Emerging National Data Buoy Center (NDBC) Wave Systems

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Abstract— The U.S. National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) reports directional wave observations from a fleet of weather observation buoys. Emerging technologies allow for the development of new systems to improve NDBC's wave mission in support of the National Weather Service (NWS). NDBC is developing a new wave system, the Ocean Wave Linux (OWL). The OWL system uses a Linux-based processor to reduce computational time, but retains existing NDBC wave system data processing techniques and algorithms, as well as the pitch and roll angle method to calculate wave direction. This configuration allows NDBC to retain data continuity, reduce development costs, and avoid problems associated with changing data message formats.

NDBC is testing a newly developed 2.1-m foam hull, which is designed to house NDBC's new, advanced Self-Contained Ocean Observing Payload (SCOOP). The 2.1-m foam hull reduces the superstructure area, which improves operational efficiency. Field evaluations of wave data between two 2.1-m foam hulls with SCOOP's and nearby Datawell Waveriders show only small biases among the different systems. These comparisons indicate that the 2.1-m foam hull with SCOOP allows for good agreement with historic and operational wave systems, minimizing the impact of a smaller hull on present wave applications and long-term records.

Keywords—waves, buoy, instrumentation, sensors, technology refresh

Introduction

The National Data Buoy Center (NDBC) Ocean Wave Linux (OWL) wave system development is driven by the fact that the NDBC legacy wave processor, the Digital Directional Wave Module (DDWM), will soon be electronically obsolete. This development provides NDBC with the opportunity to reduce the wave system power requirement. With the availability of new motion sensors and Linux based processing technologies that provide significantly faster processing efficiency, NDBC is developing a state of the art wave system to replace the legacy DDWM.

NDBC is evaluating a newly developed 2.1-m foam hull that is smaller and lighter than the standard NDBC 3-m aluminum hull (Figure 1). The 2.1-m foam hull is designed to house NDBC's new, advanced Self-Contained Ocean Observing Payload (SCOOP), which offers increased data reliability and more frequent meteorological observations (10 minute reporting from previous hourly measurements) than preceding NDBC payloads.

The 2.1-m foam hull SCOOP aims to lower operational and maintenance costs, as well as allow for efficient and safer handling, as the complete payload stack is installed into the buoy receptacle during installation and service. This reduces the need for technicians to spend prolonged periods perched on a deployed buoy to replace individual sensors during services.

