by RDI Workhorse and Aanderaa ZPulse.

Box plots of the measured northern and eastern components of velocity are shown below. The eastern component of velocity shows a greater range of values and less data outliers than the northern component.

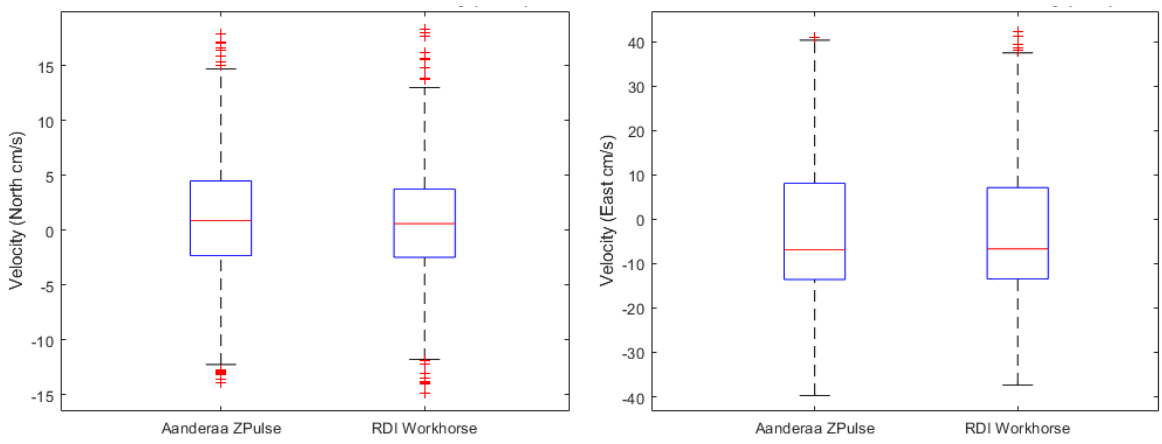

Figure 10a(left). Box plot of velocity (North) measurements. Figure 10b(right) Box plot of velocity (east) measurements.

Linear regression models for current velocity magnitude and direction were created to compare the two sensors. These regression models showed a strong linear curve fit, with R^2 values of .904 and .832, respectively. The velocity magnitude regression RMSE value is 2.46 cm/s. The direction regression RMSE is 22°. The true difference between measurements was used to calculate the direction regression RMSE, rather than the numerical difference (Equation 1). The fitted linear curves for current velocity magnitude and direction are depicted in Figure 11 and Figure 12. The velocity magnitude fitted linear curve intercept, slope, R^2, and other descriptive values are summarized in Table 2. These same values are summarized for the direction linear regression in Table 3.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\left(\alpha_i - \rho_i + 180\right)\ \%\ 360 - 180\right)^2}{N}}$$

$$where:$$

$$\alpha_i = Aanderaa\ ZPulse\ direction\ measurement\ in\ degrees\ (0\ to\ 360\ scale)$$

$$\rho_i = RDI\ Workhorse\ direction\ measurement\ in\ degrees\ (0\ to\ 360\ scale)$$

$$N = number\ of\ directional\ measurements$$

Equation 1. RMSE calculation of direction measurements using true difference between directions.

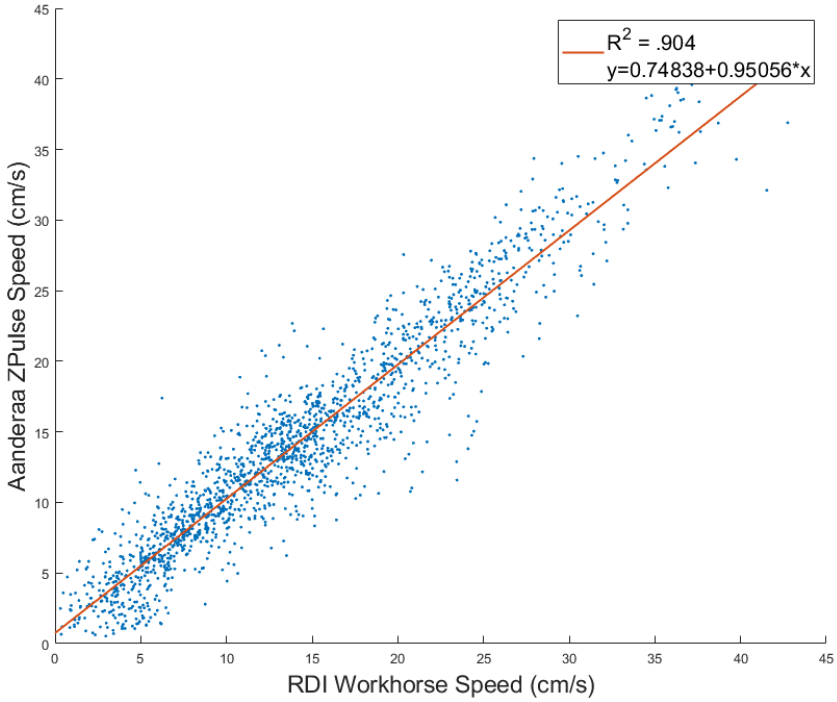

Figure 11. RDI Workhorse vs. Aanderaa ZPulse speed calculations (cm/s) with linear regression curve.

