Hawaii National Marine Renewable Energy Center (HINMREC)

U.S. Department of Energy Award Number: DE-FG36-08GO18180

Task 4: Environmental Impact Monitoring at WETS

WETS Comparison of Waverider Data & Sentinel V100 ADCP Data Reports

Prepared by:
Sea Engineering, Inc.

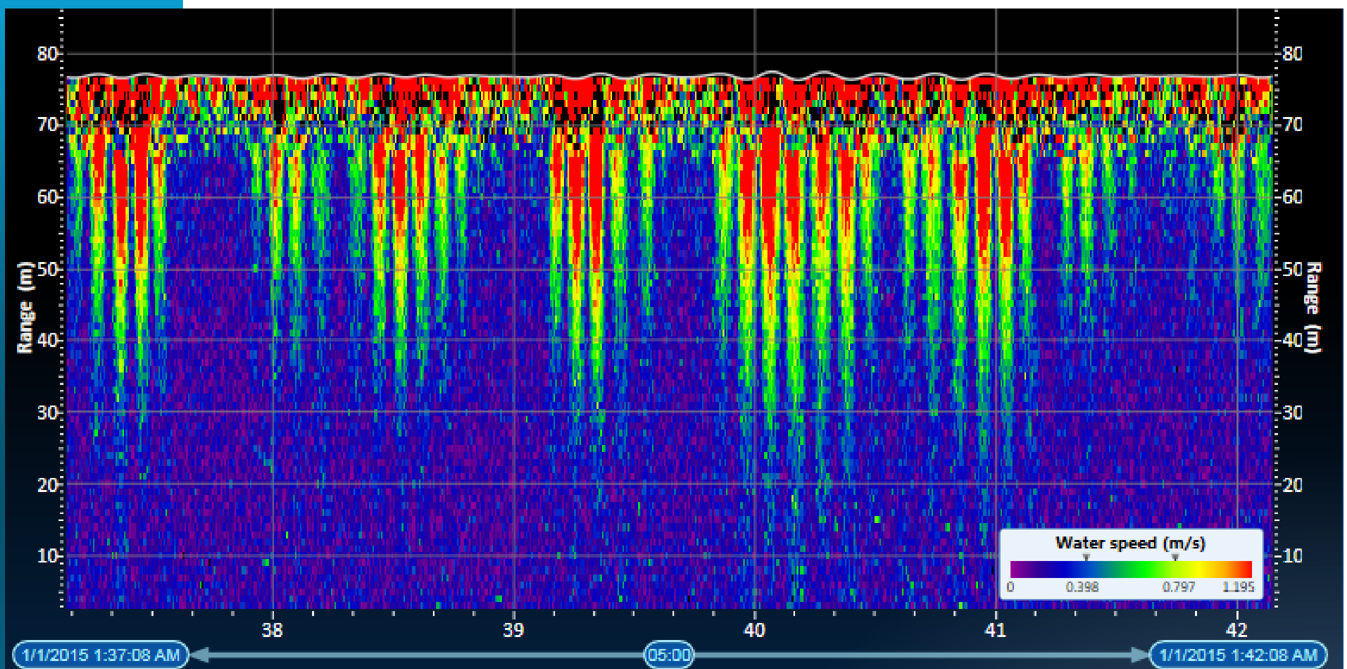
Prepared for:
Hawaii Natural Energy Institute, University of Hawaii

May - September 2015

HNEI
Hawaiʻi Natural Energy Institute
University of Hawaiʻi at Mānoa

Wave Energy Test Site Comparison of Waverider Data and Sentinel V100 ADCP Data

May 2015



Prepared for:

Hawaii National Marine Renewable Energy Center
1680 East West Road, POST 112A
Honolulu, HI 96822

Prepared by:

Sea Engineering, Inc.
Makai Research Pier
Waimanalo, HI 96795

Job No. 25419

This page intentionally left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The area north of the Mokapu Peninsula, adjacent to Kaneohe Marine Corps Base Hawaii (MCBH), has been utilized by the U.S. Navy for wave energy research since 2002. A prototype wave energy converter (WEC) was tested at the 30 m water depth offshore of North Beach at the MCBH. The Hawaii National Marine Renewable Energy Center (HNMREC) at the University of Hawaii, under contract with Department of Energy and the U.S. Navy, has expanded the test site to water depths of 100 m to allow for the testing of other wave energy devices.

Sea Engineering has been contracted by the HNMREC to conduct site investigations in support of the expanded test site. One of these investigations is intended to determine wave climate at the site.

The project location within the state of Hawaii is shown in Figure 1-1. The test site is 1600 to 2000 m wide and extends approximately 2600 m offshore from the 30 m depth contour to the approximate 100 m depth contour.

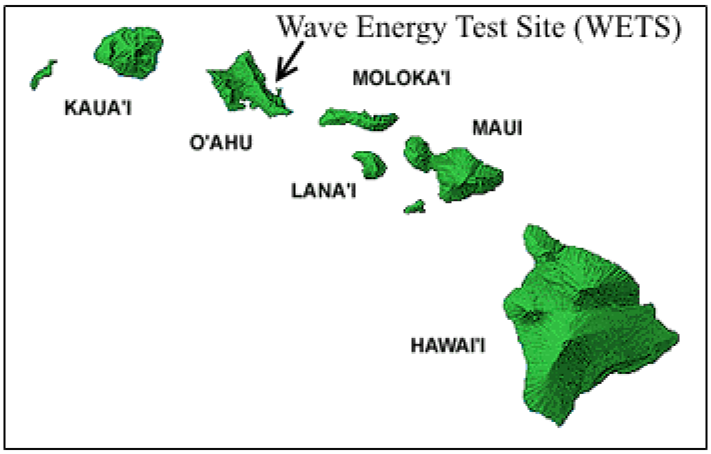


Figure 1-1 Project Location

In collaboration with HNMREC, Sea Engineering Inc. deployed a Teledyne RDI Sentinel V100 Acoustic Doppler Current Profiler (ADCP) at 10:37 AM on November 13th, 2014 at coordinates 21°28’39.1813”N and 157°44’56.3008”W in the Wave Energy Test Site (WETS). One of the new features of the Sentinel V100 is its ability to measure wave statistics using a fifth vertical beam to improve the accuracy of the measurements and provide high resolution surface tracking. The ADCP location is near a Datawell Waverider buoy that is maintained by the University of Hawaii and The Pacific Island Ocean Observing System (PacIOOS). The purpose of this report is to compare the measurements from the Sentinel V100 ADCP to the measurements of the Waverider buoy. Figure 1-2 shows the locations of the Waverider buoy and the Sentinel V100 ADCP. The wave measurement devices are approximately 413 meters (1,357ft) away from each other near the 80 meter bathymetric contour.

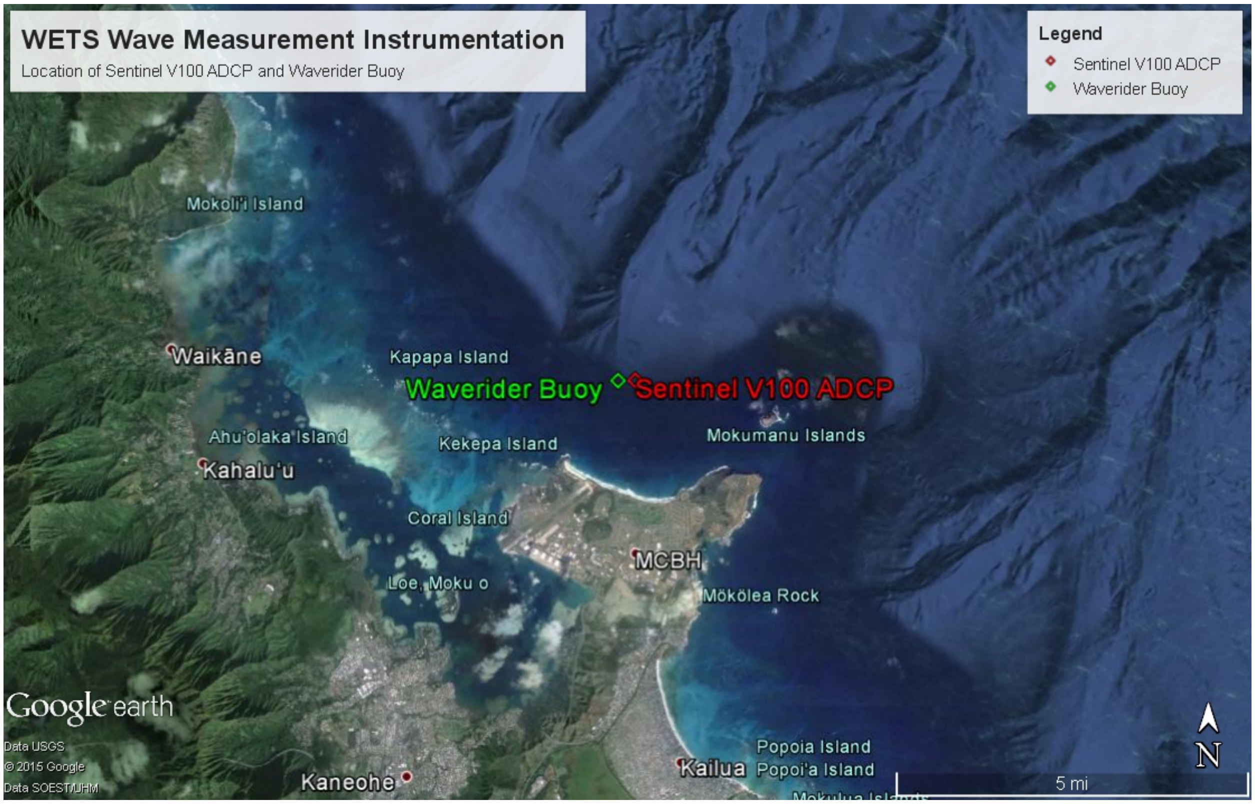


Figure 1-2 WETS Wave Measurement Instrumentation

The Sentinel V100 ADCP uses a vertical acoustic beam to measure the distance to the water surface. Sound waves reflect off the water surface and the time a reflection takes to return to the ACDP is used to determine the distance to the surface. Accurate wave statistics can be computed from the measured water surface elevation record. An ADCP relies on the Doppler Effect to determine the water currents through the water column. The direction of current can be determined by using three or four acoustic beams. The acoustic reflection of a beam of that is up current from the ACDP will arrive before the reflection of down current acoustic reflection. With the refection return timing of multiple beams the direction can be calculated.

The Waverider buoy uses sensitive accelerometers to determine the motions of a moored buoy. The buoy is designed such that the mooring line and anchor have minimal impact on the motion of the buoy. The motion of the buoy is representative of wave motion.

2. TELEDYNE RDI SENTINEL V100 SETUP

The Sentinel V100 was programmed to measure both waves and current. ReadyV software from Teledyne RDI was used to program the Sentinel V100 ADCP. The software calculates the available battery resources and data storage for desired measurement profiles. An example of these displays is shown in the bottom of Figure 2-1 under the heading “Resources”.

A screenshot of the ReadyV software showing the two measurement profiles is shown in Figure 2-1. The profile information is shown in the top right quarter of the screen display. The custom wave and current measurement profiles have the following settings:

Table 2-1 Profile Parameters

	Waves Measurement Profile	Current Measurement Profile
Ping Interval (seconds)	0.5	1
Number of Pings	2300	300
Range (meters)	84	84
Cell Size (meters)	1.0	1.0
Duration(minutes)	19.166	5

The wave measurement occurs once per hour over a 19 minute and 10 second period, from 37 to 56 minutes past the hour. Current measurements occur over a 5 minute period, from 7 to 12 minutes past the hour or 30 minutes after the start of the wave measurements.
This setup was chosen to accommodate a deployment duration of 90 days. An external battery housing was used with two additional battery packs rated at 540 watt-hours. In total three battery packs were used, one in the Sentinel V100 ADCP and two in the external housing, providing 1,620 watt-hours of energy.

The Sentinel V100 ADCP was deployed on 11:07 AM on November 13th, 2014 and recovered at 8:00 AM on February 26th, 2015, a 104 day deployment. The Sentinel V100 ADCP was still recording measurements when recovered despite being well past the planned deployment duration. The setting for the timing of each profile is shown in the Timing tab shown in Figure 2-2.

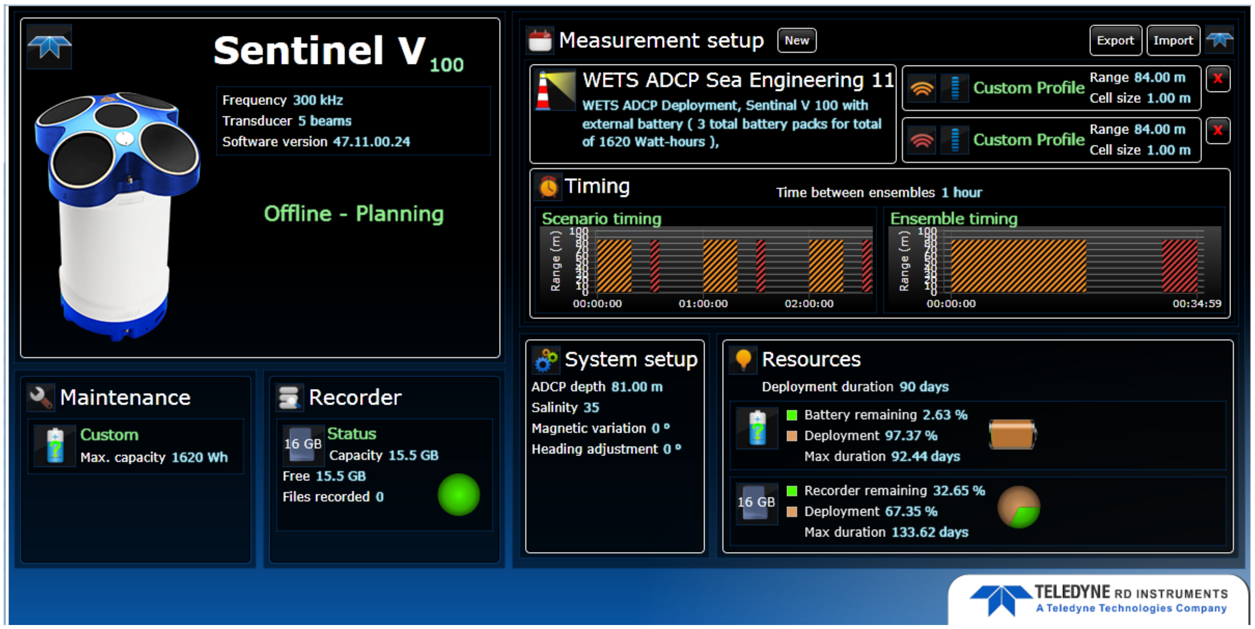


Figure 2-1 ReadyV Software Showing the Sentinel V100 Setup

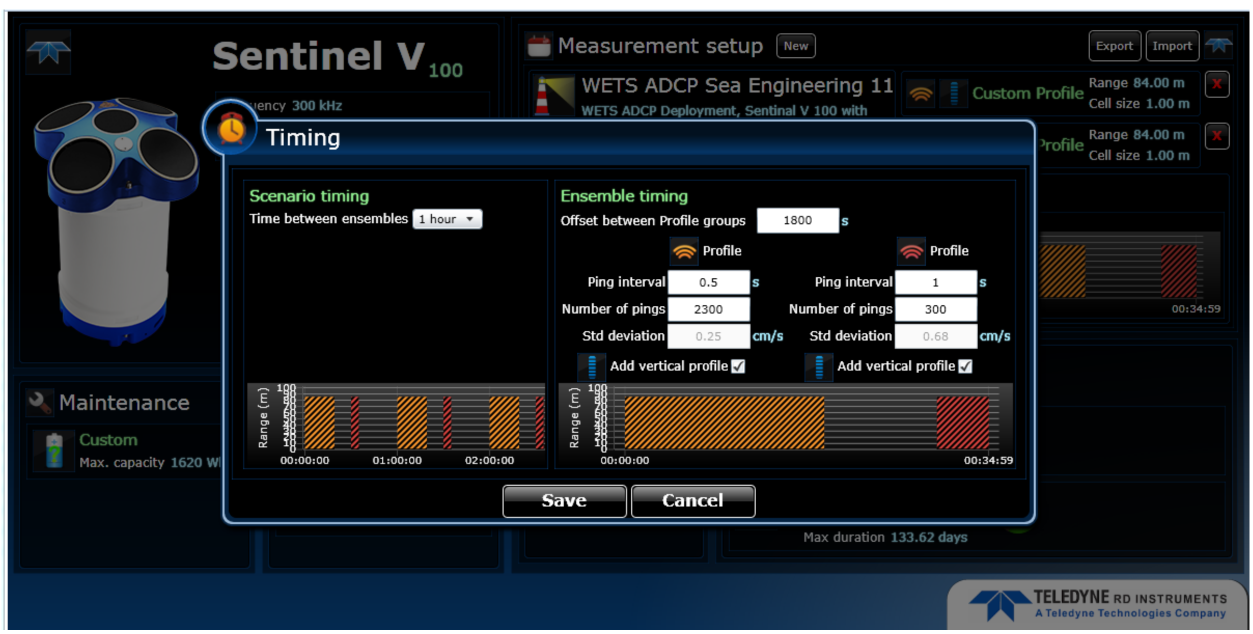


Figure 2-2 ReadyV Software Showing the Timing of Each Profile

3. SENTINEL V100 DATA

The complete data file for Sentinel V100 was 12.7 GB of which the waves profile was 11.2 GB. Only the data from the waves profile was used to calculate the wave statistics. Teledyne RDI provides multiple software options to display the data. The primary data viewing and processing software is Velocity. Velocity displays all the parameters measured. Figure 3-1 presents a Velocity display showing the water speed and water direction for the first four 19 minute wave profile measurements.

The Velocity software also calculates many different wave statistics. The three statistics that will be compared to the Waverider buoy statistics are the significant wave height (H_s), peak period (T_p), and peak direction (D_p). A screen shot of Velocity displaying the wave statistics is shown in Figure 3-2. The direction that the Sentinel V100 ADCP references is magnetic north. These readings were converted to a true north reference using the magnetic declination values for the location of the Sentinel V100 ADCP deployment. The magnetic declination for WETS is 9.6° east. A second program – WavesView - is used to display the spectral data alongside the wave statistics.