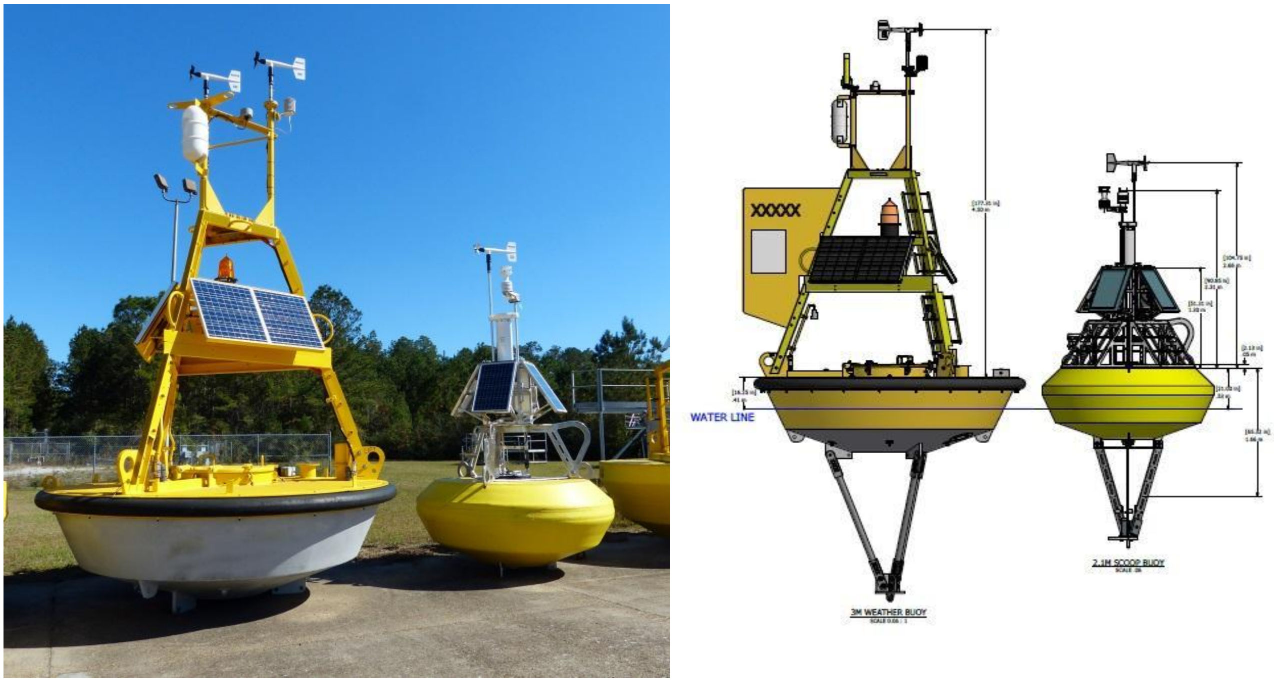

Figure 1: NDBC Standard 3-m aluminum hull, on the left in both the photograph and the schematic, next to a new 2.1-m foam hull on the right (NDBC, 2018). Of note is that the 2.1-m foam hull schematic shows the seal cage that is required on hulls destined for Pacific Ocean deployment, while the photograph shows hulls deployed in other regions.

A. OCEAN WAVE LINUX (OWL)

NDBC's legacy wave observation system is the Digital Directional Wave Module (DDWM), which uses electronic technology from the early 2000s. The DDWM, Version 3.04 uses the Lord Microstrain 3DM-GX1® (Figure 2) to produce acceleration, angular rate and magnetic flux density each along three orthogonal axes of the buoy hull [1][2]. The DDWM uses the Angular Rate System (ARS) method to calculate pitch and roll angles, which are used to calculate wave directions [3]. A tilt correction is made to the vertical acceleration to mitigate the Bender Effect [4][5].

The newly developed OWL module consists of a VectorNav VN-100 (which combines a set of 3-axis for acceleration, angular rate and magnetic flux density [6]), a Linux processing board, and a custom NDBC circuit board that provides control and data collection capabilities (Figure 2). Although the OWL is coded on a different processor, it uses the same methodology and wave algorithms as the DDWM, ensuring data continuity between NDBC wave systems.

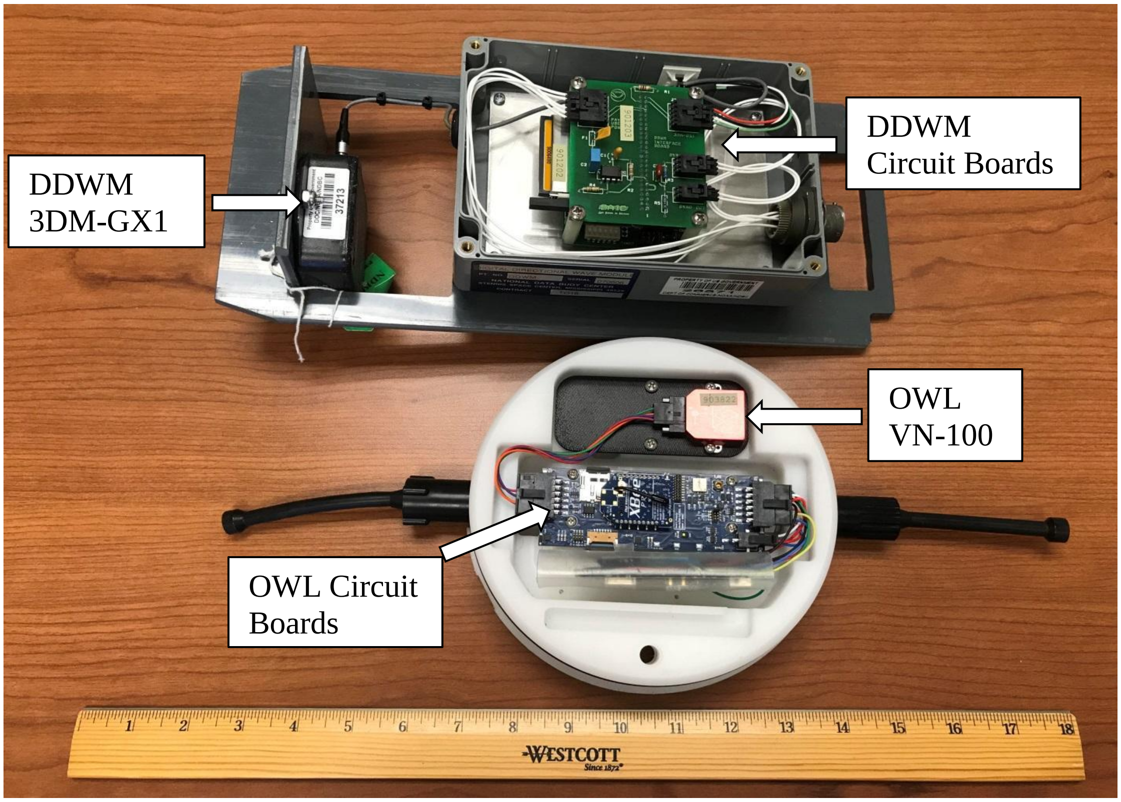

Figure 2: NDBC Legacy DDWM Module on the top and the new OWL Module on the bottom (NDBC, 2018).