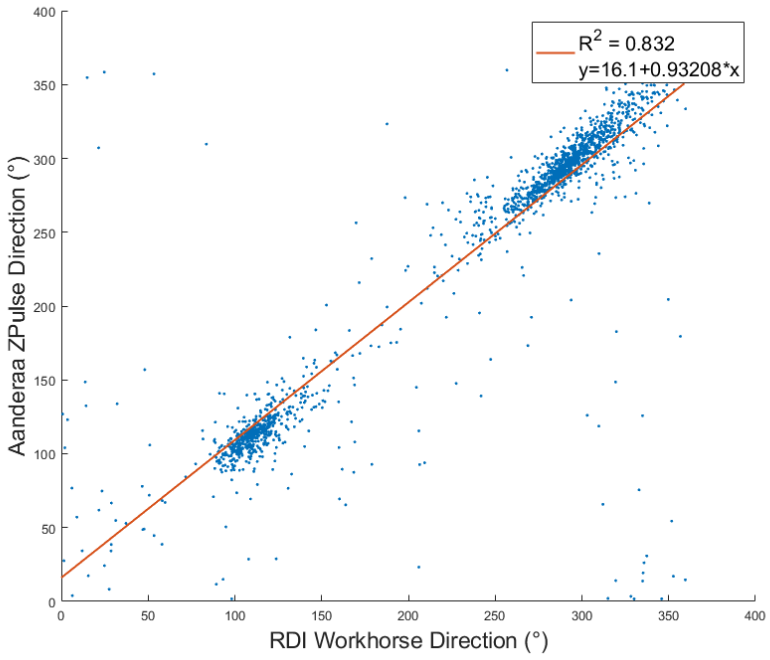

Figure 12. RDI Workhorse vs. Aanderaa Zpulse direction calculations (°) with linear regression curve.

Table 2. Linear regression model for RDI Workhorse and Aanderaa ZPulse current velocity magnitude measurements.

	Estimate	SE	tStat	pValue
(Intercept)	0.74838	0.11915	6.2809	4.2234e-10
x1	0.95056	0.0073358	129.58	0

Number of observations: 1776, Error degrees of freedom: 1774
Root Mean Squared Error: 2.46
R-squared: 0.904, Adjusted R-Squared: 0.904

Table 3. Linear regression model RDI Workhorse and Aanderaa Direction (°) Calculations

	Estimate	SE	tStat	pValue
(Intercept)	16.1	2.4433	6.5896	5.798e-11
x1	0.93208	0.0099503	93.673	0

Number of observations: 1776, Error degrees of freedom: 1774
Root Mean Squared Error: 22
R-squared: 0.832, Adjusted R-Squared: 0.832

Regression residuals, calculated as the difference between the fitted curve and the actual data value, appear centered around zero throughout the fitted value range for both velocity magnitude and direction (Figure 15 & Figure 16).

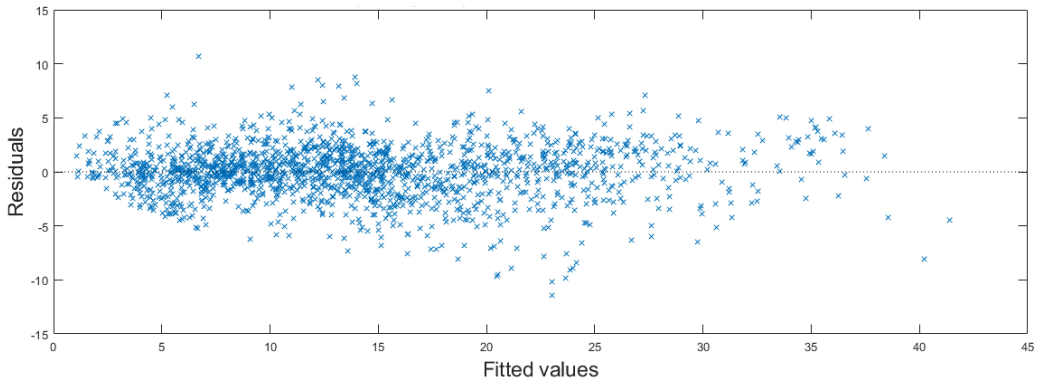

Figure 14. Fitted values vs. residuals for speed measurements linear regression model.

