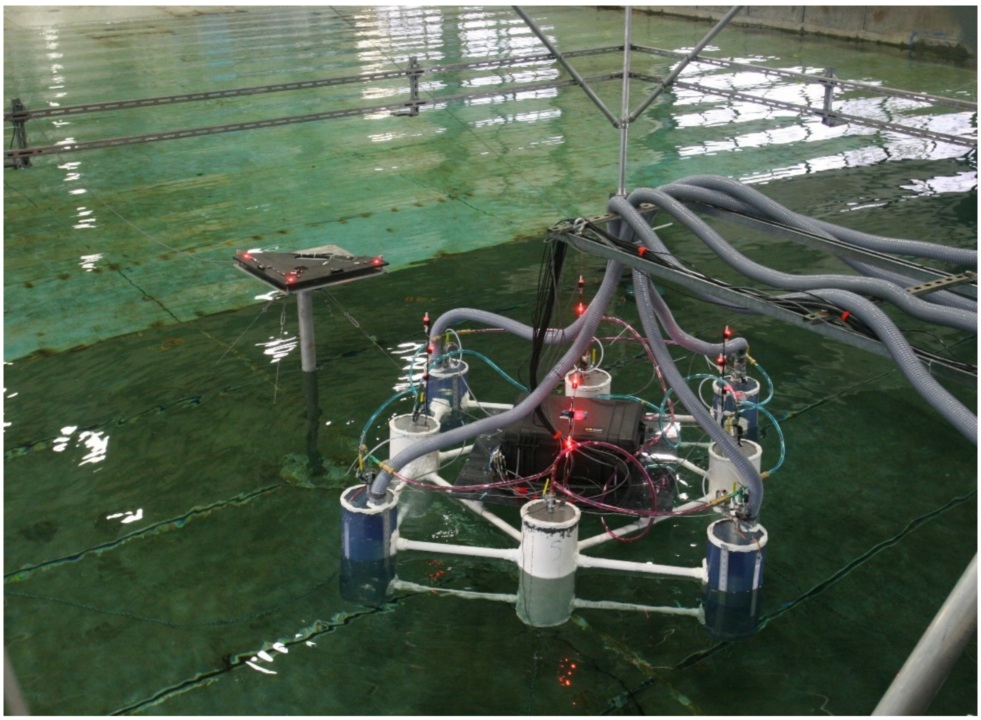
Small Scale Physical Model Tests of

ServerFloat from Principle Power

For

WEC-Prize

22 January 2016



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Executive Summary

The O.H. Hinsdale Wave Research Laboratory (HWRL) at Oregon State University conducted a physical model study of Principle Power's Server Float platform as part of the small scale testing for the WEC-Prize. The study was conducted under a Testing and Services Agreement between Ricardo, Inc. and Oregon State University. The purpose of this study was to obtain proof-of-concept testing of the reduced scale WEC device.

The tests were conducted at a model scale of 1:50. The WEC device consists of a floating platform made of 8 upright cylindrical columns arranged along the perimeter of a square. The device wave energy principle is an Oscillating Water Column (OWC). The columns at the corners are open at the bottom and the oscillating water column drives air through a series of conduits interconnected to the other 4 sealed columns. Air flowing from a high pressure column to the other would produce energy. The platform is moored to the sea bottom with a system of four catenary chains.

The platform was subject to regular and random waves at normal and oblique angles, according to the prescribed conditions by the WEC-Prize contest. Off-board measurements included wave height and period, 6 DOF platform motions, and forces in the mooring lines. On-board measurements included surface elevation and air pressure on selected columns, and air the flow rate for energy production. All data were acquired at a 50 hz sampling rate, except the motion data which were sampled at 480 hz and down sampled to 50 hz. HD video was taken for all wave tests.

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1. Introduction

The Wave Energy Prize (WEC-Prize) is a public prize challenge sponsored by the U.S. Department of Energy (DOE)'s Water Power Program. Is a prize competition to simulate the development of innovative Wave Energy Converters (WEC). The winner of the prize will be determined through physical model testing in the Naval Warfare Centre's Maneuvering and Seakeeping (MASK) basin, Carderock, in 2016.