A.1 NDBC OWL Tests

NDBC is performing extensive tests on the OWL to verify proper code operation, motion sensing, and operation of the electronics. The NDBC wave product performance specifications are listed in Table 1. The OWL was tested in an environmental chamber to subject the electronics and sensor to extreme cold and heat (e.g. -20°C and +50°C). The system soaked at each extreme for a twenty four hour period. Recorded raw signals were plotted and statistics computed to determine if there was any shift in signal levels across the temperature extremes and at startup, or other errant behavior. Differences in signal levels were found to be within tolerance and the electronics performed as expected.

Table 1: NDBC wave product performance specifications [7]

Parameter	**Range**	**Resolution**	**System Accuracy**
Wave Height	0 to 35 m	0.1 m	± 0.2 m
Wave Period	0 to 30 sec	1.0 sec	± 1.0 sec
Wave Direction	0 to 360 °	0.1°	± 10 °

Magnetic performance was verified at NDBC's compass rose facility. This is a magnetically clean area that contains a marked turntable for true compass directions. OWL results show accurate magnetic performance. Power analysis shows the OWL uses 65% less power than the DDWM. The overall impact of this reduction on the total SCOOP buoy power budget is 14%.

Laboratory tests included using NDBC’s Desktop Wave Simulator (DTWS) and Ocean Wave Instrumentation Facility (OWIF) to simulate wind and swell ocean waves, respectively. These machines turn a platform through a vertical circular motion while inducing tilt action on the platform. The wave height, period, and tilt are known. The DDWM 3DM-GX1 and the OWL VN-100 sensors were simultaneously tested on these machines (Figure 3).

Figure 3: DDWM 3DM-GX1 (black sensor) and the OWL VN-100 (red sensor) sensors mounted on the NDBC's Desktop Wave Simulator (DTWS).

A.2 Intercomparison Results

The DDWM 3DM-GX1 module and the OWL VN-100 wave product results were compared and referenced to the expected outcomes (Table 2). Table 2 shows a sample of comparison results for peak spectral period (listed as NDBC’s dominant wave period hereafter), significant wave height and mean wave direction for circular motion periods between 3.1 and 21.1 seconds that were recorded during DTWS tests.

Table 2: DTWS wave product comparison results for the DDWM and the OWL sensors

Dominant/Peak Period (s)			**Significant Wave Height (m)**			**Mean Wave Direction (°)**		
Expected (± 1 sec)	**DDWM**	**OWL**	**Expected (± 0.03 m)**	**DDWM**	**OWL**	**Expected (± 1 °)**	**DDWM**	**OWL**
3.1	3.03	3.03	**0.67**	0.64	0.65	**153**	153	159
4.0	4	4	**0.67**	0.67	0.66	**153**	153	159
7.1	7.14	7.14	**0.67**	0.68	0.67	**153**	153	158
12.0	12.12	12.12	**0.67**	0.69	0.67	**153**	153	158
16.0	16	16	**0.67**	0.71	0.67	**153**	153	158
21.1	21.05	21.05	**0.67**	0.8	0.66	**153**	153	158

Preliminary results show good agreement between the DDWM and OWL for dominant period (Table 2). The OWL appears to perform better in significant wave height results, especially in long swell periods. Differences in the magnetic headings between the OWL and DDWM require additional testing.

Analyses of non-directional wave power spectral density, represented by C11m (vertically-stabilized heave acceleration spectrum uncorrected for noise), show that the OWL agrees with the DDWM, and attenuates electronic noise interference. Figure 4 highlights the one order of magnitude noise reduction, showing the C11m results collected during periods of 4 and 12 seconds on the DTWS.

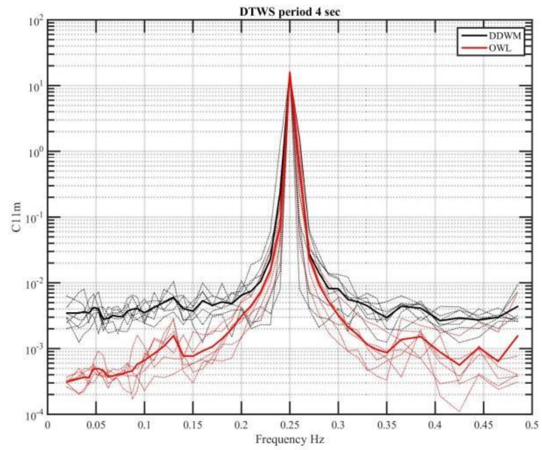

Figure 4: NDBC's Desktop Wave Simulator spectral C11m (uncorrected for noise) test results where the DDWM (black) and OWL (red) sensors were subjected to circular motions of 4-seconds (left) and 12-seconds (right).