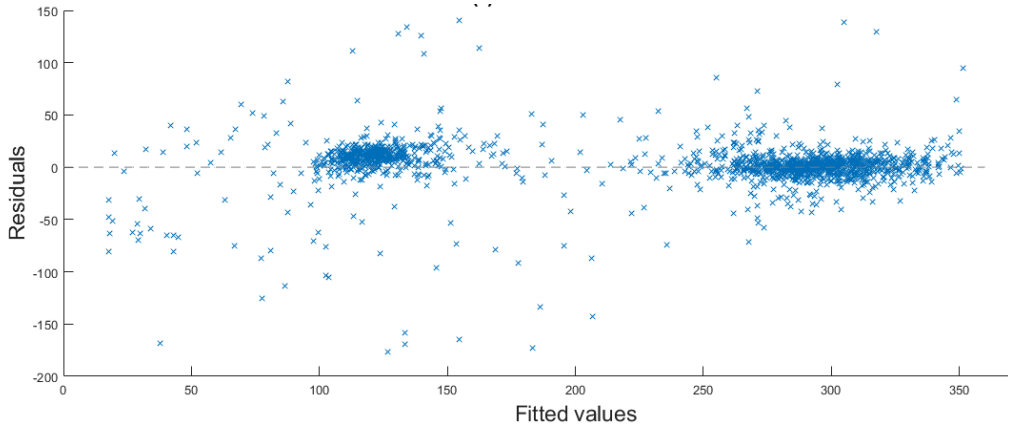

Figure 15. Fitted values vs. residuals for direction measurements linear regression model.

Direction residuals were calculated by finding the minimum absolute distance between the fitted and data values.

Linear regression models for the northern and eastern measured velocity components were calculated as well. The fitted linear curves for current velocity magnitude and direction are depicted in Figure 13 and Figure 14. The velocity magnitude fitted linear curve intercept, slope, R^2, and other descriptive values are summarized in Table 4. These same values are summarized for the direction linear regression in Table 5.

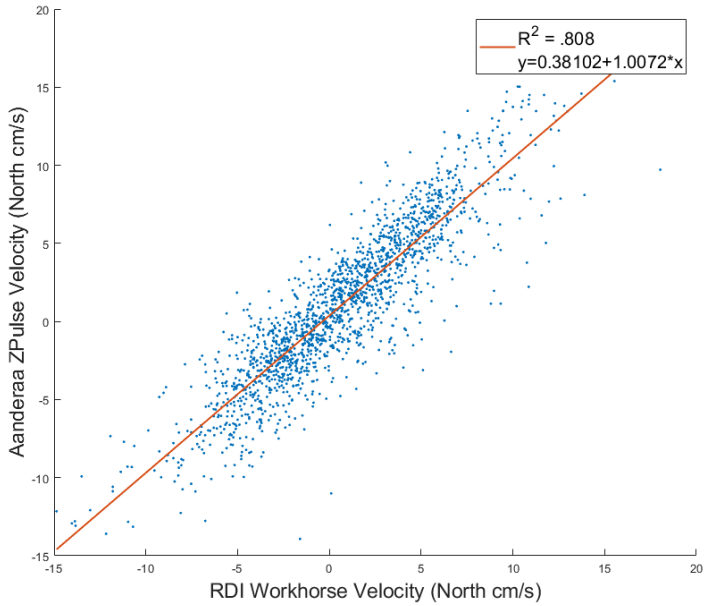

Figure 16. RDI Workhorse vs. Aanderaa ZPulse velocity (North cm/s) measurements with linear regression curve.

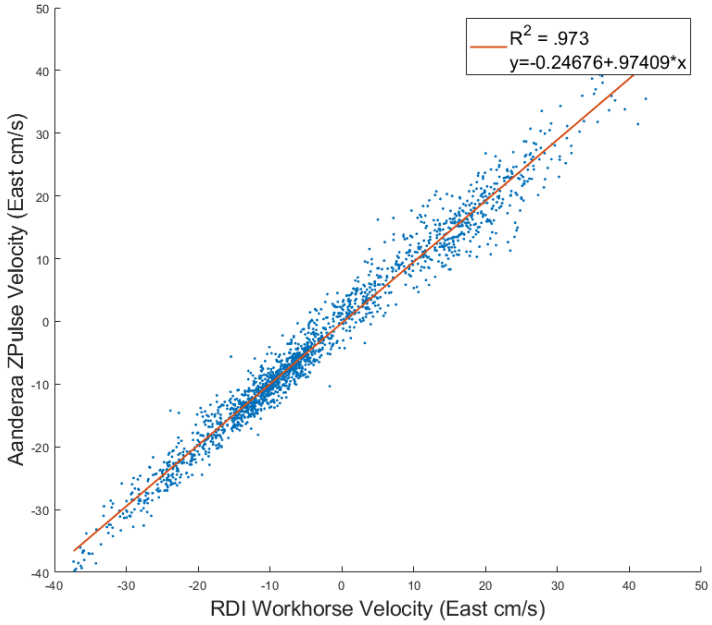

Figure 17. RDI Workhorse vs. Aanderaa Zpulse velocity (East cm/s) measurements with linear regression curve.