Prior to the prize competition in MASK, participants have performed proof of concept small-scale testing of their WEC devices in selected facilities elsewhere, primarily to determine which participant team will be allowed to take their WEC device concepts for testing in the MASK basin.

The O.H. Hinsdale Wave Research Laboratory (HWRL) at Oregon State University has been selected as one of the Small-Scale Testing Facilities (SSTF), and conducted a series of physical model tests of Principle Power's ServerFloat platform as one of the contestants for the WEC-Prize. Test were run from January 11th to January 15th, 2016. The tests were conducted at a model scale of 1:50 in the Directional Wave Basin (DWB). This document reports on the experimental facility, test setup, instrumentation, methodology, and procedures. Data prost-processing and results are included in the SSTF submission spreadsheet.

2. Testing Facility

Wave tests were conducted in the DWB at the HWRL. The rectangular basin is 48.8 m long x 26.5 m wide x 2.1 meters deep. The wavemaker can generate simple periodic, random, and directional waves as well as tsunamis. The wavemaker has 29 piston-type wave boards that are edge driven by electric motors. The maximum wave height is approximately 0.8 m in a 1.36 m depth and the wave period range is 0.5 – 10 s.

Figure 1 is a photograph of the DWB taken from the elevated control room looking to the east toward the wavemaker. At the west end of the basin a 1V:10H steel beach was installed to dissipate wave energy. A movable bridge spans the basin. The bridge was used to support instrumentation for the load cells and wave gauges, routing for signal cables, air reservoirs for the model, and provide access for video and photography. Figure 2 is a photograph of the wavemaker taken from the bridge.

Figure 3 shows a drawing of the DWB. The wavemaker is located at the east end of the basin. The basin coordinate system is defined in Figure 3. Basin coordinates are used to define the locations of the model and instrumentation in the basin. The coordinate origin is located at the mean wavemaker position at the center line of the basin on the basin floor.

Figure 1. Directional wave basin.

Figure 2. Wave maker of the Directional Wave Basin.