A.3 Conclusions

Overall, these preliminary tests confirm the proper operation of the OWL system and its integration with NDBC shoreside data collection protocols, indicating an increase in accuracy due to the use of new technologies. Field prototypes, incorporating both the older DDWM and OWL systems in one enclosure, have been fabricated and have completed initial bench testing. Thus the OWL prototype can be tested side-by-side at sea with the operational DDWM system.

In the spring and early summer of 2019, NDBC anticipates field tests will begin with two systems on the east coast and two on the west coast of the United States. The OWL performance will be verified in these different wave environments by comparing the outputs to the collocated, reference DDWM outputs.

B. Field Evaluations of the 2.1-m Foam Hull SCOOP

Field evaluations are crucial to determine how well new systems compare to the operational systems, and are a NDBC standard requirement to advance a candidate system to full operational status.

Two candidate NDBC 2.1-m foam hulls employing SCOOP are presently under review. One of the many benefits of the SCOOP is that data transfer no longer requires encoding compression, providing full-fidelity data. Previous NDBC payloads required encoding compression of wave spectral data, resulting in a fidelity loss of up to 1.9%.

These candidate stations are presently outfitted with a legacy DDWM Version 3.04 wave system (detailed in the OWL section above). The Datawell Directional Waverider-MkIII (Waverider) [8] is used as the reference standard for this wave evaluation. The Waverider is a stabilized platform, accelerometer-based wave motion sensor embedded in a 0.9 m spherical, stainless steel hull. The Waverider is built exclusively to measure waves, has decades of documented performance, and has been accepted as the standard by the Task Team on Wave Measurement of the Data Buoy Cooperation Panel (DBCP). The data are received and processed by the SCRIPPS Coastal Data Information Program (CDIP).

NDBC's primary wave products were reviewed: significant wave height, average wave period, dominant wave period, and mean wave direction (at the dominant wave period). The accuracies for NDBC's wave measurements are documented on the NDBC website [7]. A full description of NDBC wave measurements can be found in the NDBC Technical Document 96-01 (2009), Nondirectional and Directional Wave Data Analysis Procedures [9]. The equivalent Waverider wave measurements are detailed in the Datawell Waverider Reference Manual [8]. Of note is that the spectral frequency range is slightly different, with a Waverider frequency range of 0.033 Hz. to 0.64 Hz. [8], and a NDBC frequency range 0.0325 Hz to 0.485 Hz.

The evaluation datasets form a 'Common Good Dataset' in that missing records and quality control (QC) hard flags are removed. The remaining good records that are nearest in time to comparison stations datasets are compared. Mean wave direction statistics were computed using only those records where the difference in dominant wave period between the SCOOP and Waverider were less than 1 second. Selecting those records where there is good agreement between the dominant wave periods isolates the purely directional wave errors from the dominant wave period errors.

Wave parameters are assessed using a wave spectra comparison tool, WavEval. WavEval computes bias and spread of various parameters as a function of wave frequency and energy. WavEval was co-developed by CDIP and the U.S. Army Corps of Engineers, Engineer Research & Development Center, Coastal and Hydraulics Laboratory.

B.1 Comparisons Descriptions

Two field evaluation studies of wave data from NDBC 2.1-m foam buoys were conducted. An intercomparison was made between NDBC Station 44T14 and the Waverider at Station 44088 (CDIP ID 171), located near Virginia Beach, Virginia, USA. The buoys are separated by 0.84 km. After NDBC real-time QC checks, these stations provide 7615 wave reports for comparison, spanning 7824 hours (19 April 2017 23:33:00 UTC - 10 March 2018 22:33:00 UTC).

A second intercomparison was made between NDBC Station 46T29 and the Waverider at Station 46248 (CDIP ID 179), located near Columbia River Bar, Washington, USA. The buoys are separated by about 13 km. After NDBC real-time QC checks, these stations provide 7116 wave reports for comparison, spanning 7295 hours (04 August 2017 00:53 UTC - 03 June 2018 22:53 UTC).

B.2 Intercomparison Results

i) Stations 44T14 and 44088, Virginia Beach, Virginia

Statistical comparisons (Table 3) of 7615 significant wave heights samples from Stations 44T14 and 44088 show a bias (mean error) of -0.08 m (standard deviation of 0.12), with a correlation coefficient of 0.99 (Figure 5: top left). An average wave period bias of +0.34 s (standard deviation of 0.22) and a dominant wave period bias of -0.13 s (standard deviation of 1.52) are calculated.