Table 4. Linear regression model for RDI Workhorse and Aanderaa ZPulse Velocity (North) Measurements

	Estimate	SE	tStat	pValue
(Intercept)	0.38102	0.053386	7.137	1.3852e-12
x1	1.0072	0.011643	86.505	0

Number of observations: 1776, Error degrees of freedom: 1774
Root Mean Squared Error: 2.22
R-squared: 0.808

Table 5. Linear regression model RDI Workhorse and Aanderaa Zpulse Velocity (East) Measurements

	Estimate	SE	tStat	pValue
(Intercept)	-0.24676	0.059909	-4.1189	3.9823e-05
x1	0.97409	0.0038448	253.35	0

Number of observations: 1776, Error degrees of freedom: 1774
Root Mean Squared Error: 2.46
R-squared: 0.973

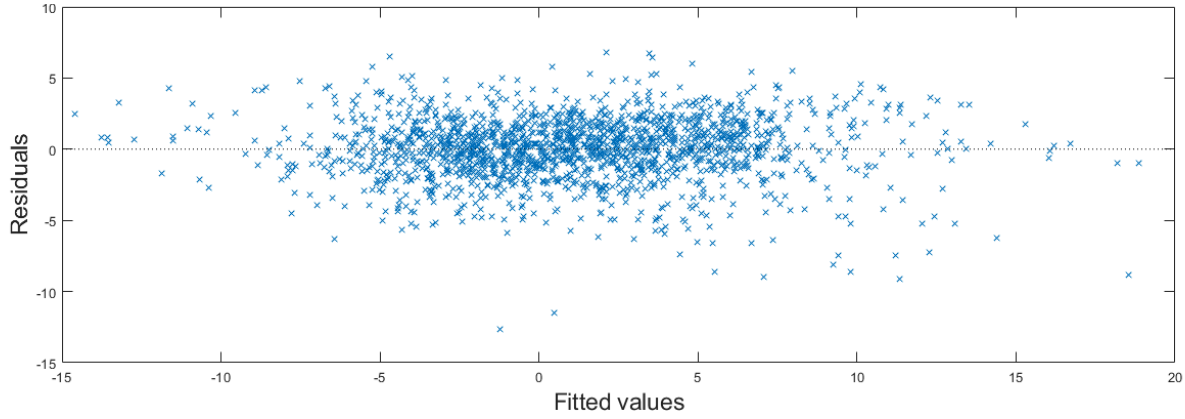

Figure 18. Fitted values vs. residuals for velocity (North) measurements.

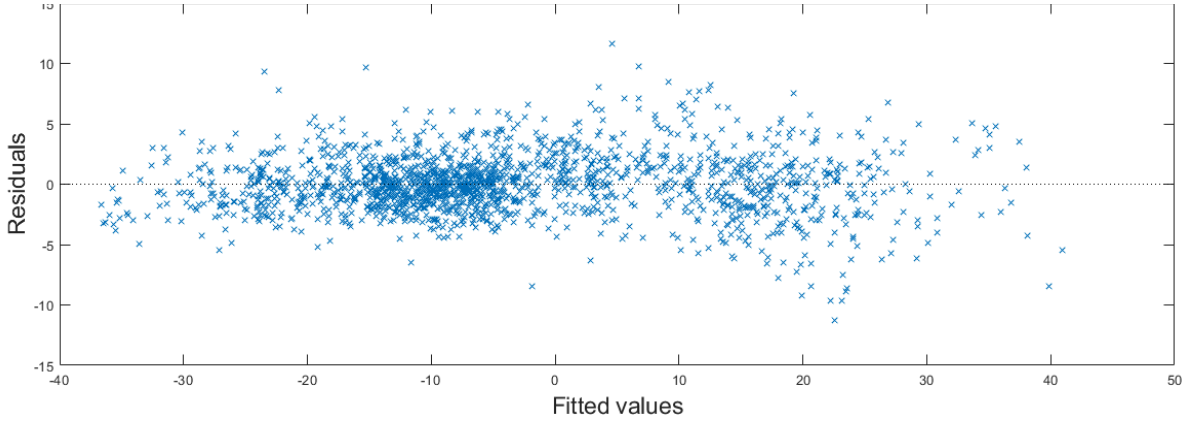

Figure 19. Fitted values vs. residuals for velocity (East) measurements.