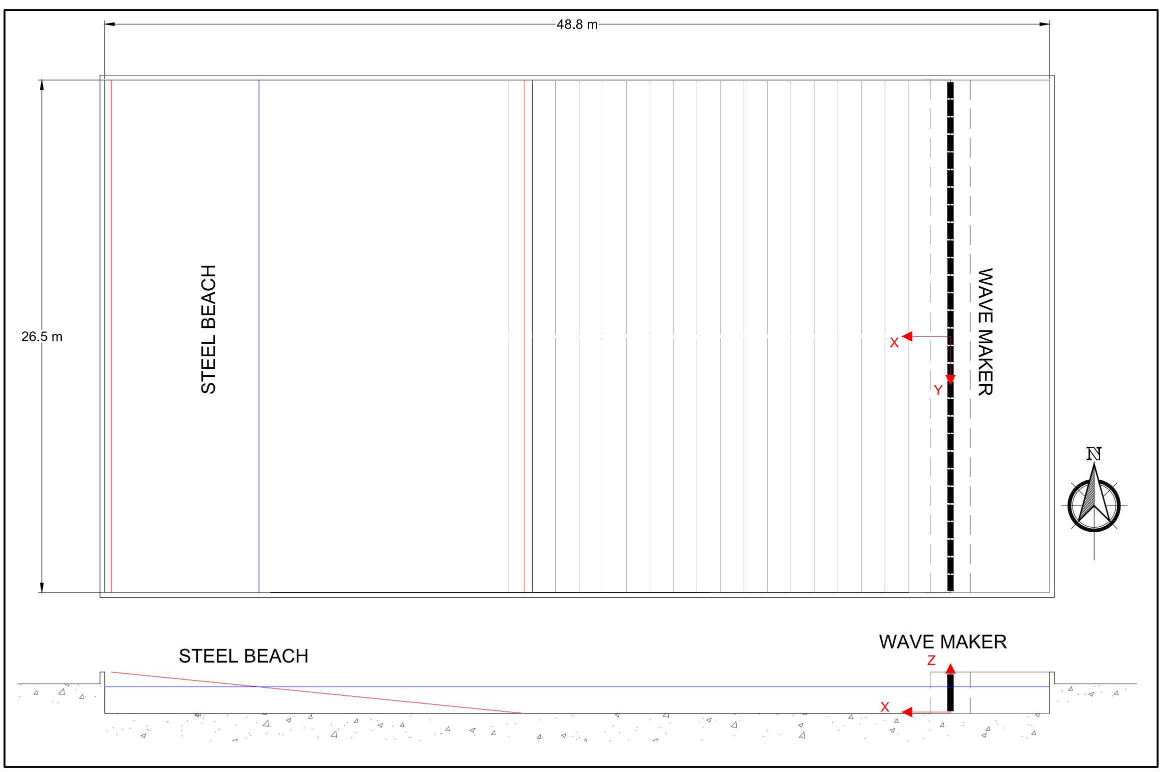

Figure 3. Coordinate definition and general layout of the Directional Wave Basin.

3. Test Program

The proof of concept testing considers a series of a 1:50 model scale of each contestant WEC device, subject to varying wave conditions, including monochromatic (regular) and random (irregular) waves.

The wave conditions are identified in 3 groups:

1. Regular waves for 2 constant wave steepness and a single head direction
2. Regular waves with a constant wave steepness and 2 incident wave directions
3. Random waves at a head direction with no spreading

All regular wave conditions have been initially defined in 100 m depth, and were recomputed at the corresponding depth for each SSTF assuming the incident Wave Energy Flux (i.e. the Wave Power per unit width) remains constant.

The wave conditions defined at 100 m depth are presented in Table 1, and the prescribed incident wave conditions for the maximum water depth at HWRL (1.36 m) are presented in Table 2.

Note that in Table 2, the wavelength for the irregular wave cases has been estimated using the peak period, and the wave power has been computed with the following expression (Falnes, 2007):

$$J = \rho g \int_0^\infty Cg(f) S(f) df = \frac{\rho g^2}{64\pi} Hm_0^2\, T_j$$

Where: ρ is the water density,
g is the acceleration of gravity,
Cg is the group celerity,
S(f) is the wave energy density spectrum,
f is the wave frequency,
H_{m0} is the significant wave height, and
T_j is the energy period, defined as $T_j = T_{0,-1} = m_{-1}/m_0$, and $m_i = \int_0^\infty f^i S(f) df$

The irregular wave tests are defined by a parameterized Bretschneider spectrum:

$$S(f) = \frac{A}{f^5} exp(-B/f^4)$$

Where: $A = \frac{0.0081}{K^4} g^2$,
$B = \frac{4A}{Hm_0^2}$, and
$K = \frac{Tp}{2.492}\sqrt{\frac{g}{Hm_0}}$.