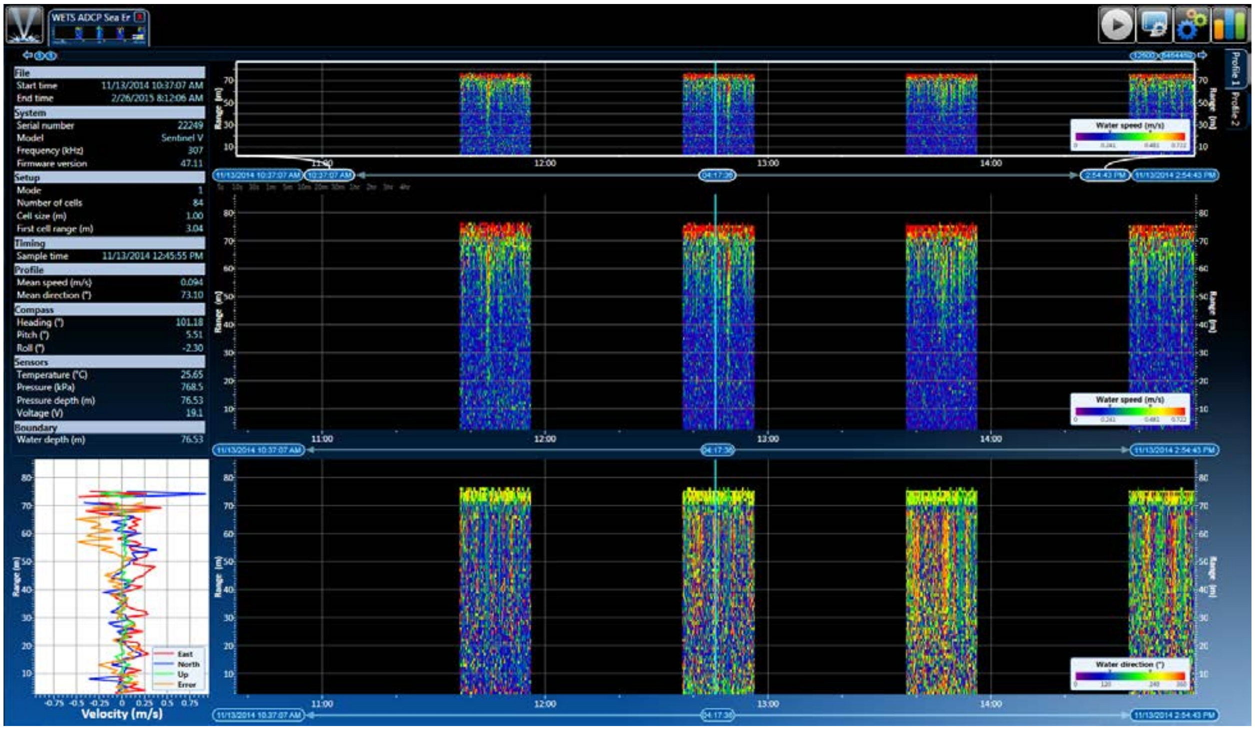


Figure 3-1 Velocity Software Showing Wave Speed and Direction

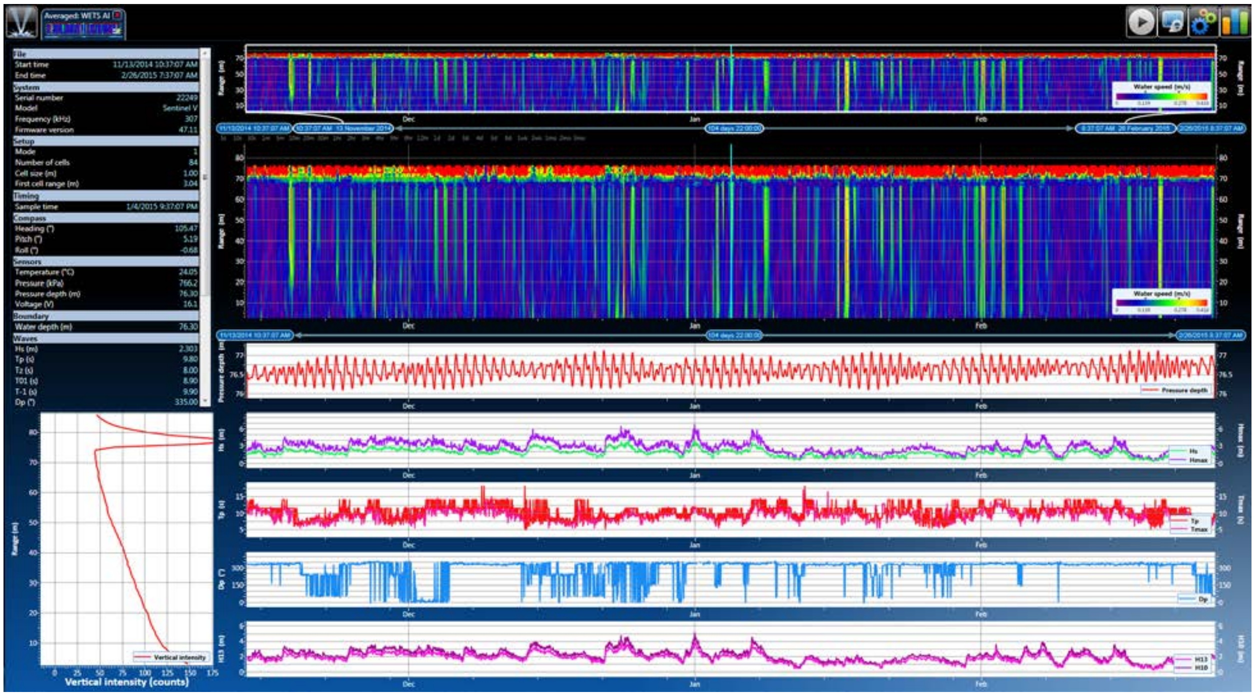


Figure 3-2 Velocity Software Showing Wave Statistics

4. WAVERIDER BUOY DATA

The Waverider buoy is a standard wave measurement buoy that is located near to the Sentinel V100 ADCP. This particular buoy is managed by the Coastal Data Information Program (CDIP) and is Station 198 in Kaneohe Bay. Data from all CDIP buoys can be easily downloaded from the following website: http://cdip.ucsd.edu/ . The wave statistics are measured every half hour by the Waverider buoy. This buoy was out of operation for repairs from September 11th 2014 to November 7th, 2014. It was redeployed on November 7th, 2014 at 21°28’39”N and 157°45’9.4753”W by Sea Engineering Inc. The Waverider data is reference to Universal Coordinated Time (UTC) which was converted to Hawaii-Aleutian Time Zone (HAST).

5. COMPARSION OF WAVE STATISTICS

The time series of wave data measured by the Sentinel V100 ADCP was compared with the Waverider buoy time series. The Waverider measurements were recorded twice per hour, while the Sentinel V100 ADCP measurements were recorded once per hour. The timestamps for each measurement device did not coincide. Each Sentinel V100 ADCP measurement was compared to the corresponding Waverider measurement closest in time. There were some gaps in the Waverider data over the 104 days of deployment of the Sentinel V100 ADCP. Only the measurements made by the Waverider that were within 30 minutes of a measurement made by the Sentinel V100 ADCP are used in the comparison.

Figure 5-1 shows the time series of the significant wave height (H_s), peak period (T_P), and the peak direction (D_P) from the Sentinel V100 ADCP data and the Waverider data. The time series runs from November 13th, 2014 at 10:37 AM to February 26th, 2015 at 7:56 AM. These time series show overall agreement for each parameter throughout the time series. Monthly time series plots are presented in Appendix A.

A comparison of the significant wave heights measured by both devices is shown in Figure 5-1 and Figure 5-2. A solid line from the linear regression calculations is plotted in red with red dashed lines on either side that incorporate 50% of the data. The slope of the line is 0.93 and the bound for 50% of the data is ±0.17.

Figure 5-3 shows the ranked significant wave height from both the Sentinel V100 ADCP and the Waverider in a quantile-quantile plot. Since the number of measurements for each data set is equal the quantile-quantile plot is simply a plot of ranked data from the Sentinel V100 ADCP against the ranked data of Waverider. This plot shows that generally the Sentinel V100 ADCP does a good job of predicting the Waverider wave height; however, there is a slight underrepresentation at low wave heights.

A rose plot is good way to display the direction and frequency of directionally varying data. Figure 5-4 and Figure 5-5 are rose plots of the significant wave height from the Sentinel V100 ADCP and the Waverider respectively. Figure 5-6 and Figure 5-7 are rose plots of the peak period from the Sentinel V100 ADCP and the Waverider respectively.

The following error metrics were used to test the accuracy of the Sentinel V100 ADCP measurements against the Waverider measurements: Mean Error (ME), Normalized Bias, Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMS), Correlation (COR), and scatter index (SI). Mean error, also known as bias, is an average difference between Sentinel V100 ADCP data and Waverider data. The mean error is helpful to determine whether one instrument is consistently measuring higher or lower than the other. Root mean squared error is a measure of how close, on average, the instrument measurements are to each other. A small RMSE and NRMS indicates a small difference between compared measurements. Correlation (COR) is the statistical relationship between two or more variables such that systematic changes in the value of one variable are accompanied by systematic changes in the other. The closer COR is to 1, the closer the relationship between the Sentinel V100 ADCP measurements and the Waverider measurements. Scatter index is the RSME between the Sentinel V100 ADCP measurements and the Waverider measurements divided by the mean of the Waverider measurements. It represents the average difference in measurements as a percent of wave height or period. These metrics were calculated by the following equations:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})$$

$$NME = \frac{1}{N}\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})}{\sum_{i=1}^{N}(X_{WRi})}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$NRMSE = \frac{1}{(\max(X_{WR}) - \min(X_{WR}))}\sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$COR = \frac{\sum_{i=1}^{N}(X_{ADCPi} - \overline{X_{ADCP}})(X_{WRi} - \overline{X_{WR}})}{\sqrt{\sum_{i=1}^{N}(X_{Pi} - \overline{X_P})^2}\sqrt{\sum_{i=1}^{N}(X_{WRi} - \overline{X_{WR}})^2}}$$

$$SI = \frac{1}{\overline{X_{WR}}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(X_{ADCPi} - X_{WRi}) - \overline{(X_{ADCP} - X_{WR})}\right]^2}$$

In the equations listed above, ADCP and WR subscripts denote between the Sentinel V100 ADCP data and Waverider data respectively, and N is the number of data pairs. The over bar denote mean of values. The statistics for both the significant wave height and peak period are shown in Table 5-1.

Table 5-1 Measurement Statistics

Column1	Root Mean Squared Error, m or s (RMSE)	Normalized Root Mean Squared Error, % (NRMSE)	Mean Error (ME), m or s	Normalized Mean Error (NME), %	Correlation	Scatter Index
Significant Wave Height (Hs)	0.1854	0.0502	-0.0483	-2.6251	0.9577	0.0973
Peak Period (Tp)	1.8122	0.1553	-3.1531	-3.1531	0.6632	0.1632