Table 3: Evaluation Results for Stations 44T14 and 44088

Statistic	Significant Wave Height (m)	Average Wave Period (s)	Dominant Wave Period (s)	Mean Wave Direction (°) Abs(ΔDPD) < 1 s
Number of Samples	7615			6117
Mean Error (Bias)	-0.08	+0.34	-0.13	-0.12
Standard Deviation	0.12	0.22	1.52	11.1
Mean Absolute Error (MAE)	0.10	0.36	0.79	N/A
Correlation Coefficient	0.9929	0.9845	0.8048	N/A
Absolute Maximum Error	1.32	1.80	11.9	N/A
Scatter Index (RMSE / Mean Waverider)	0.09	0.82	0.18	N/A

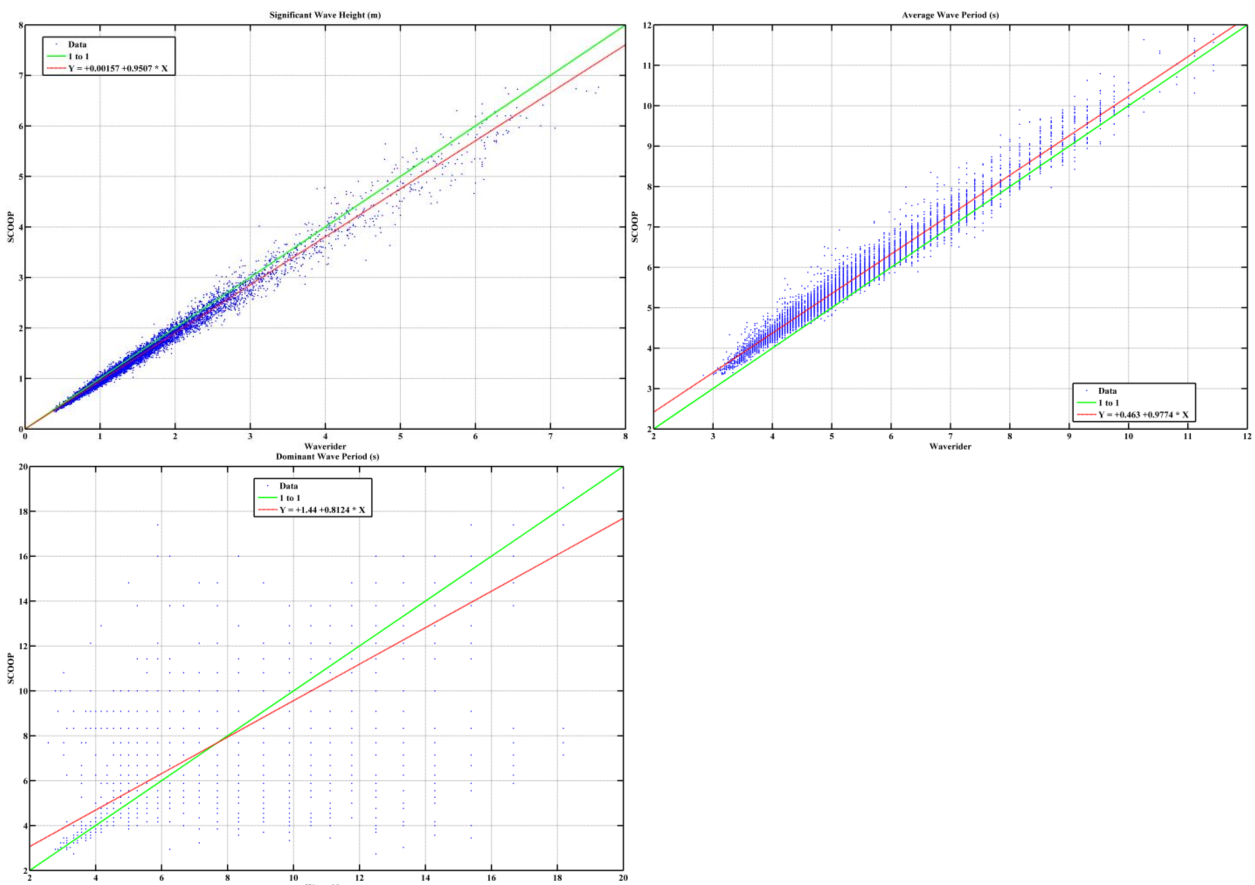

Figure 5: Scatter Plots of Significant Wave Height (top left), Average Wave Period (top right), and Dominant Wave Period (bottom left) observed by Stations 44T14 and 44088.

Correlation coefficients of 0.98 for average wave period (Figure 5: top right) and 0.80 for dominant wave period (Figure 5: bottom left) were returned. Statistical mean wave direction comparisons (Table 3) of 6117 samples, with absolute difference of dominant wave periods of less than 1 second, show a bias of -0.12 ° (standard deviation of 11.1).

Wave directional bias as a function of wave frequency and energy between Stations 44T14 and 44088 is evaluated using WavEval. Fourier coefficients for June 2017 were compared between the two systems (figure 6), producing derived alpha1 directional bias of above 5 ° for 15 % of the spectral frequencies (gray represents a delta of below 5 °). High bias in the 0.4 – 0.5 Hz frequency range is attributed to NDBC's use of PhiX tables that correct for a delayed hull response to wave trains. NDBC 2.1-m foam hull PhiX tables are currently under development.