Test Waves: **Base Case**, Assuming a 2 m test tank water depth											
Run	Wave Type	Wave ID	Dir	1/50th Scale Waves				Equivalent Full Scale Waves			
				Period (s)	Approx. Length (m)	Height (m)	Wave Power (W/m)	Period (s)	Approx. Length (m)	Height (m)	Wave Power (W/m)
1	Mono	M1 s 80	0	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
2	Mono	M2 s 80	0	1.06	1.76	0.022	0.489	7.5	88.0	1.10	8644
3	Mono	M3 s 80	0	1.27	2.53	0.032	1.218	9	126.5	1.58	21523
4	Mono	M4 s 80	0	1.48	3.45	0.043	2.645	10.5	171.9	2.15	46754
5	Mono	M5 s 80	0	1.7	4.46	0.056	5.221	12	223.2	2.79	92288
6	Mono	M6 s 80	0	1.91	5.57	0.070	9.507	13.5	278.4	3.48	168063
7	Mono	M7 s 80	0	2.12	6.7	0.084	15.985	15	335.1	4.19	282584
8	Mono	M1 s 40	0	0.85	1.12	0.028	0.641	6	56.2	1.41	11329
9	Mono	M2 s 40	0	1.06	1.76	0.044	1.956	7.5	87.8	2.20	34575
10	Mono	M3 s 40	0	1.27	2.53	0.063	4.870	9	126.5	3.16	86090
11	Mono	M4 s 40	0	1.48	3.45	0.086	10.579	10.5	171.9	4.30	187015
12	Mono	M5 s 40	0	1.7	4.46	0.112	20.882	12	223.2	5.58	369151
13	Poly	P1	0	0.82		0.035		5.8		1.75	
14	Poly	P2	0	1.27		0.050		8.95		2.5	
15	Poly	P3	0	2.19		0.104		15.5		5.2	
16	Poly	P4	0	1.77		0.054		12.5		2.7	
17	Poly	P5	0	1.61		0.027		11.4		1.35	
18	Mono	M1 s 80	20	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
19	Mono	M2 s 80	20	1.06	1.76	0.022	0.489	7.5	88.0	1.10	8644
20	Mono	M3 s 80	20	1.27	2.53	0.032	1.218	9	126.5	1.58	21523
21	Mono	M4 s 80	20	1.48	3.45	0.043	2.645	10.5	171.9	2.15	46754
22	Mono	M5 s 80	20	1.7	4.46	0.056	5.221	12	223.2	2.79	92288
23	Mono	M6 s 80	20	1.91	5.57	0.070	9.507	13.5	278.4	3.48	168063
24	Mono	M7 s 80	20	2.12	6.7	0.084	15.985	15	335.1	4.19	282584
25	Mono	M1 s 80	50	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
26	Mono	M2 s 80	50	1.06	1.76	0.022	0.489	7.5	88.0	1.10	8644
27	Mono	M3 s 80	50	1.27	2.53	0.032	1.218	9	126.5	1.58	21523
28	Mono	M4 s 80	50	1.48	3.45	0.043	2.645	10.5	171.9	2.15	46754
29	Mono	M5 s 80	50	1.7	4.46	0.056	5.221	12	223.2	2.79	92288
30	Mono	M6 s 80	50	1.91	5.57	0.070	9.507	13.5	278.4	3.48	168063
31	Mono	M7 s 80	50	2.12	6.7	0.084	15.985	15	335.1	4.19	282584

Table 1. Wave conditions defined at 100 m water depth. Base case.