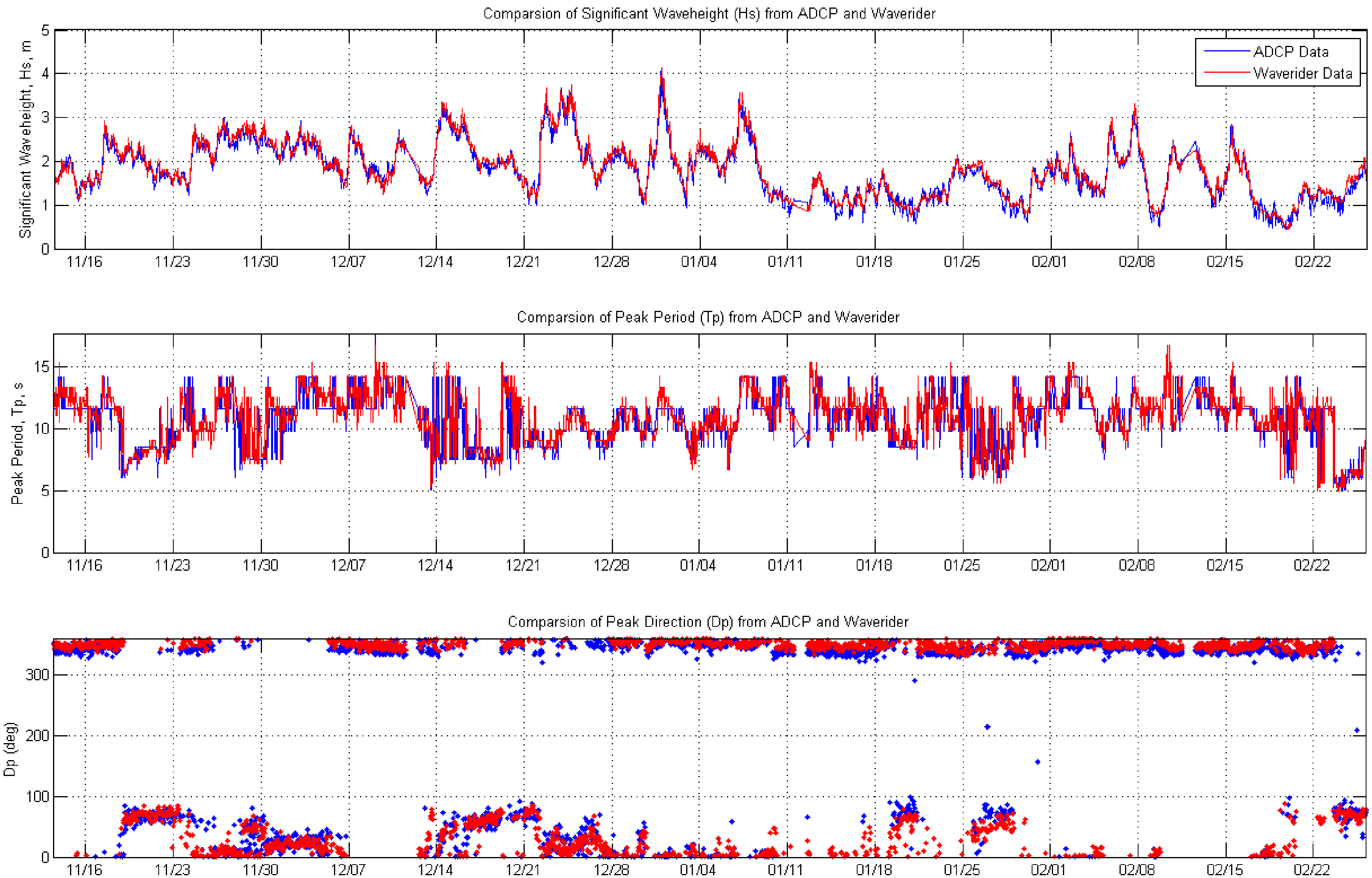


Figure 5-1 Time Series of Sentinel V100 ADCP and Waverider Data

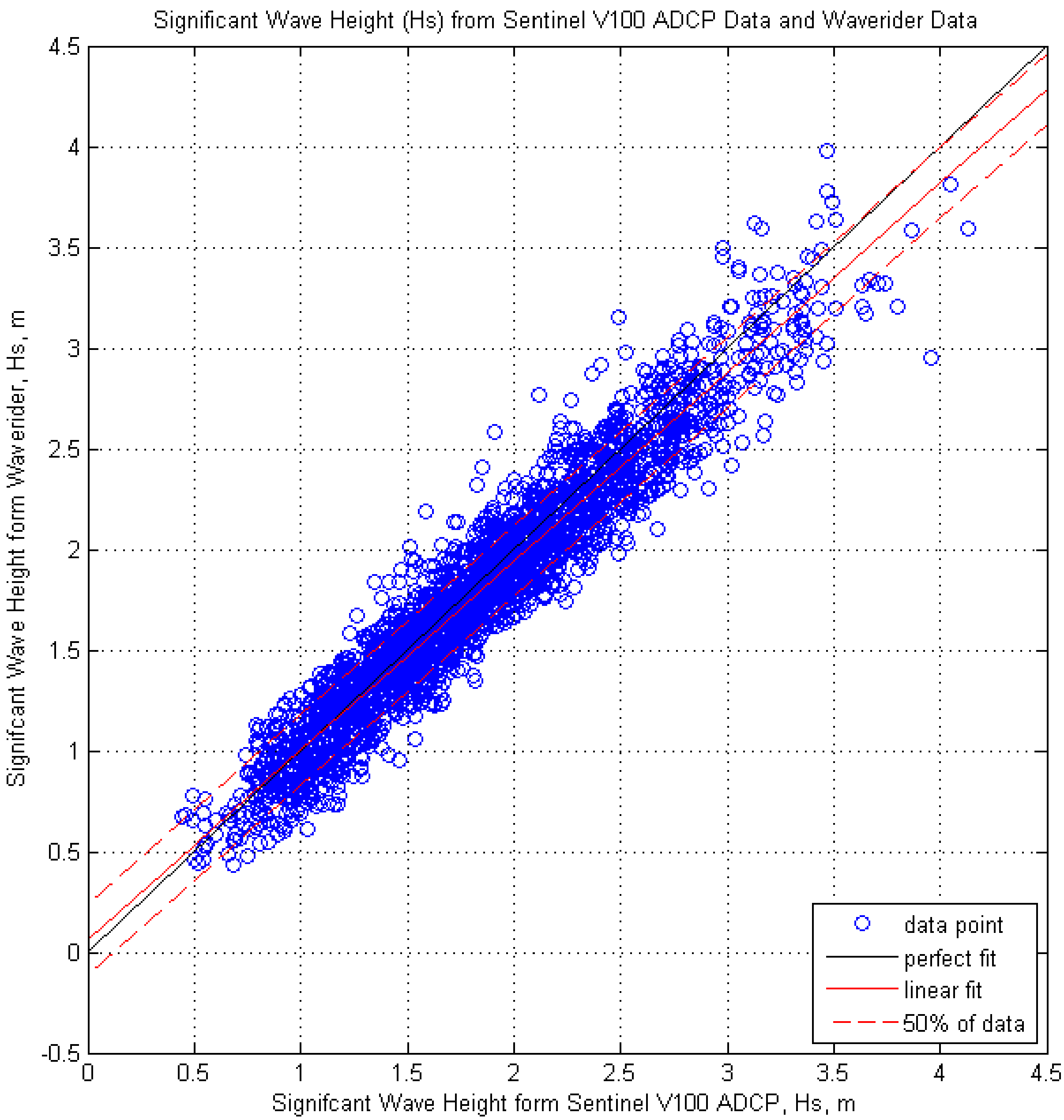


Figure 5-2 Comparison of Wave Height Measurements

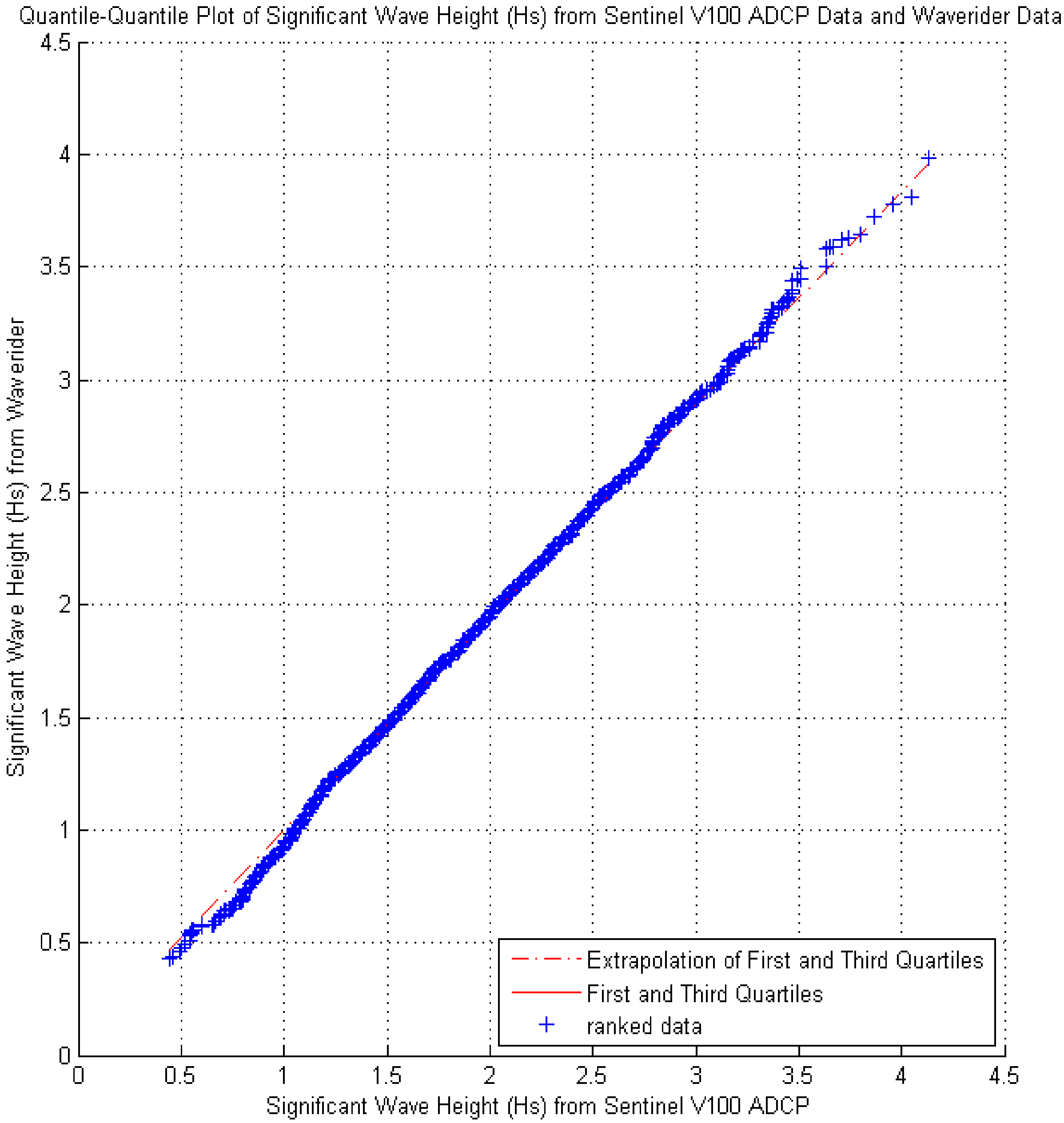


Figure 5-3 Q-Q Plot of Wave Height

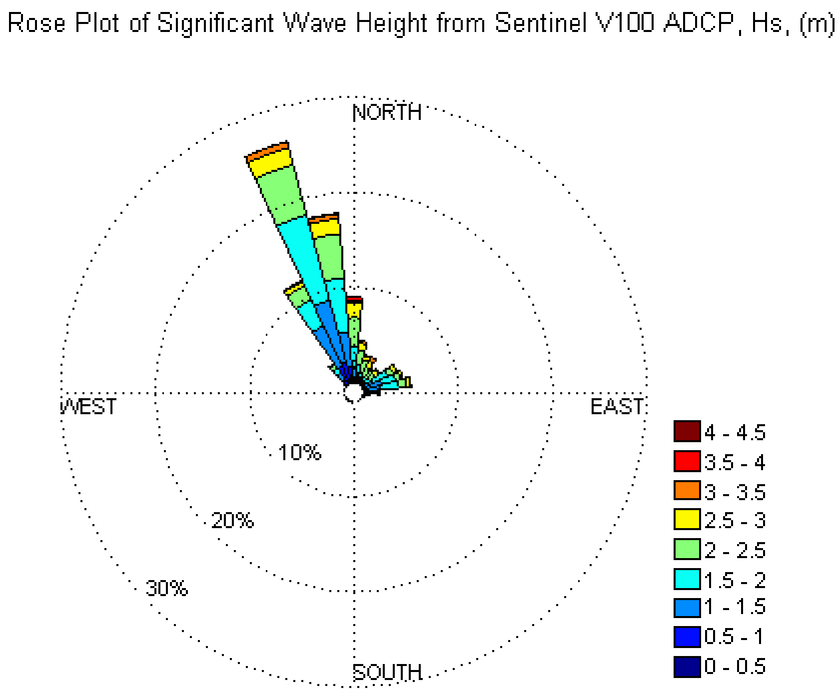


Figure 5-4 Rose plot of Significant Wave Height from Sentinel V100 ADCP

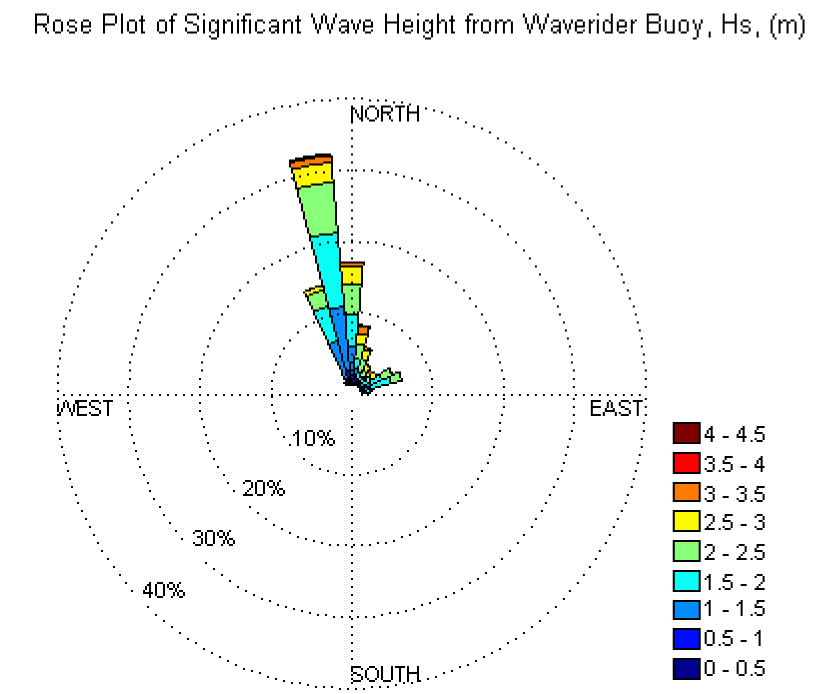


Figure 5-5 Rose Plot of Significant Wave Height from Waverider

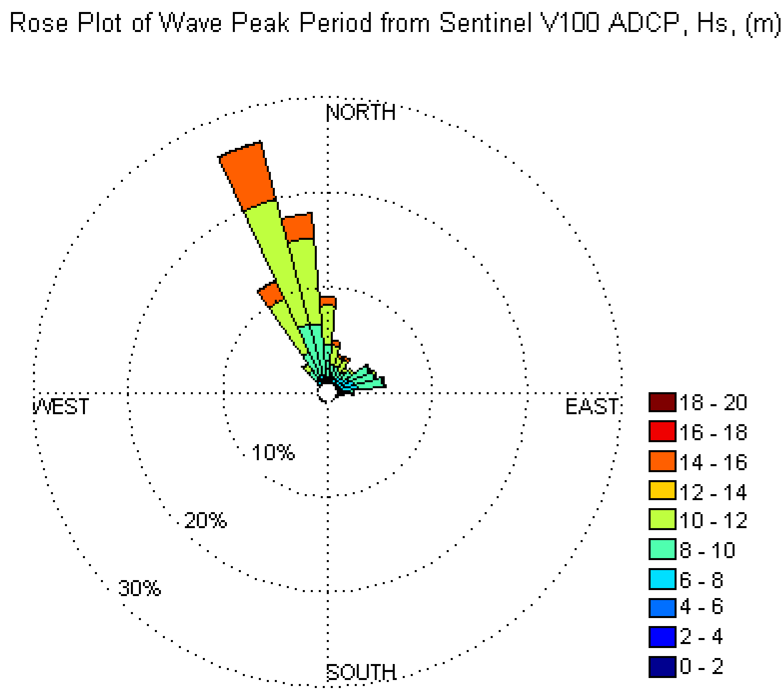


Figure 5-6 Rose Plot of Wave Peak Period from Sentinel V100 ADCP

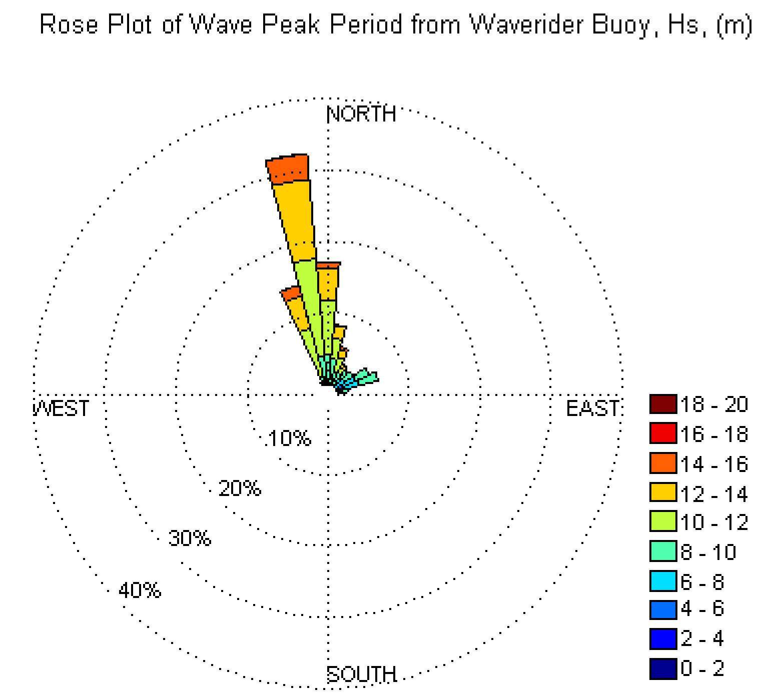


Figure 5-7 Rose Plot of Wave Peak Period from Waverider

6. CONCLUSION

Sea Engineering Inc. deployed a Teledyne RDI Sentinel V100 ADCP with wave measurement capabilities at WETS from November 13th, 2014 to February 26th, 2015 (104 days). This deployment was in close proximity to the WETS Waverider buoy. Figure 5-1 through Figure 5-7 show a close correspondence between the measurements from the Sentinel V100 and the Waverider for the parameters of significant wave height, peak period, and peak direction. Table 5-1 shows that Sentinel V100 ADCP measurements compare closely with the Waverider measurements. The low mean error and low root mean error indicate that the Sentinel V100 ADCP measurements are accurate compared to the Waverider measurements. The correlation of near 1 for the significant wave height signifies that that there is a very close relationship between the Sentinel V100 ADCP measurements and the Waverider measurements. The lower correlation of the peak period is due to the large range of directional values, and the large jumps in direction – from 360 to 70 degrees – that can occur quickly as a swell event subsides and trade wind seas become dominant.

APPENDIX A

Monthly Time Series of Significant Weight Height, Peak Period, and Peak Direction

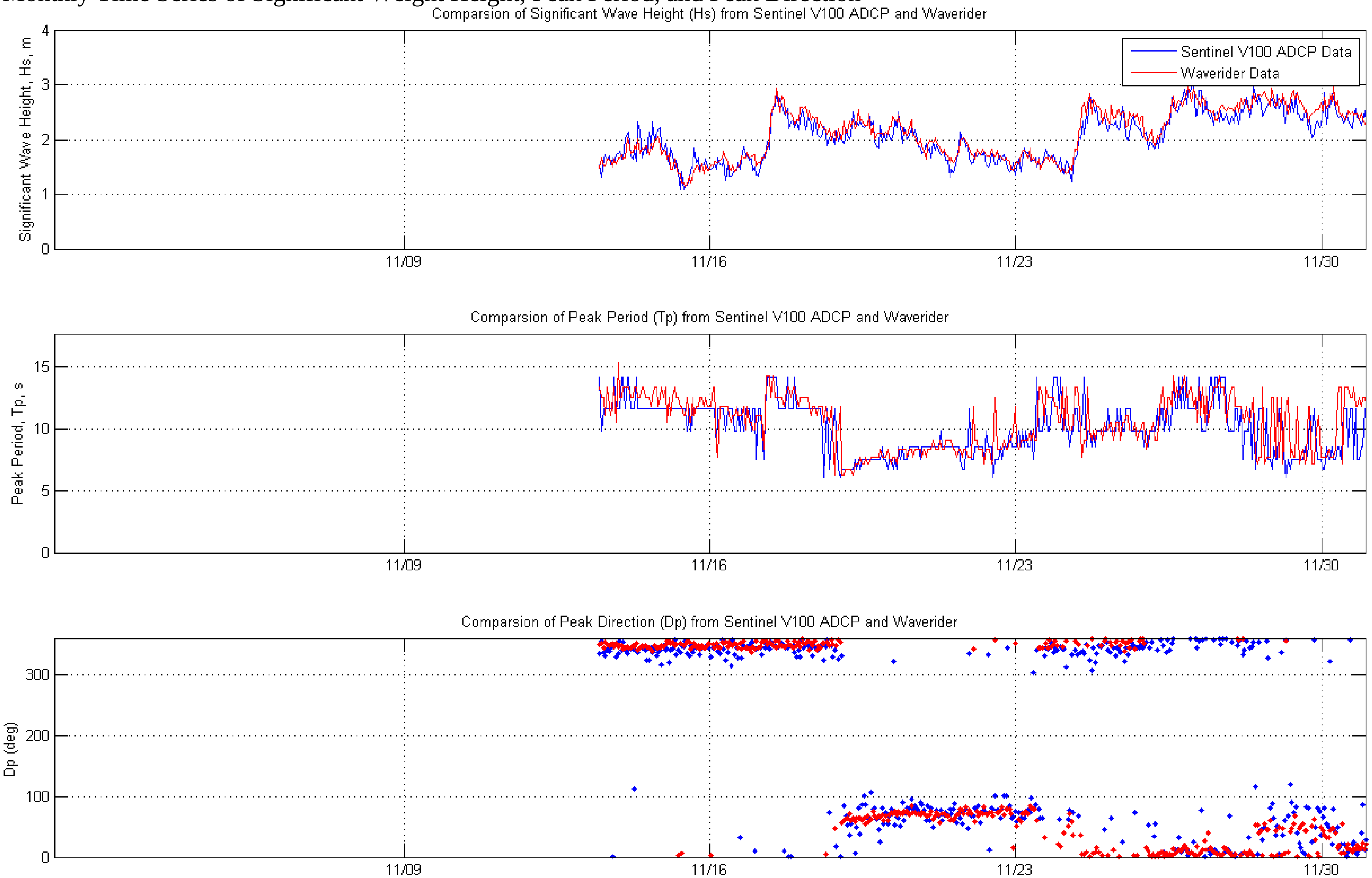


Figure A-1 November 2014 Significant Wave Height, Peak Period, and Peak Direction