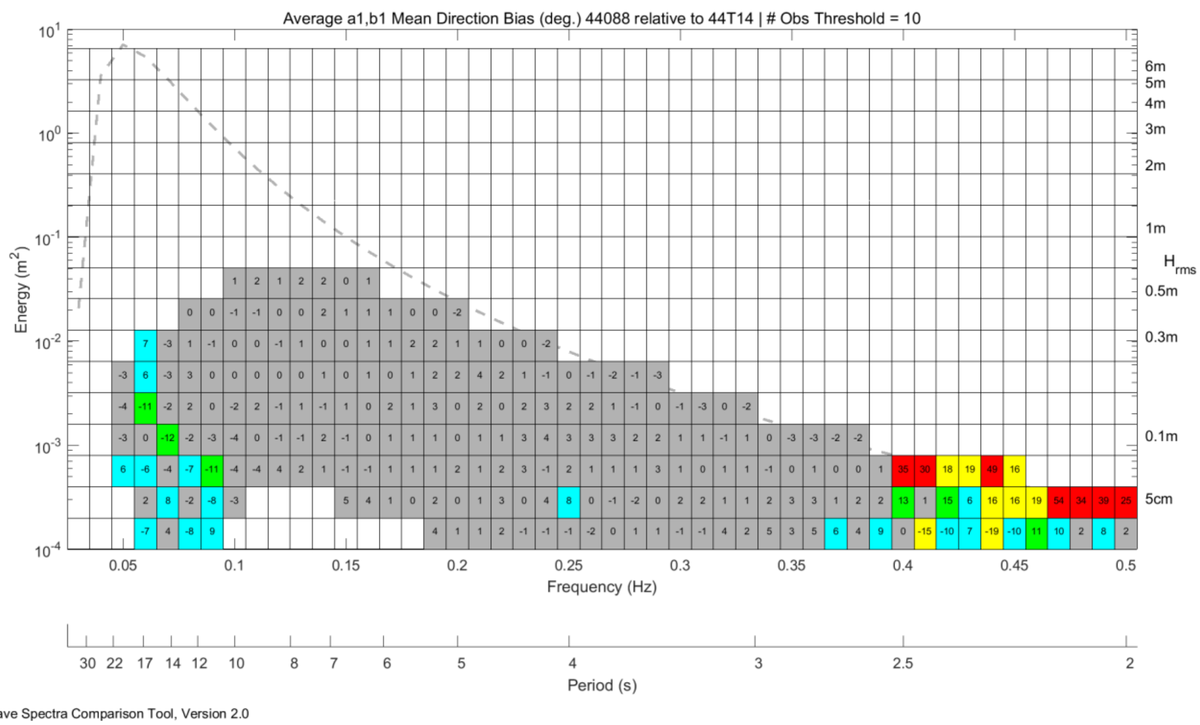

Figure 6: Wave directional bias as a function of wave frequency and energy between Stations 44T14 and 44088 for June 2017 (WavEval, Version 2.0). Gray represents deltas below 5 °, blue represents deltas between 5-10 °, green represents deltas between 10-15 °, yellow represents deltas between 15-20 °, and red represents deltas of higher than 20 °.

ii) Stations 46T29 and 46248, Columbia River Bar, Washington

Statistical comparisons (Table 4) of 7116 significant wave heights samples from Stations 46T29 and 46248 show a bias of -0.10 m (standard deviation of 0.12), with a correlation coefficient of 0.99 (Figure 7: top left). An average wave period bias of +0.29 s (standard deviation of 0.22) and a dominant wave period bias of -0.26 s (standard deviation of 1.52) are calculated.

Correlation coefficients of 0.97 for average wave period (Figure 7: top right) and 0.77 for dominant wave period (Figure 7: bottom left) were returned. Statistical mean wave direction comparisons

(Table 4) of 6350 samples, with absolute difference of dominant wave periods of less than 1 second, show a bias of 0.56 ° (standard deviation of 21.0).

Table 4: Evaluation Results for Stations 46T29 and 46248

Statistic	Significant Wave Height (m)	Average Wave Period (s)	Dominant Wave Period (s)	Mean Wave Direction (°) Abs(ΔDPD) < 1 s
Number of Samples	7116			6350
Mean Error (Bias)	-0.10	+0.29	-0.26	+0.56
Standard Deviation	0.12	0.22	1.52	21.0
Mean Absolute Error (MAE)	0.16	0.35	1.06	N/A
Correlation Coefficient	0.9871	0.9698	0.7619	N/A
Absolute Maximum Error	2.0	3.2	23.9	N/A
Scatter Index (RMSE / Mean Waverider)	0.0931	0.0663	0.1663	N/A