Test Waves: **Oregon State University**, 1.36 m test tank water depth											
Run	Wave Type	Wave ID	Dir	1/50th Scale Waves				Equivalent Full Scale Waves			
				Period (s)	Approx. Length (m)	Height (m)	Power Flux (W/m)	Period (s)	Approx. Length (m)	Height (m)	Power Flux (W/m)
1	Mono	M1 s 80	0	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
2	Mono	M2 s 80	0	1.06	1.75	0.022	0.489	7.5	88.0	1.10	8644
3	Mono	M3 s 80	0	1.27	2.51	0.031	1.218	9	126.5	1.58	21523
4	Mono	M4 s 80	0	1.48	3.35	0.042	2.645	10.5	171.9	2.15	46754
5	Mono	M5 s 80	0	1.70	4.29	0.054	5.221	12	223.2	2.79	92288
6	Mono	M6 s 80	0	1.91	5.34	0.067	9.507	13.5	278.4	3.48	168063
7	Mono	M7 s 80	0	2.12	6.50	0.081	15.985	15	335.1	4.19	282584
8	Mono	M1 s 40	0	0.85	1.12	0.028	0.641	6	56.2	1.41	11329
9	Mono	M2 s 40	0	1.06	1.75	0.044	1.956	7.5	87.8	2.20	34575
10	Mono	M3 s 40	0	1.27	2.51	0.063	4.870	9	126.5	3.16	86090
11	Mono	M4 s 40	0	1.48	3.35	0.084	10.579	10.5	171.9	4.30	187015
12	Mono	M5 s 40	0	1.70	4.29	0.107	20.882	12	223.2	5.58	369151
13	Poly	P1	0	0.82	1.05	0.035	0.441	5.8	52.5	1.75	7788
14	Poly	P2	0	1.27	2.50	0.050	1.345	8.95	124.8	2.5	23771
15	Poly	P3	0	2.19	6.49	0.104	11.172	15.5	324.7	5.2	197495
16	Poly	P4	0	1.77	4.64	0.054	2.330	12.5	232.0	2.7	41187
17	Poly	P5	0	1.61	3.95	0.027	0.520	11.4	197.6	1.35	9188
18	Mono	M1 s 80	20	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
19	Mono	M2 s 80	20	1.06	1.75	0.022	0.489	7.5	88.0	1.10	8644
20	Mono	M3 s 80	20	1.27	2.51	0.031	1.218	9	126.5	1.58	21523
21	Mono	M4 s 80	20	1.48	3.35	0.042	2.645	10.5	171.9	2.15	46754
22	Mono	M5 s 80	20	1.70	4.29	0.054	5.221	12	223.2	2.79	92288
23	Mono	M6 s 80	20	1.91	5.34	0.067	9.507	13.5	278.4	3.48	168063
24	Mono	M7 s 80	20	2.12	6.50	0.081	15.985	15	335.1	4.19	282584
25	Mono	M1 s 80	50	0.85	1.12	0.014	0.160	6	56.0	0.70	2832
26	Mono	M2 s 80	50	1.06	1.75	0.022	0.489	7.5	88.0	1.10	8644
27	Mono	M3 s 80	50	1.27	2.51	0.031	1.218	9	126.5	1.58	21523
28	Mono	M4 s 80	50	1.48	3.35	0.042	2.645	10.5	171.9	2.15	46754
29	Mono	M5 s 80	50	1.70	4.29	0.054	5.221	12	223.2	2.79	92288
30	Mono	M6 s 80	50	1.91	5.34	0.067	9.507	13.5	278.4	3.48	168063
31	Mono	M7 s 80	50	2.12	6.50	0.081	15.985	15	335.1	4.19	282584

Table 2. Wave conditions defined at 68 m water depth. Conditions for testing at HWRL, Oregon State University.

4. Wave Calibration Tests

Waves portray a natural spatial and temporal variability in the ocean as well as in the laboratory. The variability in the laboratory might be induced by different sources, including boundary reflections, wave diffraction patterns, non-linear instabilities, wave-induced currents, and generation of sub- and super-harmonics. Moreover, wave generation techniques are based on a series of theoretical and ideal conditions which deviate from reality.

Nevertheless, current wave generation and laboratory techniques have proven to be reliable, and the accuracy depends on the target conditions and model configuration.

The target wave conditions for the WEC-Prize small scale testing are, in some cases, relatively small for the design operation of the DWB wave machine. Moreover, the requested accuracy of the wave conditions, and particularly the strict tolerance on the incident wave energy flux at the nominal location of the device, entails a comprehensive series of wave calibration tests, also known as undisturbed wave tests, where the wave conditions at the nominal location of the model are measured, and the wave machine drive signal is modified to achieve the target wave conditions within a given tolerance.

To determine the spatial variability of the wave power, as well as the "offshore" wave conditions, additional measurements are made at different locations around the basin. These additional probes will remain in place so a direct comparison can be made during the experiments where the model has been deployed.

4.1 Test Layout

The instrumentation layout for the wave calibrations tests depends on the test layout of the WEC device. Firstly, it has been decided to rotate the model instead of running directional waves, since the rotation procedure is relatively easy in the basin at 1.36 m water depth, the number of wave calibration trials is reduced given the directional wave cases have the same wave height and period as the normal incident cases, and due to the lateral reflection of the basin side walls.