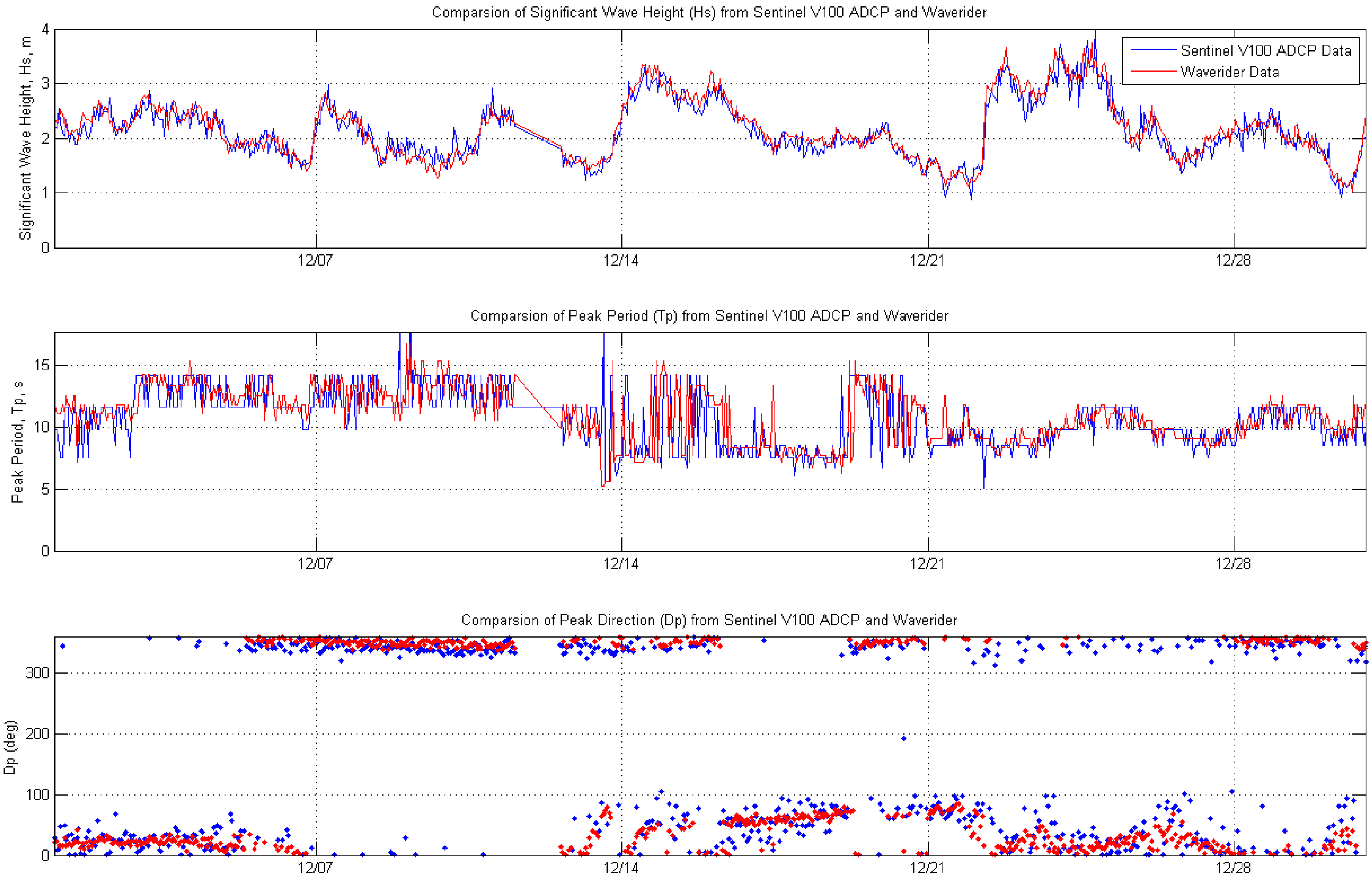


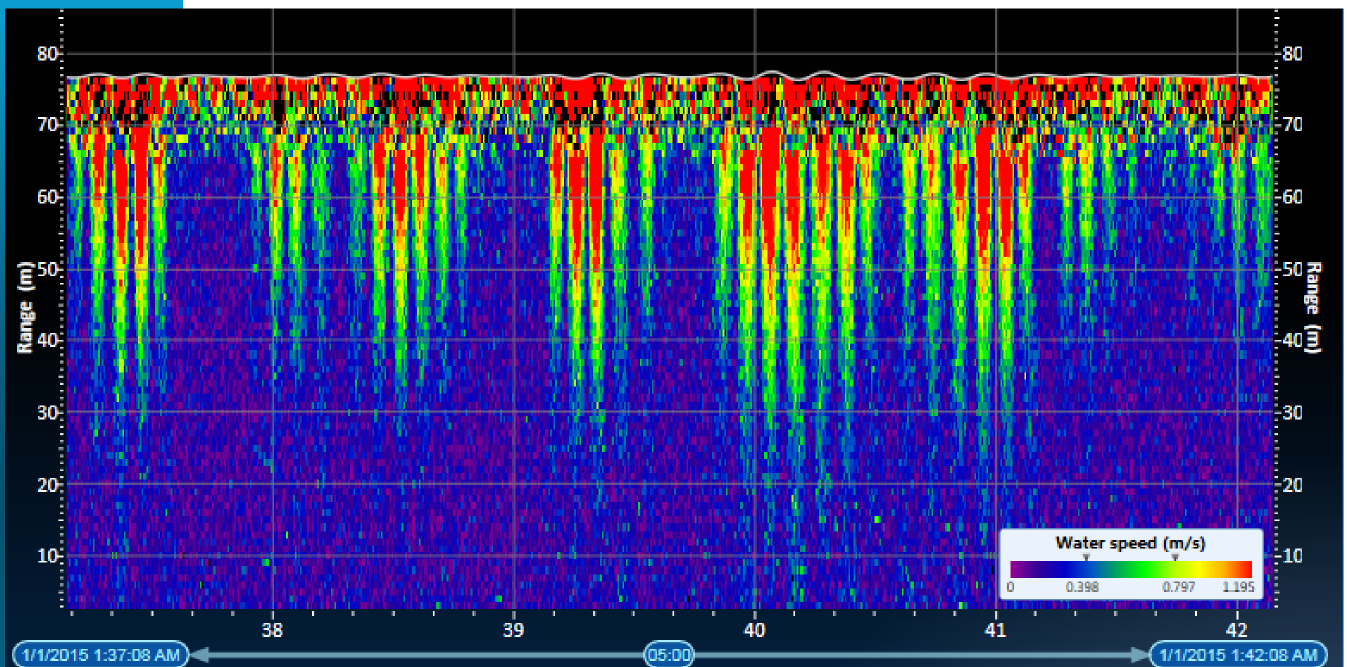
Figure A-2 December 2014 Significant Wave Height, Peak Period, and Peak Direction

Figure A-3 January Significant Wave Height, Peak Period, and Peak Direction

Figure A-4 February 2015 Significant Wave Height, Peak Period, and Peak Direction

Wave Energy Test Site Comparison of Waverider Data and Sentinel V100 ADCP Data

September 2015



Prepared for:
Hawaii National Marine Renewable Energy Center
1680 East West Road, POST 112A
Honolulu, HI 96822

Prepared by:
Sea Engineering, Inc.
Makai Research Pier
Waimanalo, HI 96795

Job No. 25419

This page intentionally left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The area north of the Mokapu Peninsula, adjacent to Kaneohe Marine Corps Base Hawaii (MCBH), has been utilized by the U.S. Navy for wave energy research since 2002. A prototype wave energy converter (WEC) is currently being tested at the 30 m water depth offshore of North Beach at the MCBH. The Hawaii National Marine Renewable Energy Center (HNMREC) at the University of Hawaii, under contract with Department of Energy and the U.S. Navy, has expanded the test site to water depths of 100 m to allow for the testing of other wave energy devices.

Sea Engineering has been contracted by the HNMREC to conduct site investigations in support of the expanded test site. One of these investigations is to determine wave climate at the site.

The project location within the state of Hawaii is shown in Figure 1-1. The test site is 1600 to 2000 m wide and extends approximately 2600 m offshore from the 30 m depth contour to the approximate 100 m depth contour.

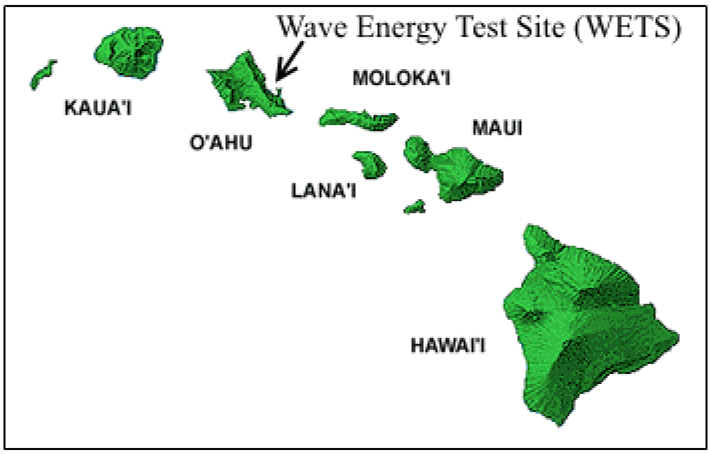


Figure 1-1 Project Location

In collaboration with HNMREC, Sea Engineering Inc. deployed a Teledyne RDI Sentinel V100 Acoustic Doppler Current Profiler (ADCP) at 10:37 AM on November 13th, 2014 at coordinates 21°28’39.1813”N and 157°44’56.3008”W in the Wave Energy Test Site (WETS). One of the features of the Sentinel V100 is its ability to measure wave statistics using a fifth vertical beam to improve the accuracy of the measurements and provide high resolution surface tracking. The ADCP location is near a Datawell Waverider buoy that is maintained by the University of Hawaii and The Pacific Island Ocean Observing System (PacIOOS). The purpose of this report is to compare the measurements from the Sentinel V100 ADCP to the measurements of the Waverider buoy. Figure 1-2 shows the locations of the Waverider buoy and the Sentinel V100 ADCP. The wave measurement devices are approximately 413 meters (1,357ft) away from each other, along the approximate 80 meter bathymetric contour.

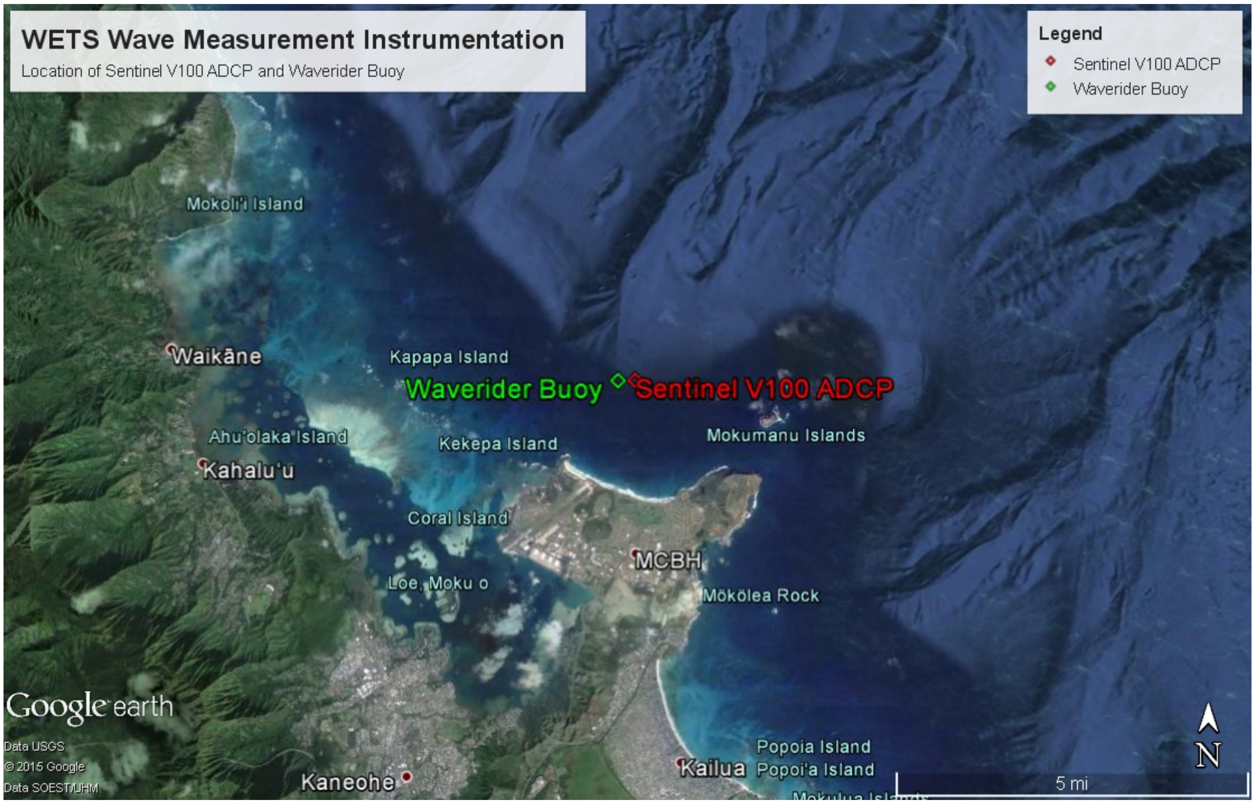


Figure 1-2 WETS Wave Measurement Instrumentation (Google Earth Image)

The Sentinel V100 ADCP uses a vertical acoustic beam to measure the distance to the water surface. Sound waves reflect off the water surface and the time a reflection takes to return to the ACDP is used to determine the distance to the surface. Accurate wave statistics can be computed from the measured water surface elevation record. An ADCP relies on the Doppler Effect to determine the water currents through the water column. The direction of current can be determined by using three or four acoustic beams. The acoustic reflection of a beam that is up current from the ACDP will arrive before the reflection of down current acoustic reflection. With the reflection return timing of multiple beams, the direction of waves and currents can be calculated.

The Waverider buoy uses sensitive accelerometers to determine the motions of a moored buoy. The buoy is designed such that the mooring line and anchor have minimal impact on the motion of the buoy. The motion of the buoy is representative of wave motion, and is used to calculate wave conditions and parameters.

2. TELEDYNE RDI SENTINEL V100 SETUP

The Sentinel V100 was programmed to measure both waves and current. ReadyV software from Teledyne RDI was used to program the Sentinel V100 ADCP. The software calculates the available battery resources and data storage for desired measurement profiles. An example of these displays is shown in the bottom of Figure 2-1 under the heading “Resources”.

A screenshot of the ReadyV software showing the two measurement profiles is shown in Figure 2-1. The profile information is shown in the top right quarter of the screen display. The custom wave and current measurement profiles have the following settings:

Table 2-1 Profile Parameters

	Waves Measurement Profile	Current Measurement Profile
Ping Interval (seconds)	0.5	1
Number of Pings	2300	300
Range (meters)	84	84
Cell Size (meters)	1.0	1.0
Duration(minutes)	19.166	5

The wave measurement occurs once per hour over a 19 minute and 10 second period. Current measurements occur over a 5 minute period 30 minutes after the start of the wave measurements. This setup was chosen to accommodate a deployment duration of 90 days. The setting for the timing of each profile is shown in the Timing tab shown in Figure 2-2. An external battery housing was used with two additional battery packs rated at 540 watt-hours. In total three battery packs were used, one in the Sentinel V100 ADCP and two in the external housing, providing 1,620 watt-hours of energy.

The Sentinel V100 ADCP was deployed on 11:07 AM on November 13th, 2014 and recovered at 8:00 AM on February 26th, 2015, a 104 day deployment. The Sentinel V100 ADCP was still recording measurements when recovered despite being well past the planned deployment duration. The data from the Sentinel V100 ADCP was downloaded by wifi connection and the compass recalibrated. It was redeployed on the same day February 26th, 2015 at 16:29 in the same location. The same setup and configuration was used as in the previous deployment.

The ADCP was recovered on June 4th, 2015. Corrosion within the connection of the external battery and the ADCP caused a failure of the pins in the connector, and the loss of external battery for powering the ADCP. The result of the failure was that data was obtained until April 24^{th,} 2015. The ADCP was sent in for repair and returned to Sea Engineering Inc. with replaced end caps for the battery and ADCP housings. The cable that connects the external battery and ADCP was replaced also.

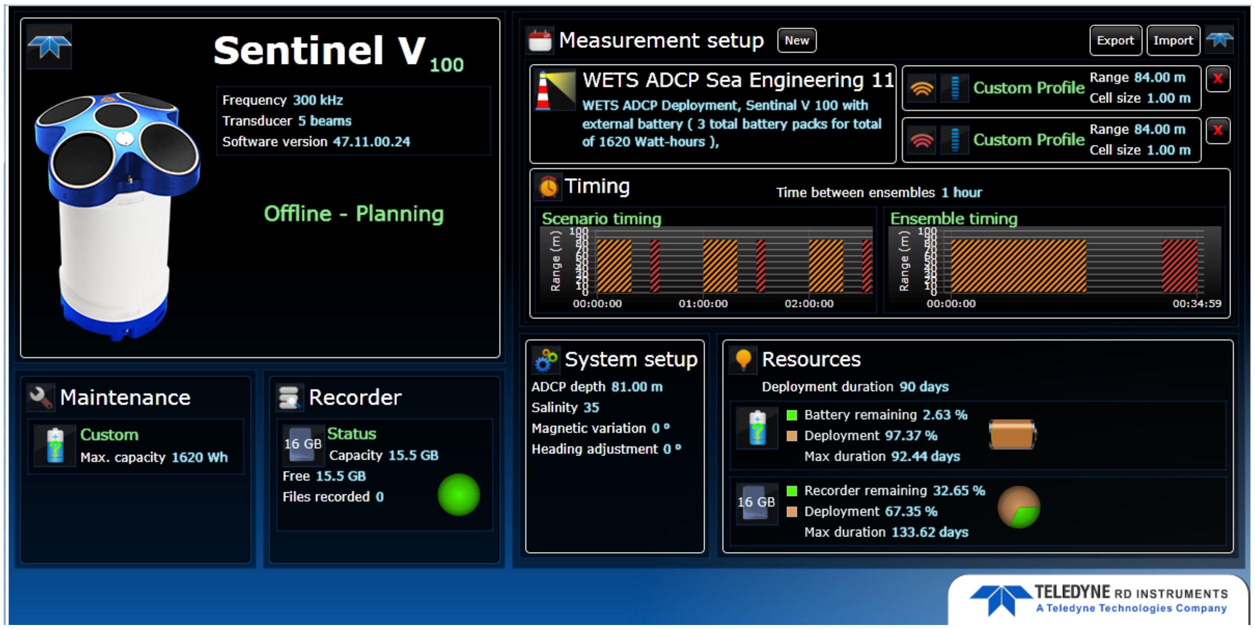


Figure 2-1 ReadyV Software Showing the Sentinel V100 Setup

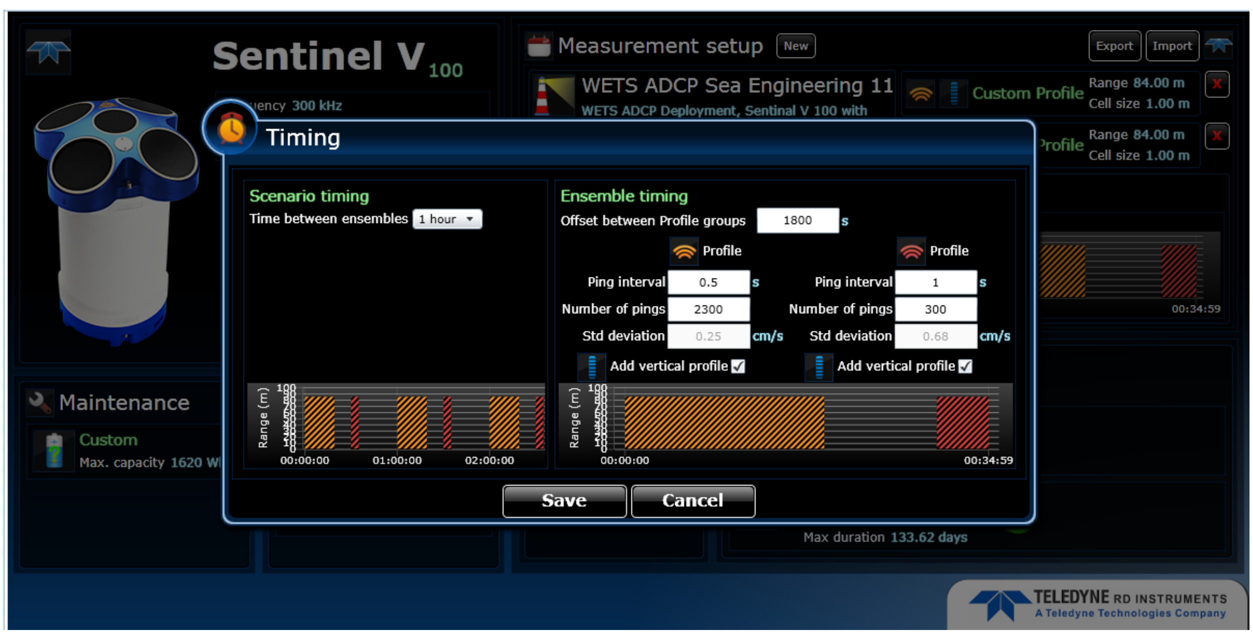


Figure 2-2 ReadyV Software Showing the Timing of Each Profile

3. SENTINEL V100 DATA

The data file for the first deployment of the Sentinel V100 was 12.7 GB of which the waves profile was 11.2 GB. The second deployment had a file size of 6.8 GB and the waves profile data was 6.1 GB. Only the data from the wave profiles was used to calculate the wave statistics. Teledyne RDI provides multiple software options to display the data. The primary data viewing and processing software is Velocity. Velocity displays all the parameters measured. Figure 3-1 presents a Velocity display showing the water speed and water direction for the first four 19 minute wave profile measurements.