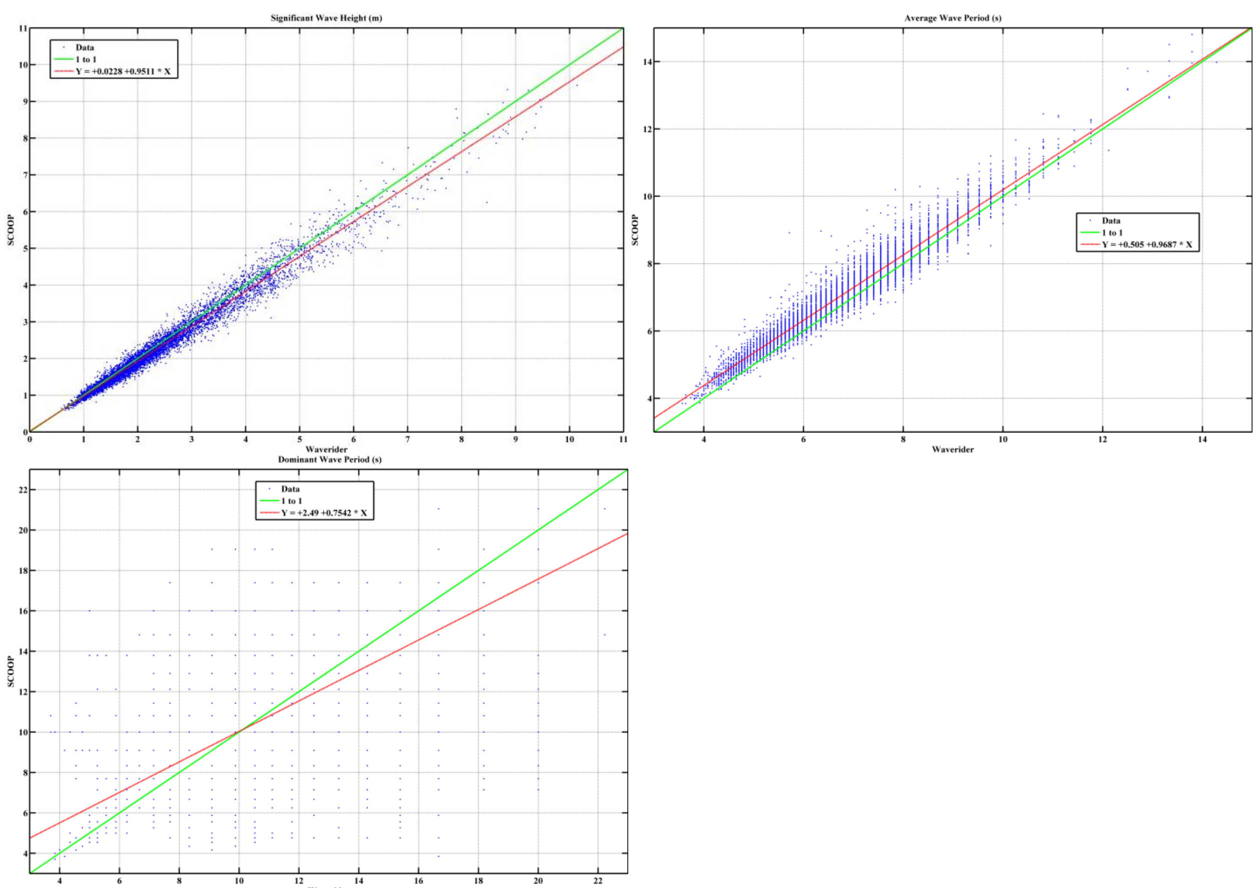

Figure 7: Scatter Plots of Significant Wave Height (top left), Average Wave Period (top right), and Dominant Wave Period (bottom left) observed by Stations 46T29 and 46248.

Wave directional bias as a function of wave frequency and energy between Stations 46T29 and 46248 is evaluated using WavEval. Fourier coefficients for November 2017 were compared between the two systems (figure 8), producing derived alpha1 directional bias of above 5 ° for 17 % of the spectral frequencies (gray represents a delta of below 5 °).