Secondly, the nominal location of the WEC devices is defined as far as possible from the wave machine, while still remains separated from the waterline at the end of the absorbing beach. The former is intended to allow a stable formation of waves, while the later aims to have the longest test duration before any reflected wave reach the model.

The nominal location of the model also needs to consider the corresponding instrumentation to be deployed, i.e. the motion tracking system, the instrumentation bridge for observation, and the mooring system.

Particularly, the motion tracking system requires a steel frame to support a series of 8 cameras, as well as a stand to install the reference coordinate system of the cameras, which is used to determine the location of the model relative to the global system in the basin. Both structures will be present during the model experiments, thus are required to be present during the wave calibration tests.

As a result, 10 wave gauges have been installed in the basin. The first 5 are pierce wire resistive probes located in-line approximately 9.4 m from the wave machine, with a separation of 2.5 m between each two adjacent probes. These probes will be capturing the "far-field" wave conditions, and its cross-shore homogeneity.

Further, 4 acoustic probes have been located surrounding half of the nominal location of the WEC device. These probes are supported by the motion tracking frame, and have been selected because are non-intrusive, since during the wave calibration tests, the geometry and footprint of the WEC device was still unknown, thus the acoustic probes would not be affected or damaged by the model.

Finally, a pierce wire resistive probe was located at the nominal location of the WEC device, i.e. at the center of the motion tracking frame. This probe will be used to perform the wave calibration for all 31 conditions, and it will be removed at the end of the wave calibration tests in order to install the WEC device.

In Figure 4, the instrumentation layout for the wave calibration tests is presented.