The Velocity software also calculates many different wave statistics. The three statistics that will be compared to the Waverider buoy statistics are the significant wave height (H_s), peak period (T_p), and peak direction (D_p). A screen shot of Velocity displaying the wave statistics is shown in Figure 3-2. The direction that the Sentinel V100 ADCP references is magnetic north. These readings were converted to a true north reference using the magnetic declination values for the location of the ADCP on Oahu. The magnetic declination for WETS is 9.6° east. A second program, WavesView, is used to display the spectral data alongside the wave statistics.

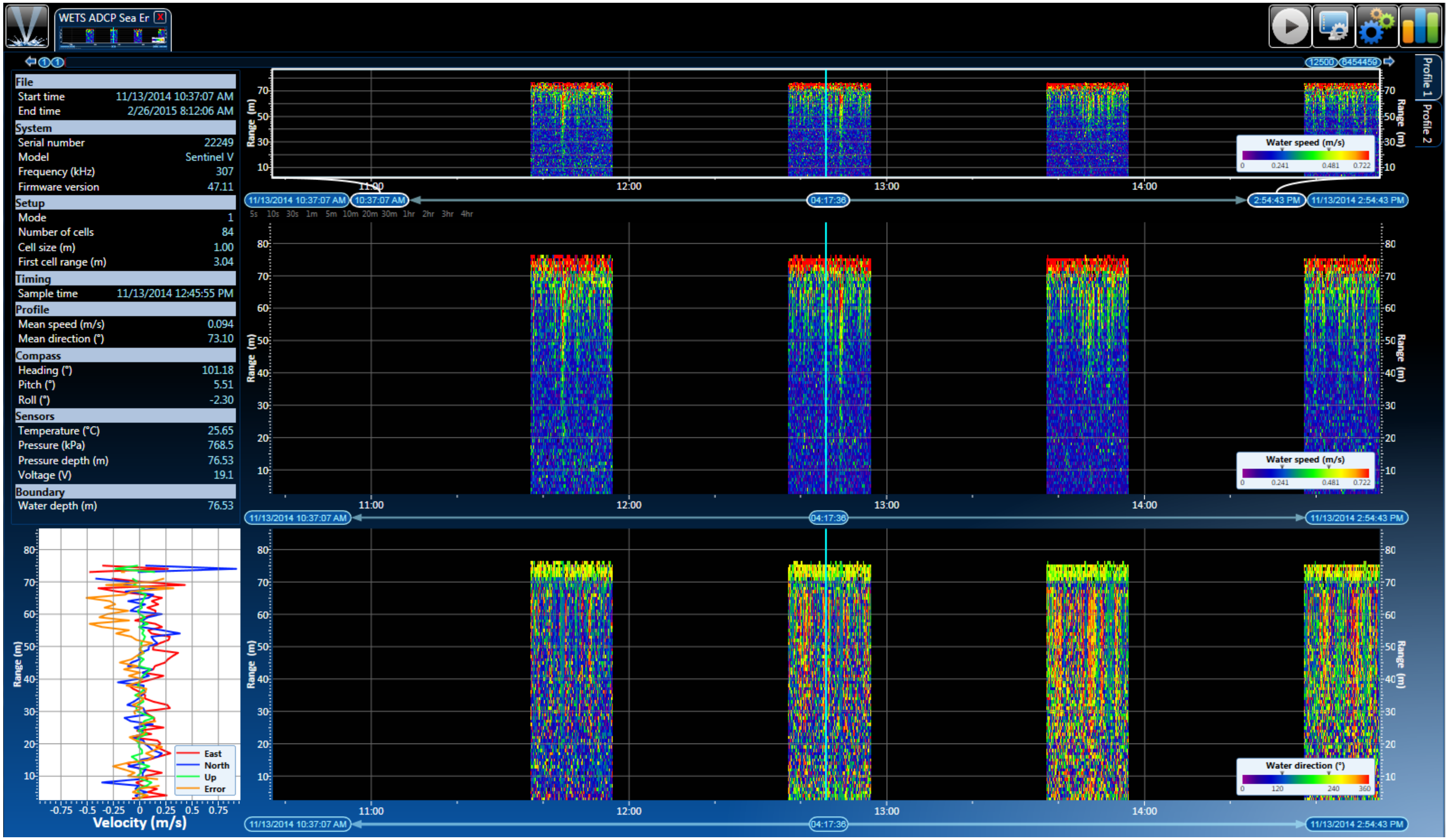


Figure 3-1 Velocity Software Showing Wave Speed and Direction

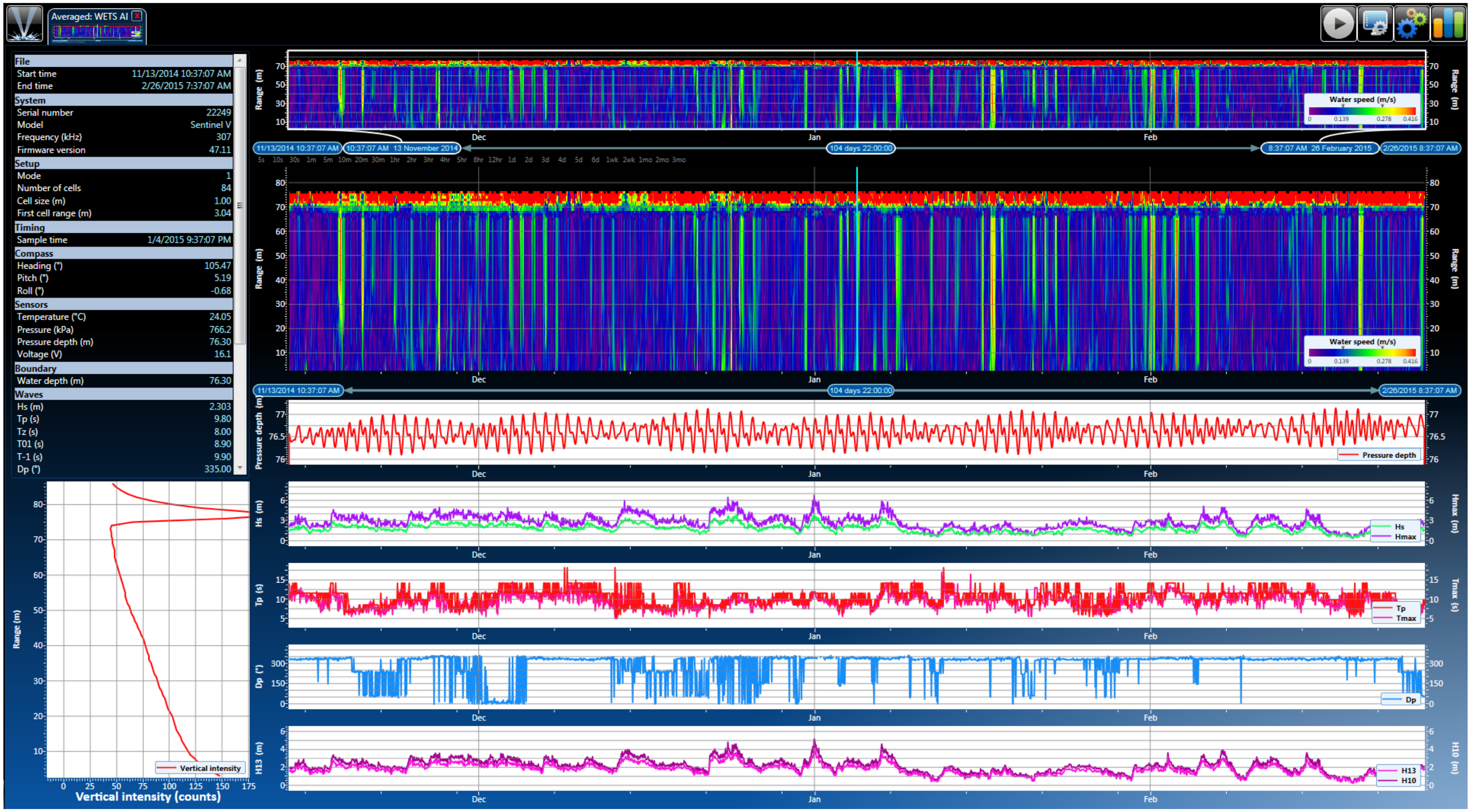


Figure 3-2 Velocity Software Showing Wave Statistics

4. WAVERIDER BUOY DATA

The Waverider buoy is a standard wave measurement buoy that is located near to the Sentinel V100 ADCP. This buoy is managed by the Coastal Data Information Program (CDIP) and is Station 198 in Kaneohe Bay. Data from all CDIP buoys can be easily downloaded from the following website: http://cdip.ucsd.edu/ . The wave statistics are measured every half hour by the Waverider buoy. This buoy was out of operation for repairs from September 11th 2014 to November 7th, 2014. It was redeployed on November 7th, 2014 at 21°28’39” N and 157°45’9.4753” W by Sea Engineering Inc. The Waverider data is reference to Universal Coordinated Time (UTC), which was converted to Hawaii-Aleutian Time Zone (HAST).

5. COMPARSION OF WAVE STATISTICS

The time series of wave data measured by the Sentinel V100 ADCP was compared with the Waverider buoy time series. The Waverider measurements were recorded twice per hour, while the Sentinel V100 ADCP measurements were recorded once per hour. The timestamps for each measurement device did not coincide. Each Sentinel V100 ADCP measurement was compared to the corresponding Waverider measurement closest in time. There were some gaps in the Waverider data over the 163 days of deployment of the Sentinel V100 ADCP. Only the measurements made by the Waverider that were within 30 minutes of a measurement made by the Sentinel V100 ADCP are used in the comparison.

Figure 5-1 shows the time series of the significant wave height (H_s), peak period (T_p), and the peak direction (D_p) from the Sentinel V100 ADCP data and the Waverider data. The time series runs from November 13th, 2014 at 10:37 AM to April 24th, 2015 at 5:29 AM. These time series show overall agreement for each parameter throughout the time series. Monthly time series plots are presented in Appendix A.

A comparison of the significant wave heights measured by both devices is shown in Figure 5-1 and Figure 5-2. A solid line from the linear regression calculations is plotted in red with red dashed lines on either side that incorporate 50% of the data. The slope of the line is 0.94 and the bound for 50% of the data is ±0.15.

Figure 5-3 shows the ranked significant wave height from both the Sentinel V100 ADCP and the Waverider in a quantile-quantile plot. Since the number of measurements for each data set is equal, the quantile-quantile plot is simply a plot of ranked data from the Sentinel V100 ADCP against the ranked data of Waverider. This plot shows that generally the Sentinel V100 ADCP does a good job of predicting the Waverider wave height; however, there is a slight overrepresentation of wave heights.

A rose plot is good way to display the direction and frequency of directionally varying data. Figure 5-4 and Figure 5-5 are rose plots of the significant wave height from the Sentinel V100 ADCP and the Waverider respectively. Figure 5-6 and Figure 5-7 are rose plots of the peak period from the Sentinel V100 ADCP and the Waverider respectively.

The following error metrics were used to compare the peak period (Tp) and significant wave height (Hs) measurements of the Sentinel V100 ADCP with the Waverider: Mean Error (ME), Normalized Bias, Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMS), Correlation (COR), and scatter index (SI). Mean error, also known as bias, is an average difference between Sentinel V100 ADCP data and Waverider data. The mean error is helpful to determine whether one instrument is consistently measuring higher or lower than the other. Root mean squared error is a measure of how close, on average, the instrument measurements are to each other. A small RMSE and NRMS indicates a small difference between compared measurements. Correlation (COR) is the statistical relationship between two or more variables such that systematic changes in the value of one variable are accompanied by systematic changes in the other. The closer COR is to 1, the closer the relationship between the Sentinel V100 ADCP measurements and the Waverider measurements. Scatter index is the RSME between the Sentinel V100 ADCP measurements and the Waverider measurements divided by the mean of the Waverider measurements. It represents the average difference in measurements as a percent of wave height or period. These metrics were calculated by the following equations:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})$$

$$NME = \frac{1}{N}\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})}{\sum_{i=1}^{N}(X_{WRi})}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$NRMSE = \frac{1}{(\max{(X_{WR})} - \min{(X_{WR})})}\sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$COR = \frac{\sum_{i=1}^{N}(X_{ADCPi} - \overline{X_{ADCP}})(X_{WRi} - \overline{X_{WR}})}{\sqrt{\sum_{i=1}^{N}(X_{ADCPi} - \overline{X_{ADCP}})^2}\sqrt{\sum_{i=1}^{N}(X_{WRi} - \overline{X_{WR}})^2}}$$

$$SI = \frac{1}{\overline{X_{WR}}}\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(X_{ADCPi} - X_{WRi}) - \overline{(X_{ADCP} - X_{WR})}\right]^2}$$

In the equations listed above, ADCP and WR subscripts denote the Sentinel V100 ADCP data and Waverider data respectively, and N is the number of data pairs. The over bar denote mean of values. The statistics for both the significant wave height and peak period are shown in Table 5-1.

The statistical analysis for the peak direction (Dp) requires a more advanced approach to account for the fact that directional measurements are angular and not linear. For instance, the mean direction of 359° and 1° is 0° and not 180°. The difference between each measurement from the Sentinel V100 and the Waverider have to account for this also. The angle measurements from the ADCP and the Waverider are broken into vector components to calculate mean and angle differences. Once the true difference is calculated it is used in the above equations. The Scatter Index is also modified to account for the angular type of measure. The first weight term, $(\frac{1}{\overline{X_{WR}}})$, is removed from the equations leaving

$$SI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[(X_{ADCPi} - X_{WRi}) - \overline{(X_{ADCP} - X_{WR})}\right]^2}.$$

Table 5-1 Measurement Statistics

	Root Mean Squared Error, m or s (RMSE)	Normalized Root Mean Squared Error, % (NRMSE)	Mean Error (ME), m or s	Normalized Mean Error (NME), %	Correlation	Scatter Index
Significant Wave Height (Hs)	0.171	0.046	-0.061	-3.281	0.959	0.086
Peak Period (Tp)	1.691	0.133	-1.802	-1.802	0.714	0.162

	Circular Mean of ADCP Data, Deg	Circular Mean of Waverider, Deg	Mean Error (ME), Deg	Root Mean Squared Error, Deg (RMSE)	Correlation	Scatter Index
Peak Direction (Dp)	10.547	17.369	-3.160	35.459	0.590	2.033

The peak direction of the Sentinel V100 data shows more scatter in late February through April. This time period coincides with the second deployment of the Sentinel V100 ADCP. Also the dominant wave condition changes over this period of time. From November to late February the dominant wave condition is longer period north swell. From late February to April the dominant wave condition is shorter period wind driven waves. A plot of peak direction from the Sentinel V100 ADCP and Waverider buoy and wind data from the Kaneohe Bay Marine Corps Air Station (Marion E. Carl Field) is shown in Figure 5-8. Wind data is from the ASOS network of airport weather observations at the following website:

http://mesonet.agron.iastate.edu/request/download.phtml?network=HI_ASOS

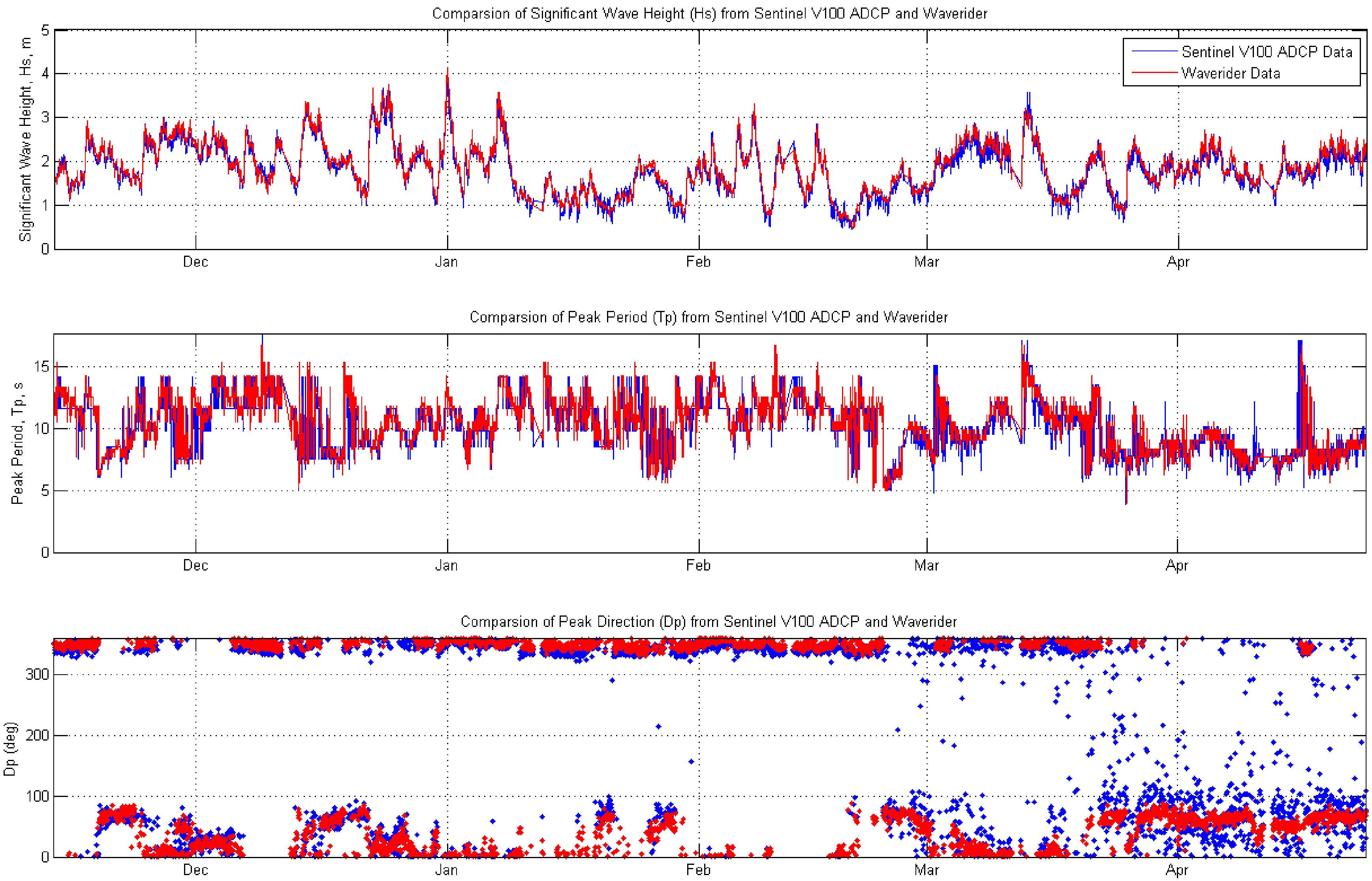


Figure 5-1 Time Series of Sentinel V100 ADCP and Waverider Data

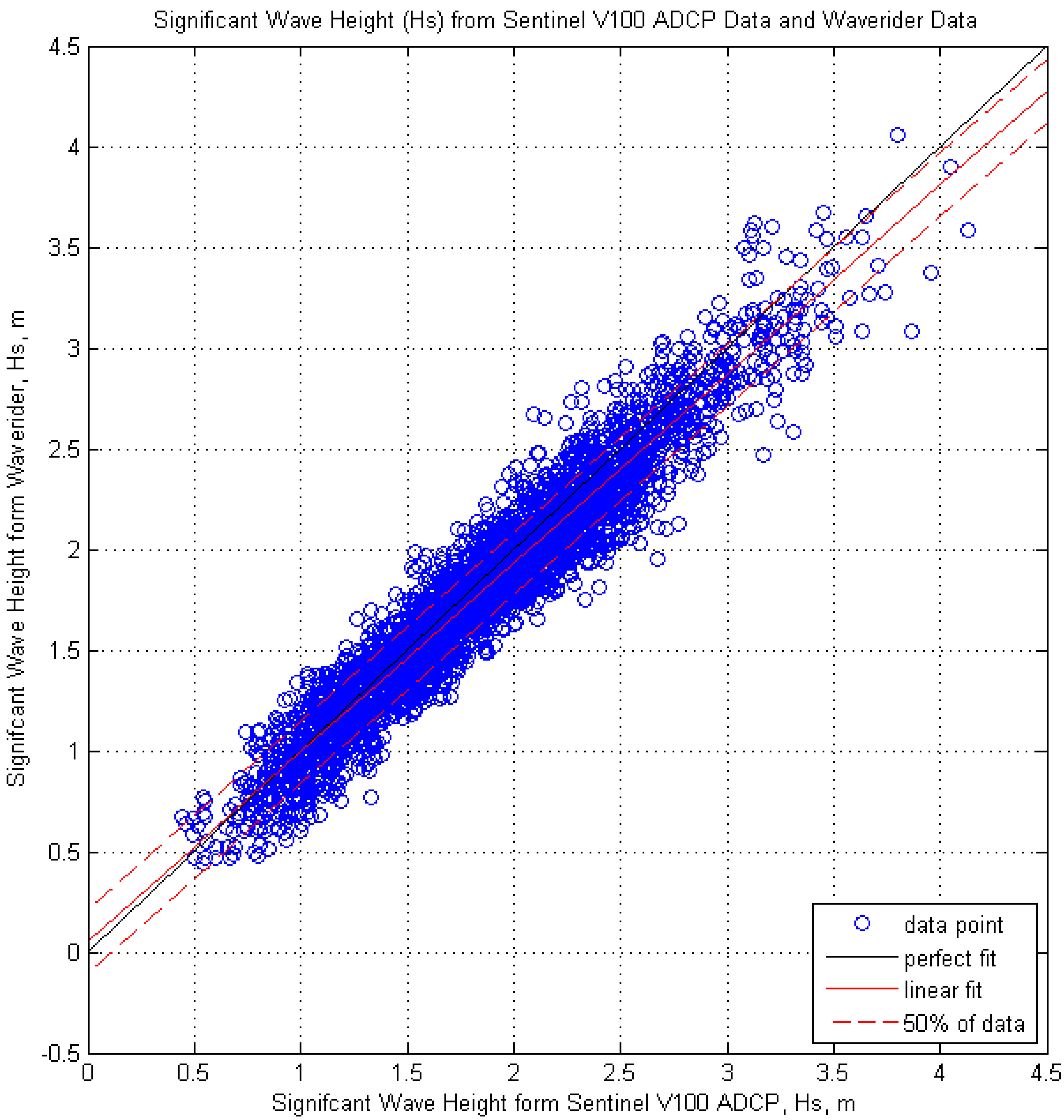


Figure 5-2 Comparison of Wave Height Measurements

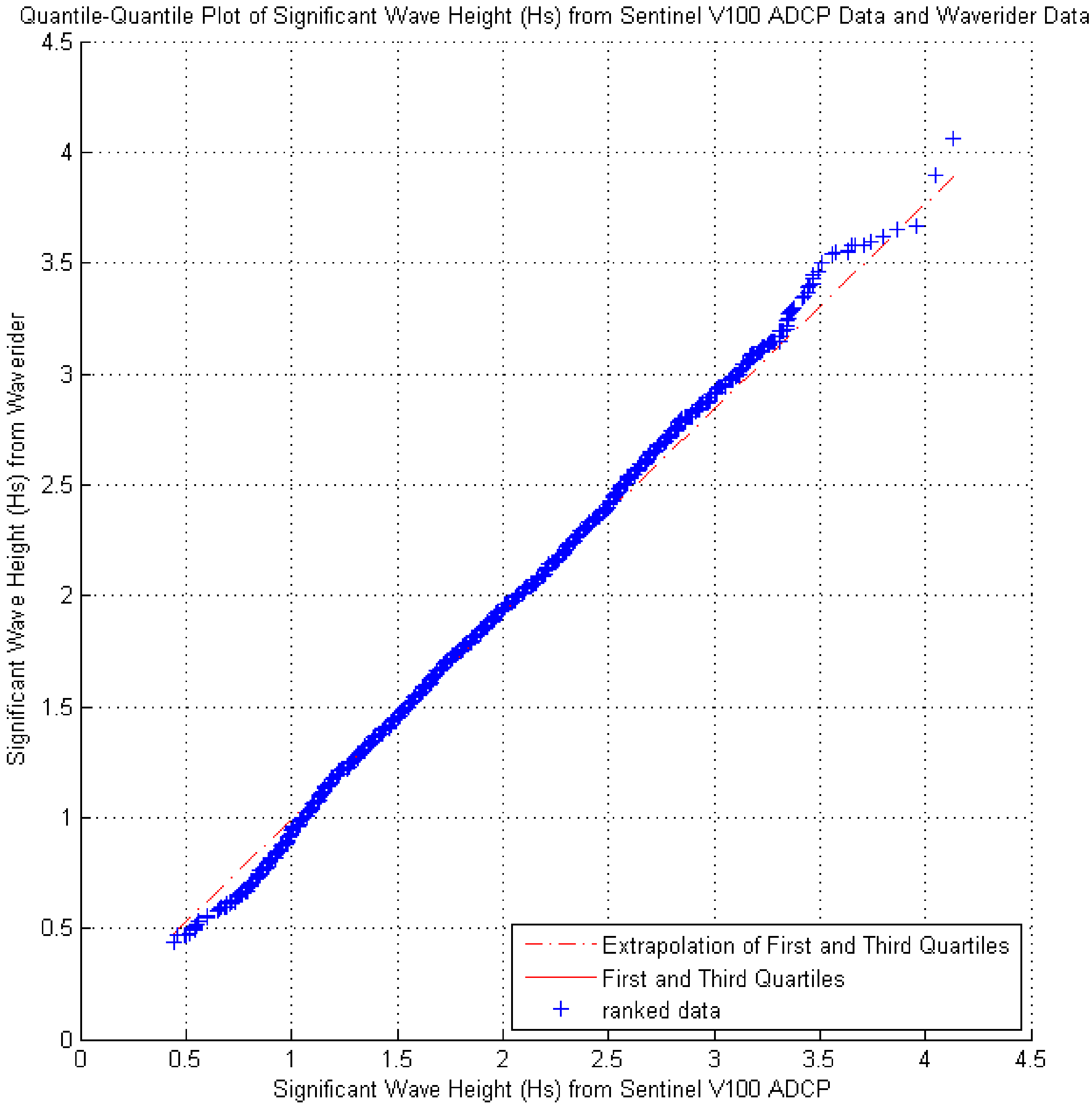


Figure 5-3 Q-Q Plot of Wave Height

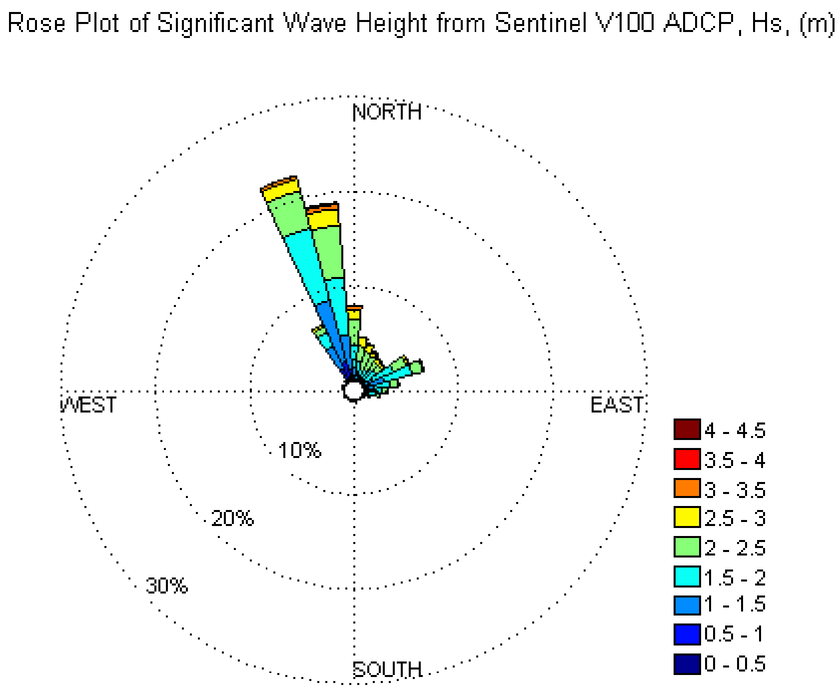


Figure 5-4 Rose plot of Significant Wave Height from Sentinel V100 ADCP

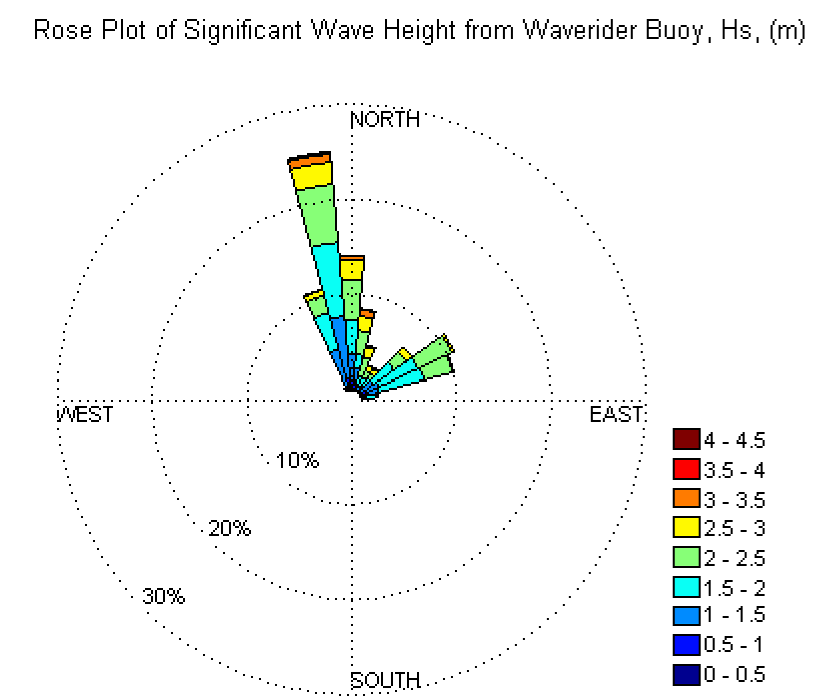


Figure 5-5 Rose Plot of Significant Wave Height from Waverider

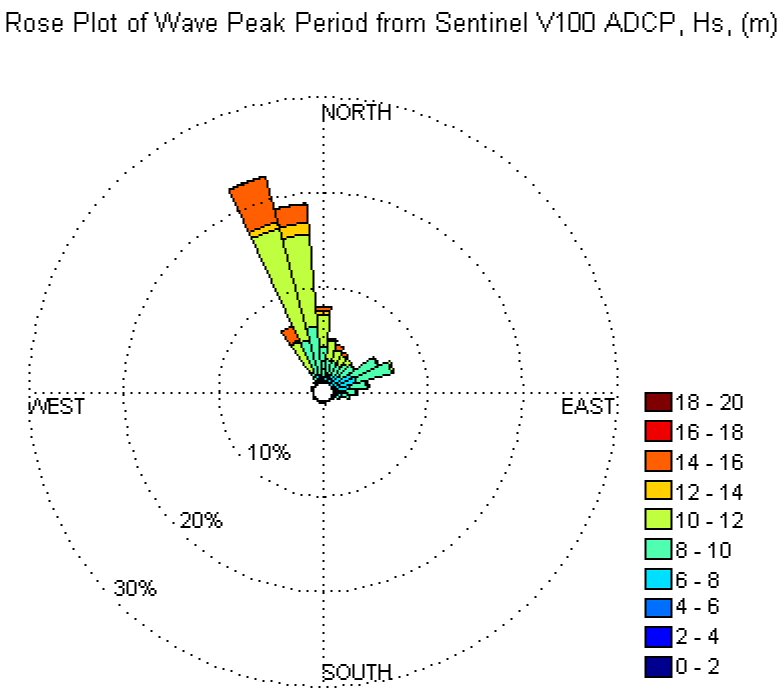


Figure 5-6 Rose Plot of Wave Peak Period from Sentinel V100 ADCP

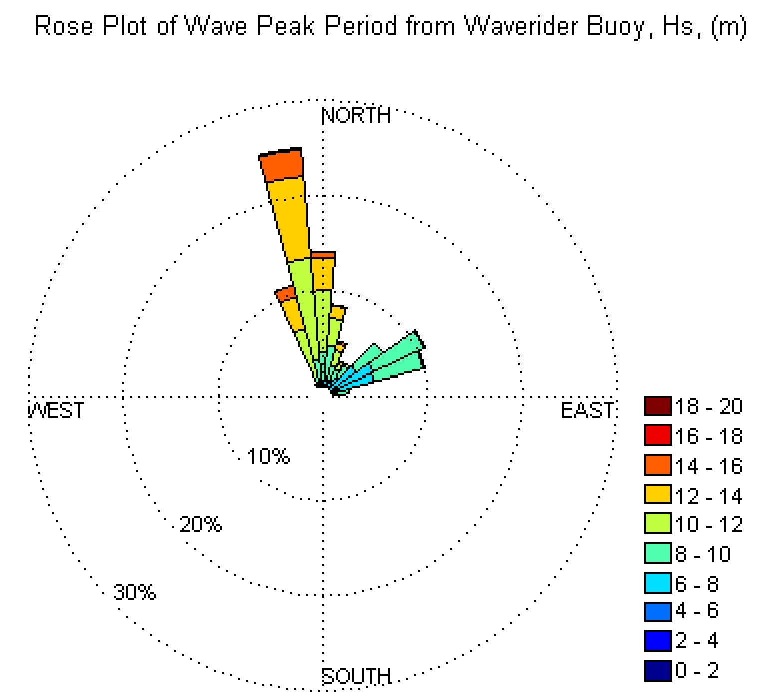


Figure 5-7 Rose Plot of Wave Peak Period from Waverider

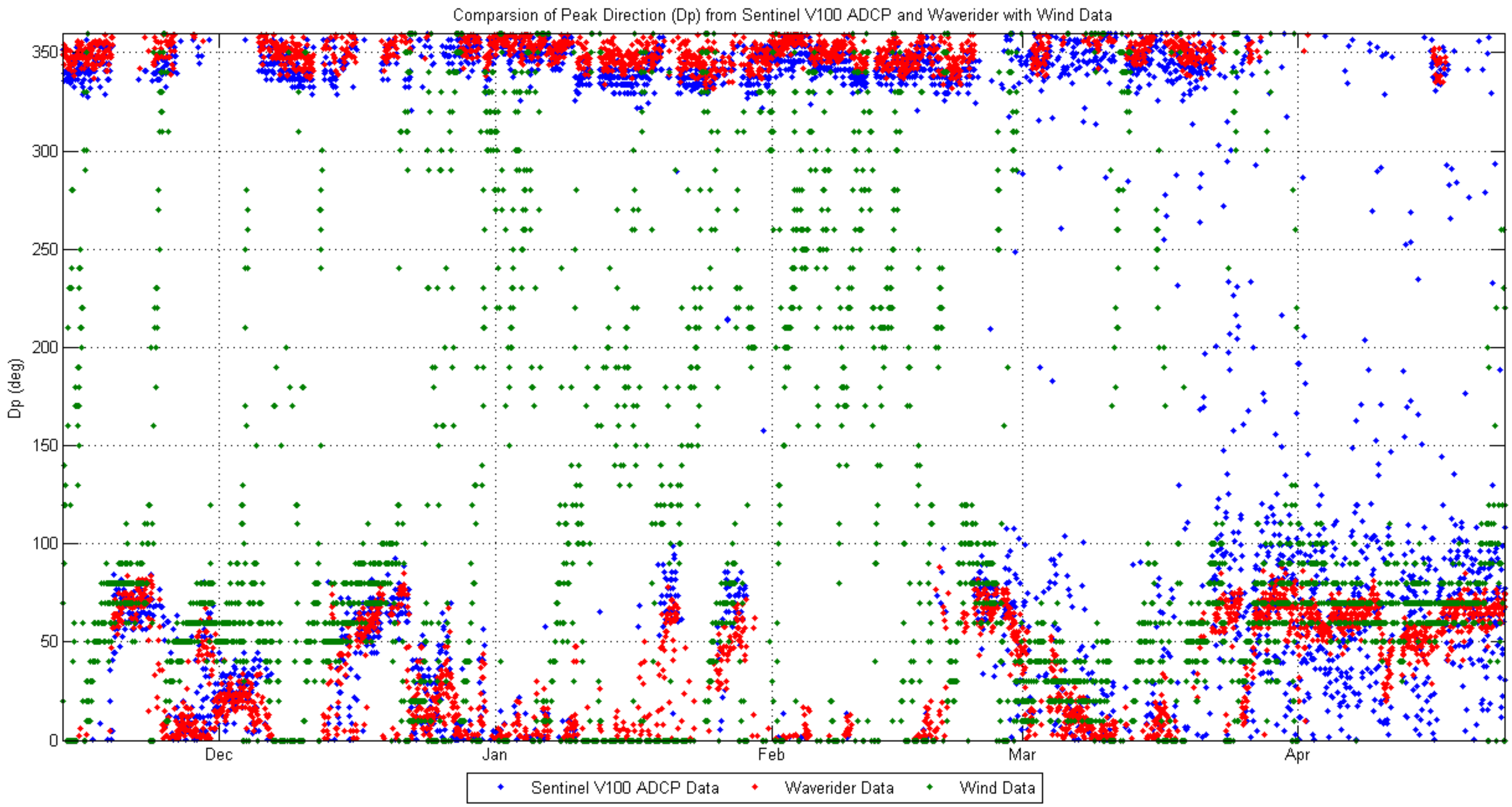


Figure 5-8 Comparison of Peak Direction (Dp) from Sentinel V100 and Waverider with Wind Data

6. CONCLUSION

Sea Engineering Inc. deployed a Teledyne RDI Sentinel V100 ADCP with wave measurement capabilities at WETS from November 13th, 2014 to June 4th, 2015. The two deployments resulted in 163 days of data from November 13th, 2015 to April 24th, 2015. The deployment was in close proximity to the WETS Waverider buoy. Figure 5-1 through Figure 5-7 show a close correspondence between the measurements from the Sentinel V100 and the Waverider for the parameters of significant wave height, peak period, and peak direction. Table 5-1 shows that Sentinel V100 ADCP measurements compare closely with the Waverider measurements. The low mean error and low root mean error indicate that the Sentinel V100 ADCP measurements closely match the Waverider measurements. The correlation of near 1 for the significant wave height signifies that that there is a very close relationship between the Sentinel V100 ADCP measurements and the Waverider measurements. The lower correlation of the peak direction is due to the large range of directional values, and the large jumps in direction – from 360 to 70 degrees – that can occur quickly as a swell event subsides and trade wind seas become dominant. Monthly plots and statistics are shown in APPENDIX A.