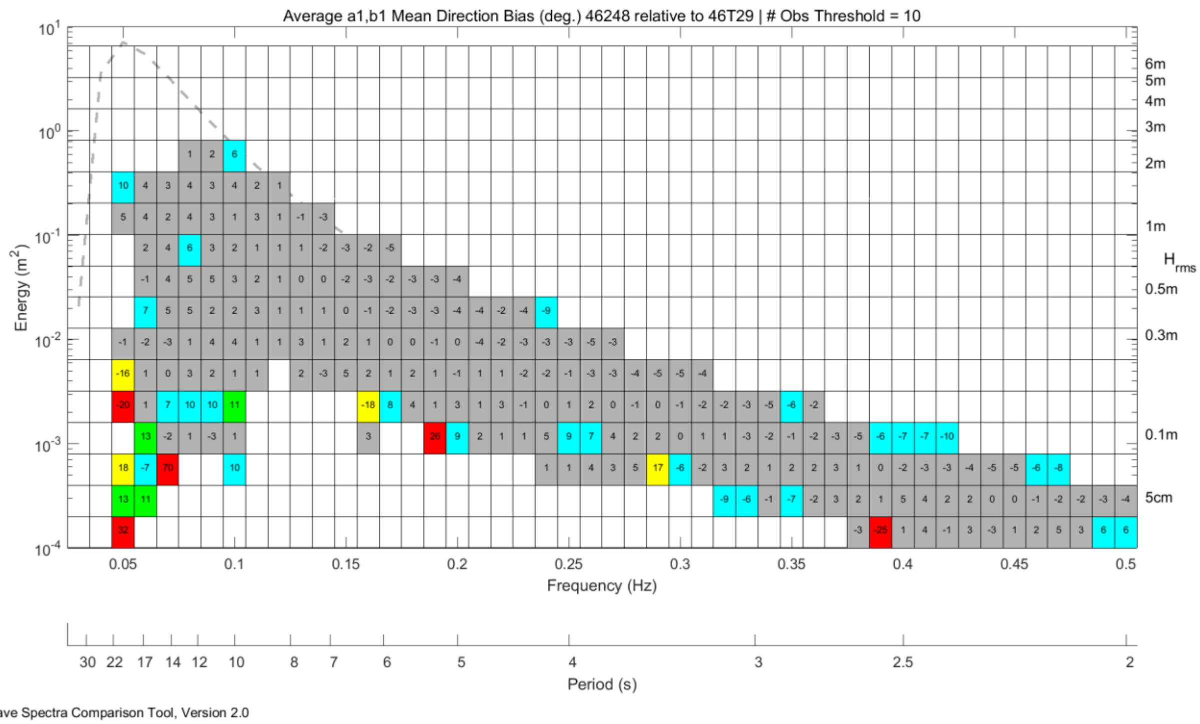

Figure 8: Wave directional bias as a function of wave frequency and energy between Stations 46T29 and 46248 for November 2017 (WavEval, Version 2.0). Gray represents deltas below 5 °, blue represents deltas between 5-10 °, green represents deltas between 10-15 °, yellow represents deltas between 15-20 °, and red represents deltas of higher than 20 °.

B.3 Reliability and Accuracy

NDBC wave data availability for Station 44T14 near Virginia Beach was 97.3% (7615/7824), while data availability for Station 46T29 near the Columbia Bar was 97.6 % (7118/7295).

Station 44T14 root mean square errors (RMSE) for significant wave height and average wave period met NDBC's accuracy specifications (Table 5), but dominant wave period and mean wave direction RMSE were higher. Station 46T29 RMSE for average wave period met NDBC's accuracy specifications (Table 5), while significant wave height, dominant wave period and mean wave direction were higher.

Table 5: 2.1-m foam hull SCOOP Accuracy (Root Mean Square Error) for Stations 44T14 and 46T29

Test Location	Significant Wave Height (m)	Average Wave Period (s)	Dominant Wave Period (s)	Mean Wave Direction (°)
NDBC Accuracy Goals:	0.20	1.0		10.0
Station 44T14, Virginia Beach	0.14	0.41	1.53	11.1
Station 46T29, Columbia River Bar	0.23	0.45	1.86	21.0

B.3 Conclusions

Field evaluation comparisons provided a suitable overlap period between existing and new systems to assess the impact of the changing system to present applications and on long-term records. Wave parameters recorded by two 2.1-m foam hull SCOOP's at Stations 44T14 and 46T29 (embedded within the SCOOP Ocean/Wave module and the DDWM Version 3.04) were compared with those reported by operational Waveriders at Stations 44088 (CDIP ID 171) and 46248 (CDIP ID 179).

Station 44T14's significant wave height and both stations' average wave period met the NDBC accuracy (root mean square errors that are sensitive to outliers) goals of ± 0.2 m and ± 1 s, respectively. Station 46T29 and both stations' dominant wave period and mean wave direction produced accuracy errors that were higher than the NDBC accuracy goals of ± 1 s and ±10 °, respectively. Observed variance in the systems are likely due to spatial effects of the comparative buoy locations. NDBC 2.1-m foam hull calibrations and spectral analyses of these data are ongoing.

Of note is that the biases (mean errors) between the systems' bulk parameters remain within the NDBC accuracy goals. Therefore bulk wave parameters recorded by the 2.1-m foam hull SCOOP's are in good agreement with those logged by the operational reference Waveriders.

Overall, the 2.1-m foam hull SCOOP meets its requirements to increase data reliability and collect 10 minute meteorological observations. Small biases between the two 2.1-m foam hull SCOOP and their operational counterparts show that the new systems are in good agreement.

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