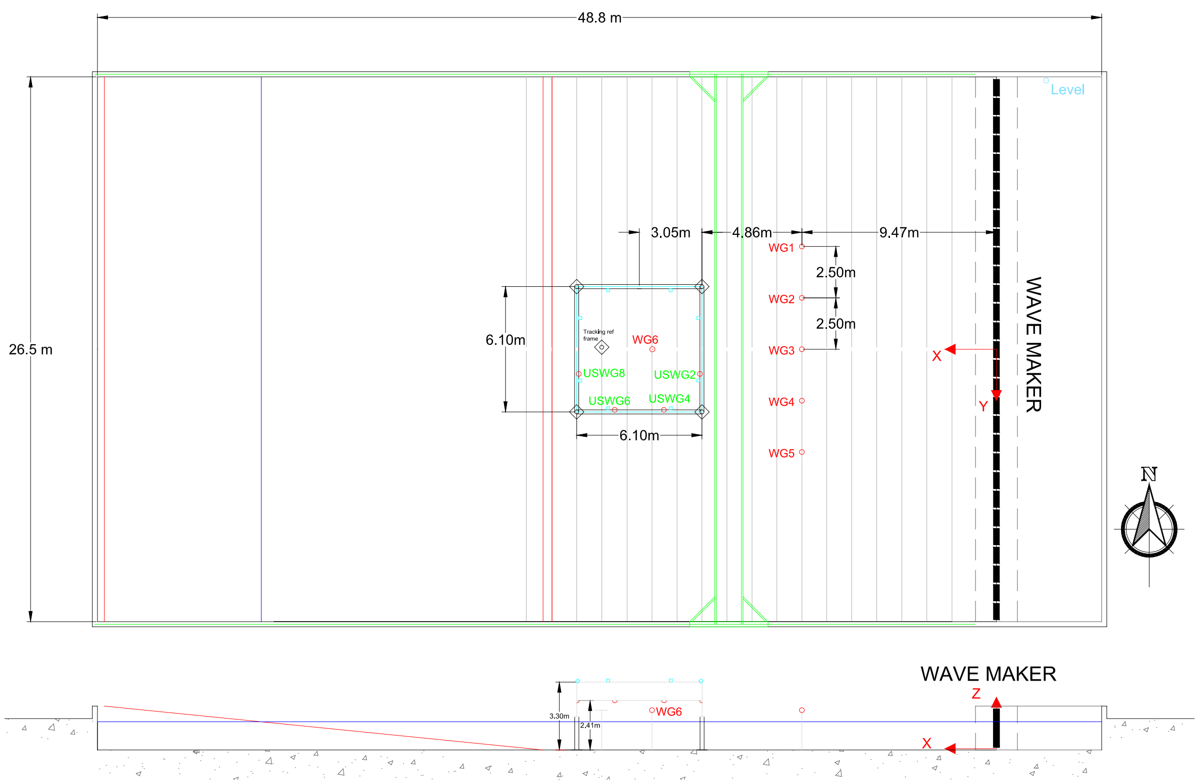

Figure 4. Coordinate definition and general layout of the Directional Wave Basin.

Figure 5 and Figure 6 present images of the instrumentation deployed in the DWB and an image of the waves generated during one trial of the wave calibration tests.

Figure 5. Instrumentation deployment in the DWB. Left, motion tracking frame and nominal model location. Right: wave gauge array for "far-field" wave conditions.

Figure 6. Wave calibration testing.

4.2 Wave Measurements

As indicated previously, wave heights were measured using resistance wave gauges and acoustic probes. The resistance gauges use the conductivity of the water between two parallel metal rods or wires. The electronics differentially drive the metal conductors with a 10 KHz signal, measuring the current as it responds to changes in the conductivity, which is the inverse of resistance, due to changing water height between the metal conductors. The electronics convert the current to voltages and amplify the results. The wave gauge electronics were designed by Terry Dibble (former electrical engineer at the HWRL) and built by ImTech.

Ultrasonic sensors, also called ultrasonic transducers, measure the distance to or the presence of a target object by sending a sound pulse, above the range of human hearing (ultrasonic), toward the target and then measuring the time it takes the sound echo to return. Knowing the speed of sound, the sensor determines the distance of the target and sets its outputs accordingly. The advantages are its resolution (~0.086 mm) and its non-intrusiveness. The acoustic probes used during the wave calibration tests for WEC-Prize were built by Senix, Inc.

The locations of the gauges as depicted in Figure 4 in the DWB coordinates are given in Table 3.

Table 3. Wave gauge locations during the wave calibration tests.

Wave Gauge	Basin x (m)	Basin y (m)
wg1	9.479	-5.002
wg2	9.490	-2.505
wg3	9.480	0.000
wg4	9.486	2.482
wg5	9.489	4.988
wg6	16.778	-0.031
uswg2	14.150	1.235
uswg4	16.135	3.233
uswg6	18.661	3.229
uswg8	20.660	1.274

4.3 Water Level Measurements

A pressure sensor was used to determine the water depth. The DWB sensor is a model PDCR 10/FD made by Druck, which is now a subsidiary of GE Sensing. The PDCR 10/FD has a 5 psig (34.47 kPa) range, and has been calibrated with associated level enclosure for 34.05 cm of water per volt. This sensor has a combined non-linearity and hysteresis of 0.25% BSL. The PDCR 10/FD model has an integral 10.6 meter cable. The sensor is temperature compensated over a 0° to 30°C range. The water temperature during the tests varied from 7 to 12°C.

The water level sensor is located in front of the wave machine paddles, on the southeast corner (see Figure 4). The coordinates of the water level sensor are indicated in Table 4.

Table 4. Water level sensor location.

Pressure Gauge	Basin x (m)	Basin y (m)
level	2.177	12.852

4.4 Data Acquisition System (DAQ)

Data acquisition modules are manufactured by National Instruments and are based on the PXI architecture. Each system is contained in a PXI-1052 chassis with a PXI-8106 dual core embedded controller. Each system also has a PXI-6259 M series multifunction DAQ module, with 16 bit resolution on differential measurements and supports LabVIEW RT software. There are eight SCXI-1143 modules each comprised of eight channels of Butterworth filters for a total of 64 channels of analog inputs per system. The systems are capable of being setup into a master/slave mode to allow for a total of 192 synchronized analog input channels. The Butterworth filters on the analog inputs limit the maximum measurement range to ±5Vdc. Each system also contains a PXI-8420 module that allows serial data collection of up to 16 RS-232 ports. Each system is capable of generating synchronization pulses along with model PRL-414B, Pulse Research Lab line drivers. All analog signals are connected into the DAQ systems using 50 ohm coaxial cable with BNC connectors. The DAQ sampling rate is normally 50 Hz but is capable of up to 5 KHz when sampling all 64 channels.