7. APPENDIX A

Monthly Time Series of Significant Weight Height, Peak Period, and Peak Direction

Figure 7-1 November 2014 Significant Wave Height, Peak Period, and Peak Direction

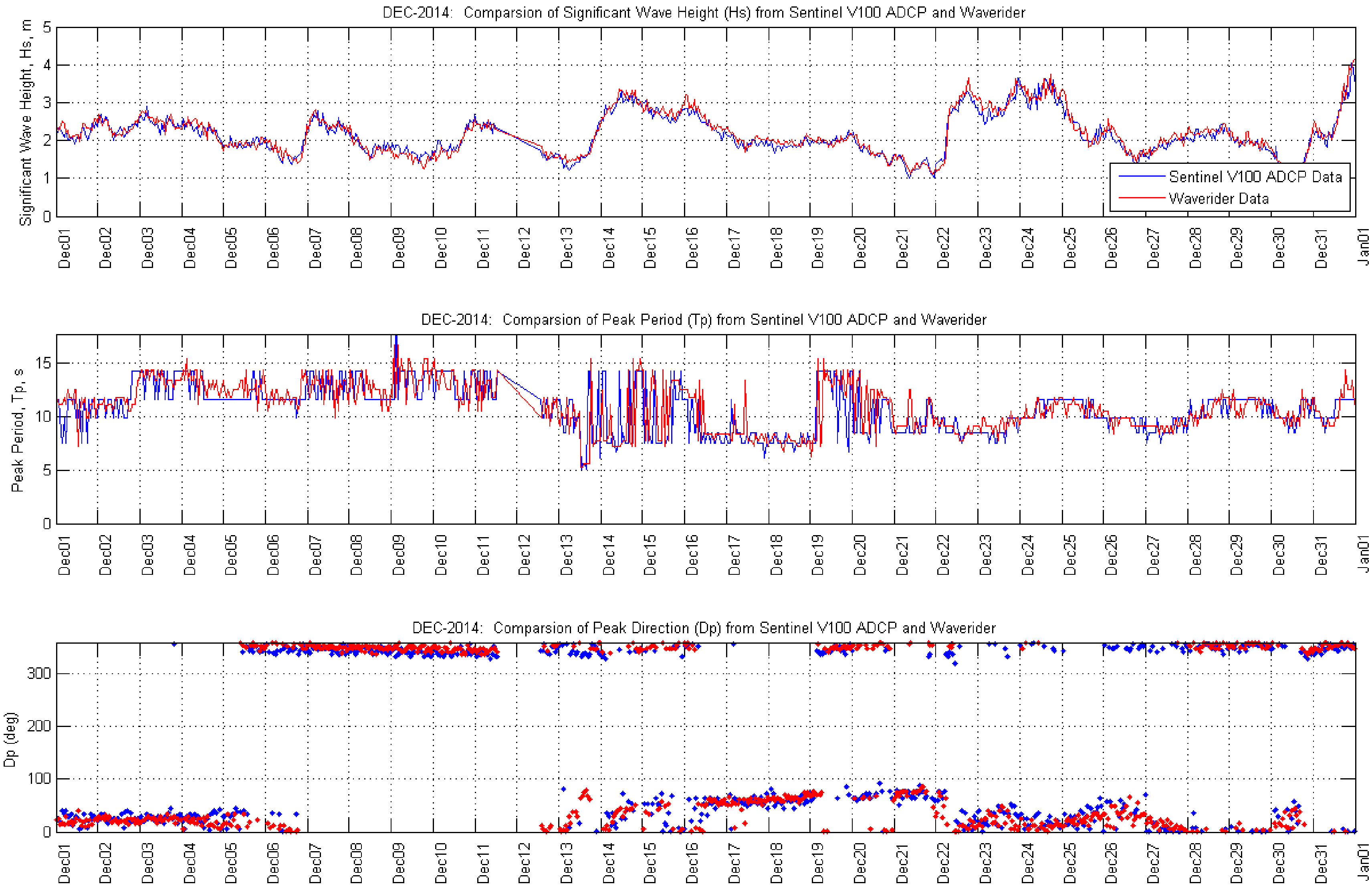


Figure 7-2 December 2014 Significant Wave Height, Peak Period, and Peak Direction

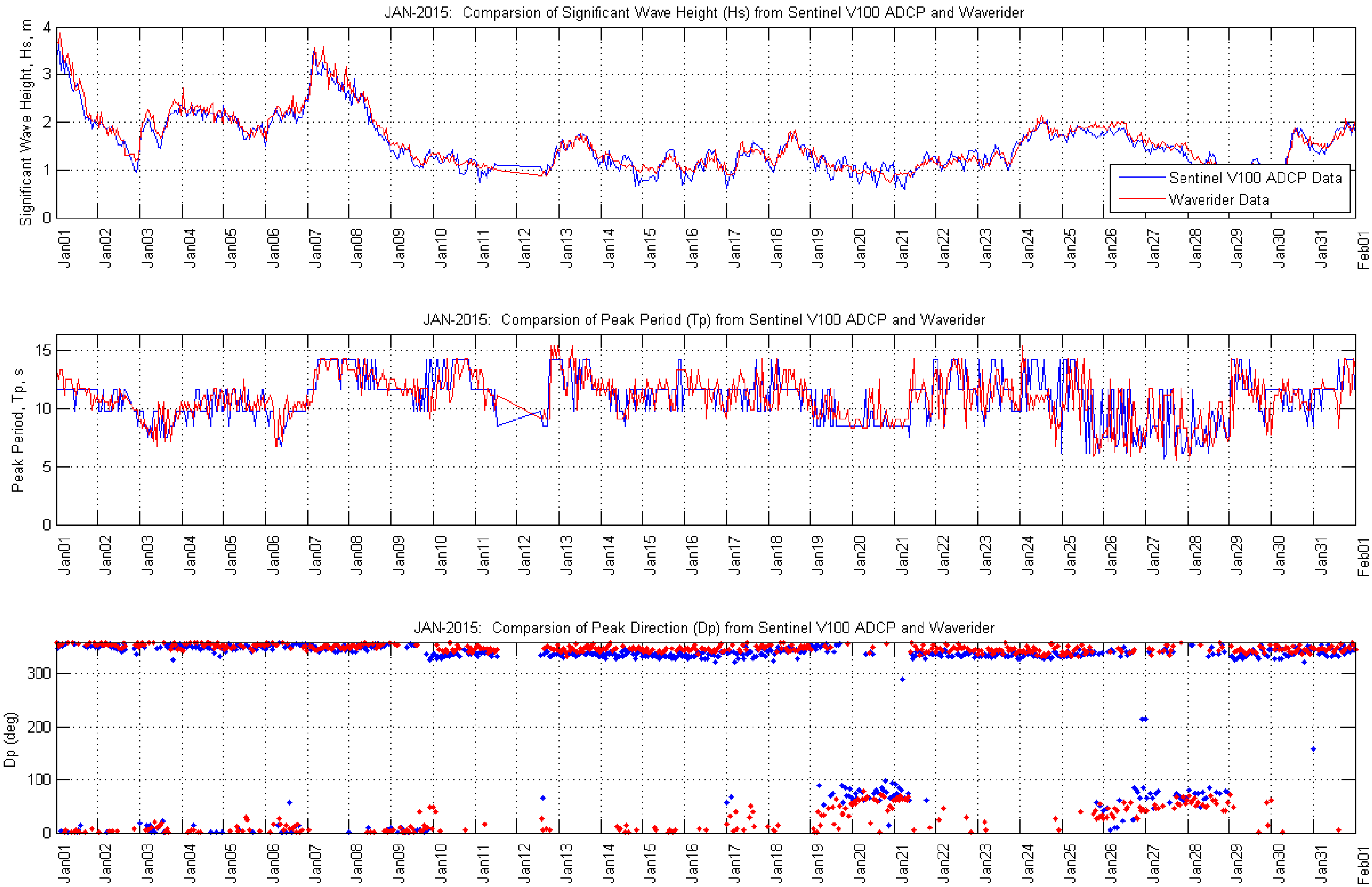


Figure 7-3 January Significant Wave Height, Peak Period, and Peak Direction

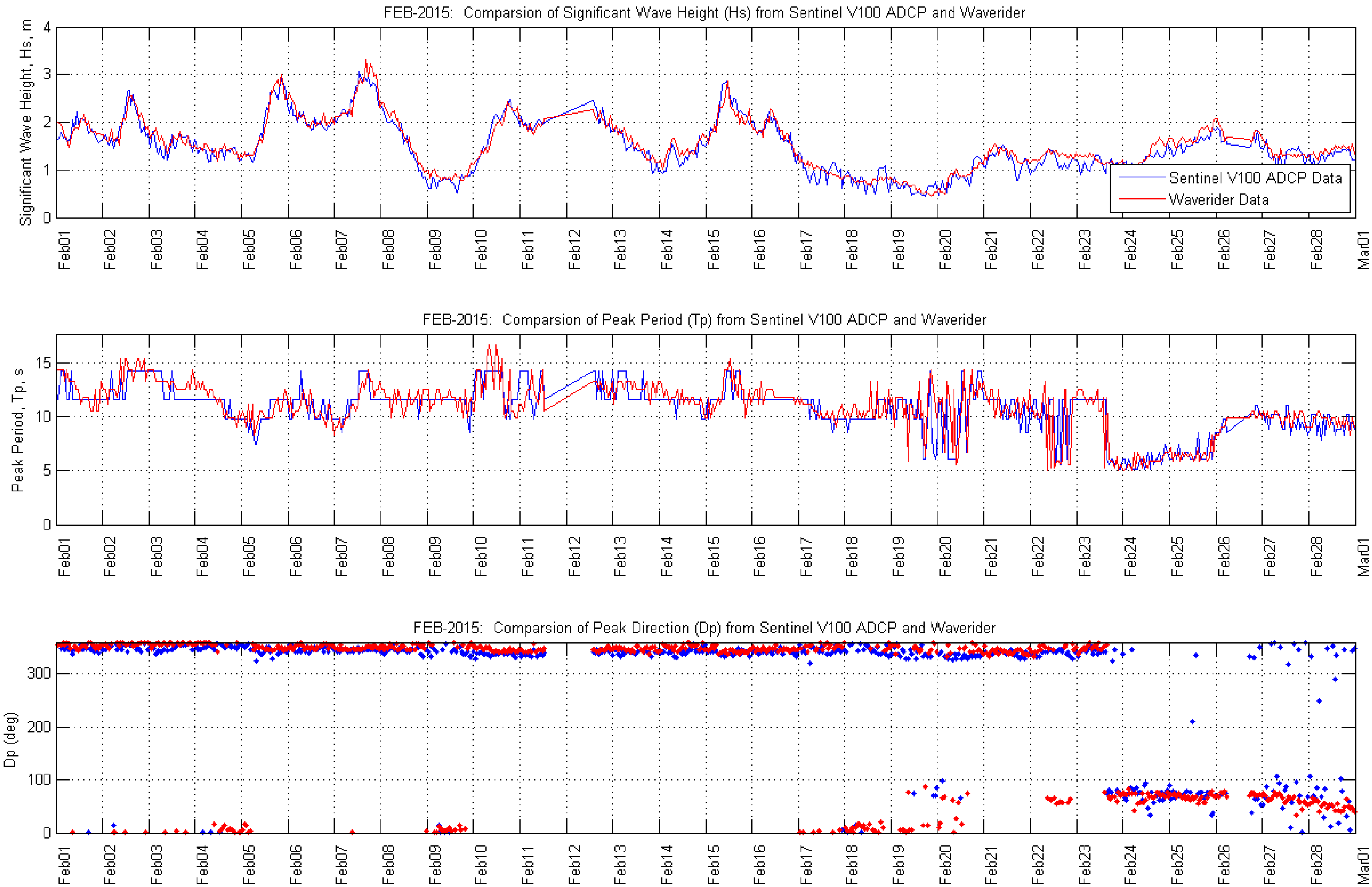


Figure 7-4 February 2015 Significant Wave Height, Peak Period, and Peak Direction

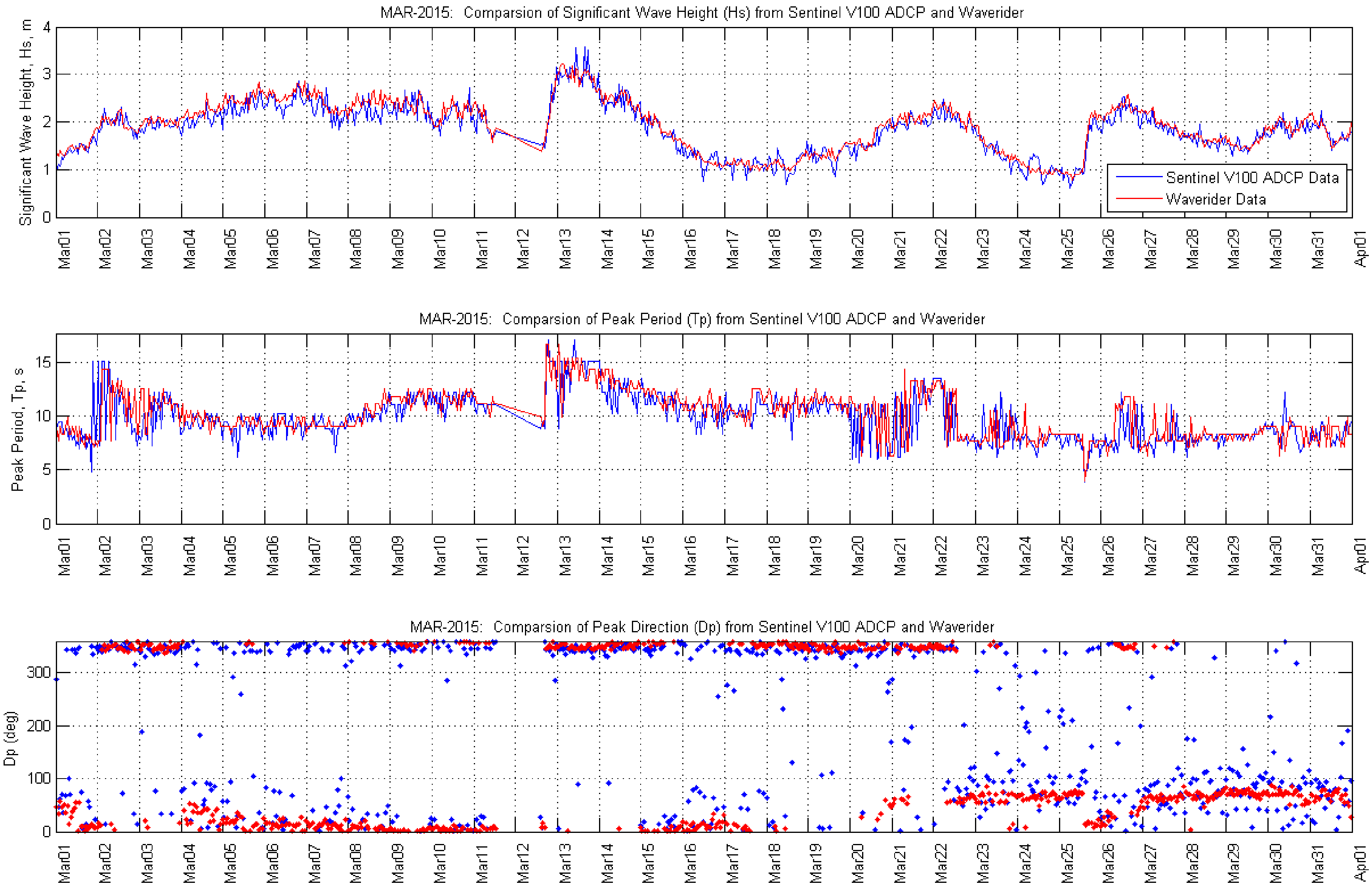


Figure 7-5 March 2015 Significant Wave Height, Peak Period, and Peak Direction

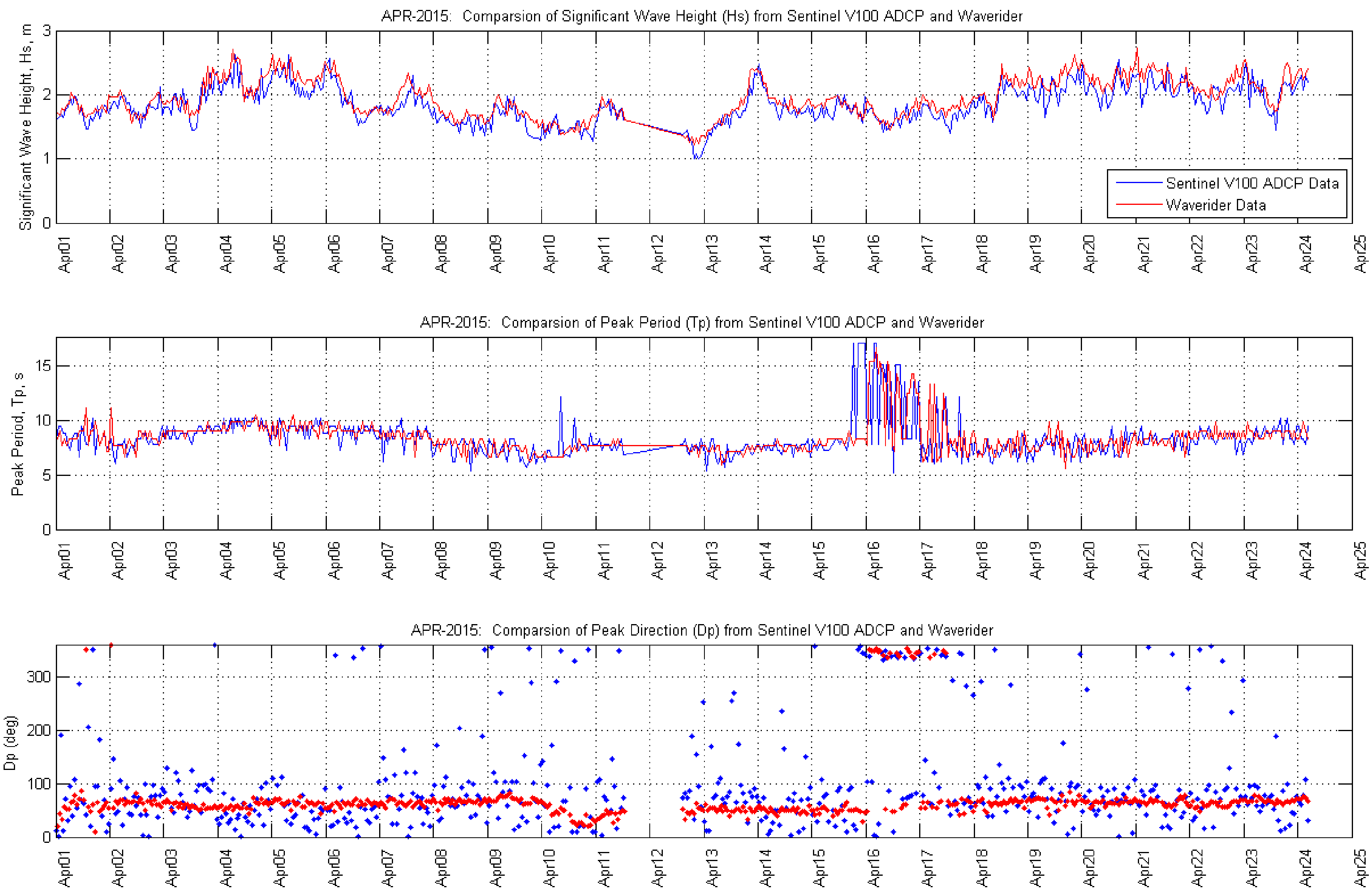


Figure 7-6 April 2015 Significant Wave Height, Peak Period, and Peak Direction

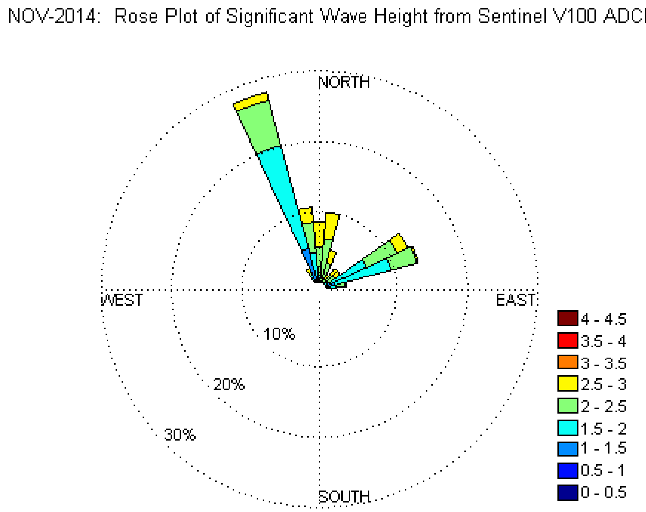


Figure 7-7 November 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

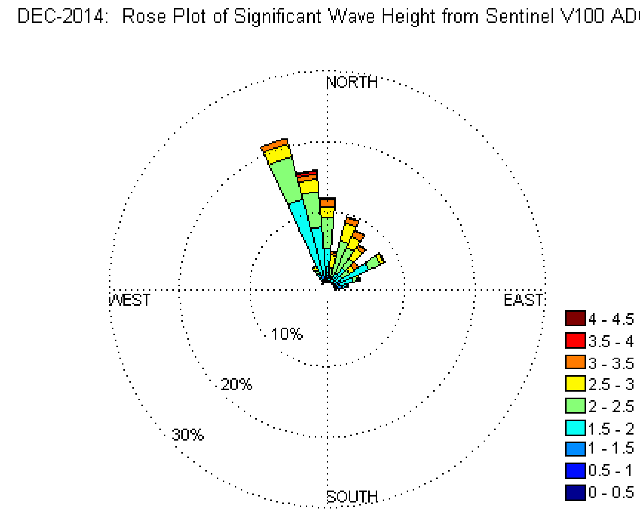


Figure 7-9 December 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

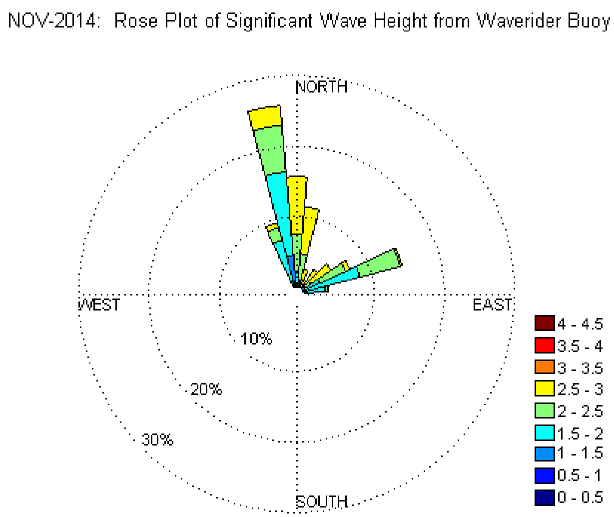


Figure 7-8 November 2015 Rose Plot of Significant Wave Height from Waverider Buoy

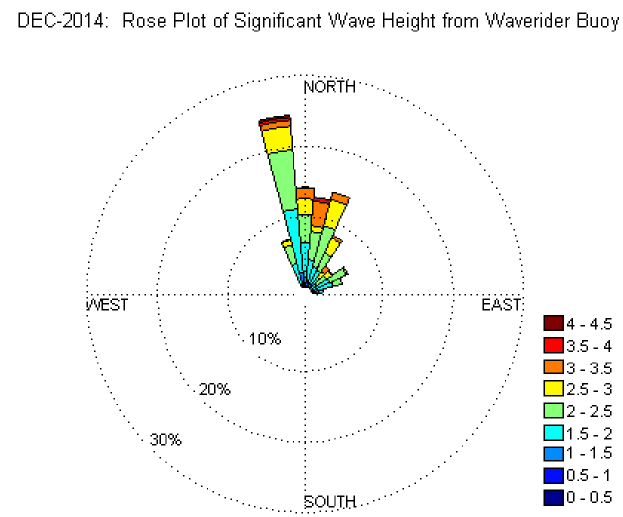


Figure 7-10 December 2015 Rose Plot of Significant Wave Height from Waverider Buoy

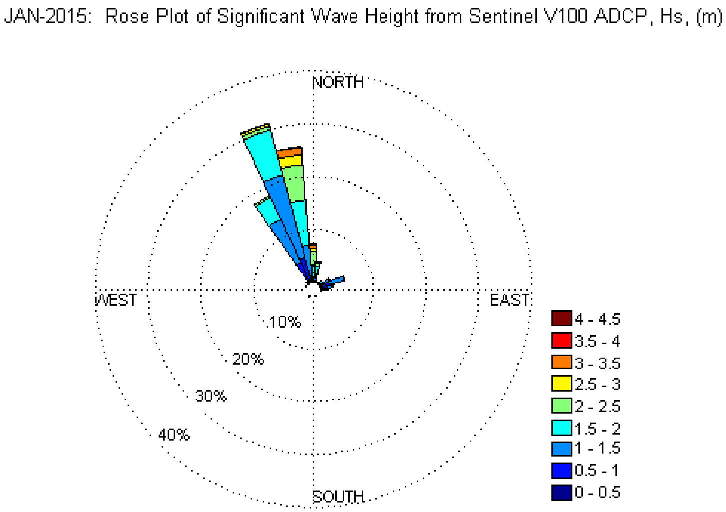


Figure 7-11 January 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

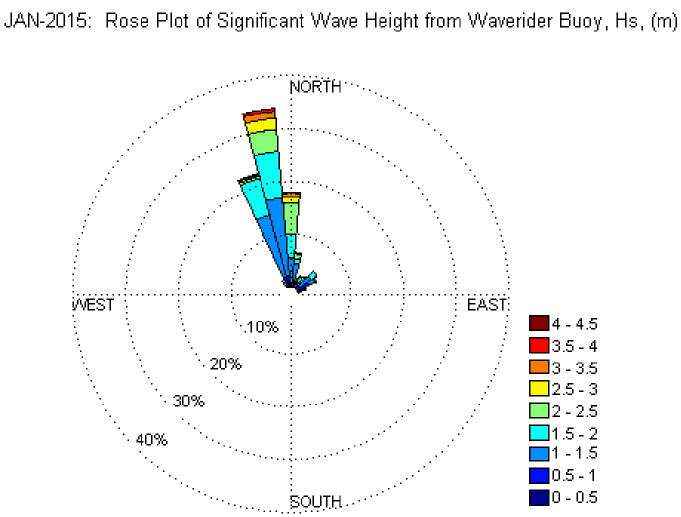


Figure 7-12 January 2015 Rose Plot of Significant Wave Height from Waverider

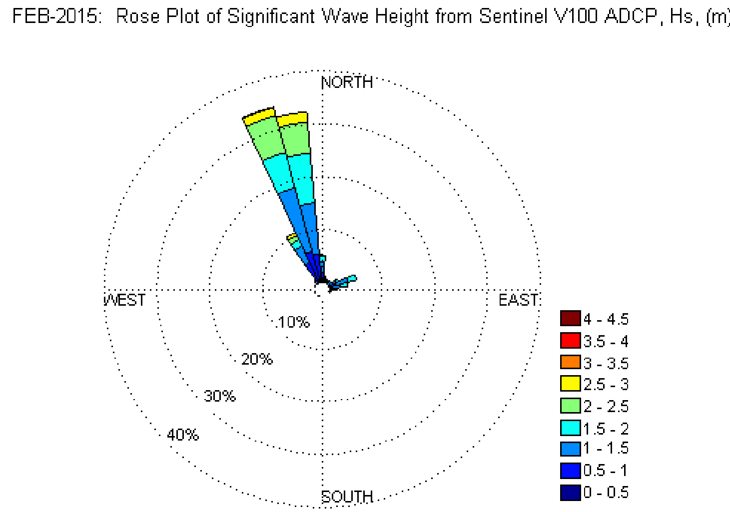


Figure 7-13 February 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

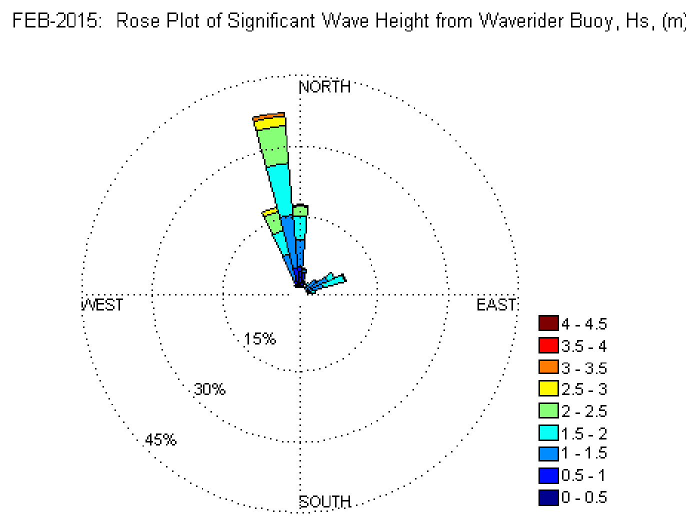


Figure 7-14 February 2015 Rose Plot of Significant Wave Height from Waverider

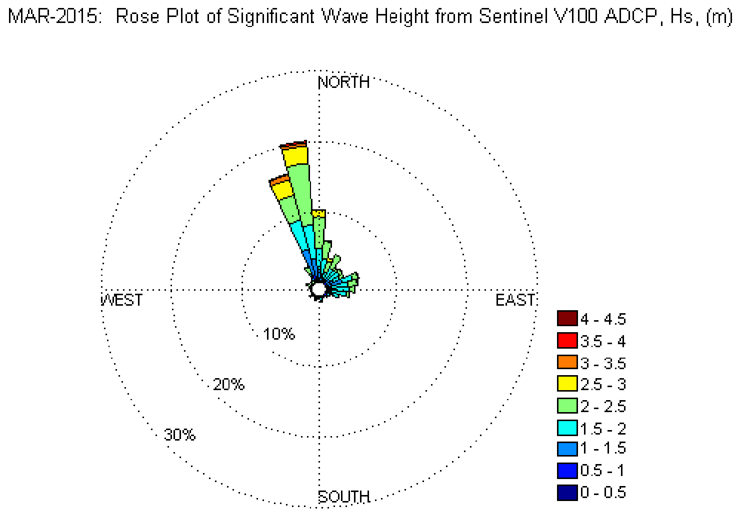


Figure 7-15 March 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

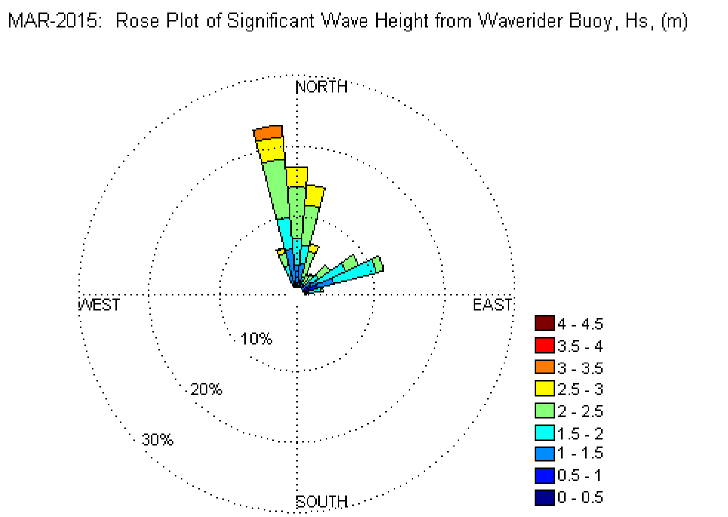


Figure 7-16 March 2015 Rose Plot of Significant Wave Height from Waverider

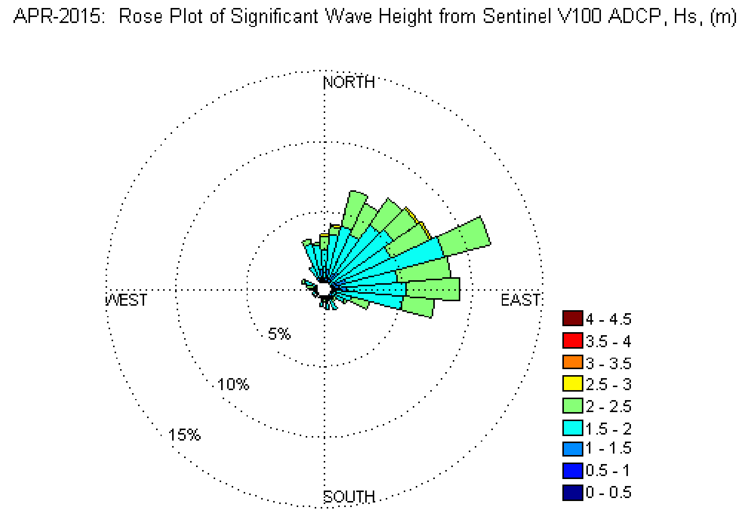


Figure 7-17 April 2015 Rose Plot of Significant Wave Height from Sentinel V100 ADCP

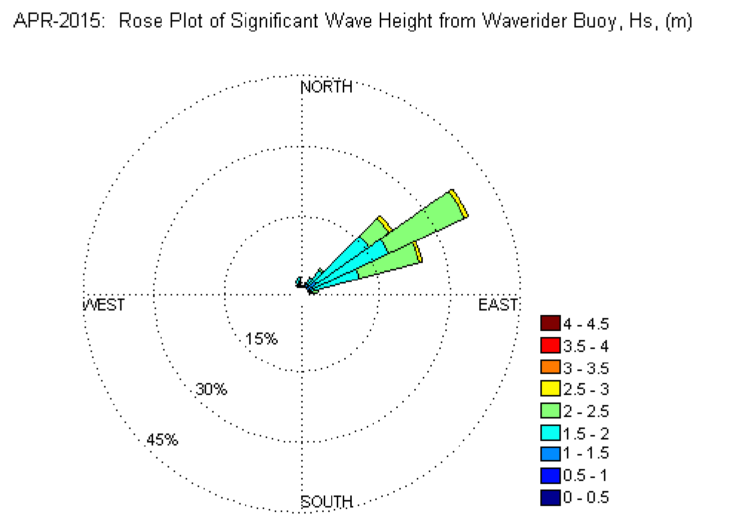


Figure 7-18 April 2015 Rose Plot of Significant Wave Height from Waverider

Table 7-1 Monthly Significant Wave Height Statistics

	Month	Root Mean Squared Error, m or s (RMSE)	Normalized Root Mean Squared Error, % (NRMSE)	Mean Error (ME), m or s	Normalized Mean Error (NME), %	Correlation	Scatter Index
Significant Wave Height (Hs)	November 2014	0.149	0.081	-0.057	-2.712	0.953	0.065
	December 2014	0.173	0.056	-0.042	-1.898	0.954	0.077
	January 2015	0.163	0.052	-0.048	-3.034	0.962	0.099
	February 2015	0.171	0.060	-0.059	-3.881	0.955	0.105
	March 2015	0.186	0.076	-0.068	-3.564	0.945	0.091
	April 2015	0.175	0.116	-0.102	-5.215	0.883	0.073

Table 7-2 Monthly Peak Period Statistics

	Month	Root Mean Squared Error, m or s (RMSE)	Normalized Root Mean Squared Error, % (NRMSE)	Mean Error (ME), m or s	Normalized Mean Error (NME), %	Correlation	Scatter Index
Peak Period (Tp)	November 2014	1.717	0.188	-0.357	-3.393	0.679	0.160
	December 2014	1.840	0.161	-0.193	-1.766	0.648	0.168
	January 2015	1.769	0.180	-0.074	-0.676	0.596	0.161
	February 2015	1.496	0.128	-0.172	-1.579	0.778	0.136
	March 2015	1.678	0.132	-0.302	-2.996	0.692	0.164
	April 2015	1.582	0.142	-0.051	-0.609	0.535	0.188

Table 7-3 Monthly Peak Direction Statistics

	Month	Circular Mean of ADCP Data, Deg	Circular Mean of Waverider, Deg	Mean Error (ME), Deg	Root Mean Squared Error, Deg (RMSE)	Correlation	Scatter Index
Peak Direction, Dp	November 2014	16.182	18.250	-2.151	23.886	0.773	23.789
	December 2014	12.019	13.693	-1.565	25.306	0.613	25.257
	January 2015	-8.466	0.364	-6.134	27.763	0.549	27.077
	February 2015	-6.608	5.346	-10.256	27.802	0.668	25.841
	March 2015	14.732	18.908	1.981	47.463	0.409	47.422
	April 2015	56.601	56.844	-0.831	50.041	0.155	50.035