During the wave calibrations tests, one PXI module was installed along the south wall of the basin, and the sampling rate was 200 Hz.

4.5 Summary Results of the Wave Calibration Tests

Wave heights have been calibrated to match the target wave conditions at the nominal location of the WEC device, i.e. at wave gauge #6 (wg6). For regular waves, the averaged wave height and period was estimated once quasi-steady conditions have been met, thus considering the required time for the waves to propagate and reflect past all sensors, as suggested by the WEC-Prize. Then, the average of ten (10) waves is obtained by zero-crossing analysis and cross-correlation techniques. Hence, the average wave height and period, as well as the standard deviation, are obtained for every probe.

A similar technique is applied for the irregular wave cases, selecting the elapsed time for the group celerity to travel from the wave machine to the steel beach and reflect back to the sensors. However, the significant wave height and peak period analysis is performed for a time series of 300 waves.

Wave energy flux and energy period is also computed for comparison purposes on all instruments and for all cases.

All wave conditions, regular and irregular, have been calibrated to within +/-3% in the wave height at wg6. Wave periods for the regular cases portray a very accurate behavior, with results within +/-0.1%. The estimation of the peak period depends on the spectral resolution, which in turn depends on the sampling rate, subsampling length, and filtering. Therefore, the energy period, T_j, used to estimate the wave energy flux, seems to be more representative of the target conditions at wg6. The estimated energy period at the end of the wave calibration procedure is within +/-1.2% of the target conditions.

Finally, the wave energy flux (wave power per unit width) is also compared with the target conditions. As a result, it is observed that the calibrated wave conditions at wg6 are within +/-3% of the target wave power.

Table 5 summarizes the results of the wave calibration tests at the nominal location of the WEC device.

Table 5. Relative error between target and measured wave conditions at the nominal location of the WEC device (wg6) at the end of the wave calibration tests.

Wave Type	Wave ID	Wave Height %	Wave Period %	Wave Power %
Mono	M1 s 80	+1.0	+0.1	+1.3
Mono	M2 s 80	+0.6	+0.0	+1.7
Mono	M3 s 80	+2.7	+0.0	+2.8
Mono	M4 s 80	+0.4	+0.0	+0.5
Mono	M5 s 80	+0.0	-0.1	+0.4
Mono	M6 s 80	+0.2	+0.0	+0.4
Mono	M7 s 80	+0.7	-0.1	+0.4
Mono	M1 s 40	-1.6	+0.1	-3.7
Mono	M2 s 40	-0.8	+0.0	-1.1
Mono	M3 s 40	+0.4	+0.0	+1.3
Mono	M4 s 40	+1.4	+0.0	+2.5
Mono	M5 s 40	+1.9	-0.1	+2.4
Poly	P1	+0.6	+1.2	+2.2
Poly	P2	+0.5	+0.4	+1.4
Poly	P3	-1.1	-0.1	-2.9
Poly	P4	-0.1	-0.7	-1.3
Poly	P5	-0.5	-0.6	-1.7

Finally, Figure 7 and Figure 8 presents a comparison between the target and measured wave conditions at the nominal location of the WEC device for the regular and irregular cases, respectively. Both Figures presents, as well, the validity of the wave theories in dimensionless form. Figure 8 also includes the measured individual waves in the time series.

The spatial variability of the wave conditions measured in the basin, provide an indication on the homogeneity of the wave field. However, and as indicated previously, some variability is expected, even in laboratory and controlled conditions. The variability is induced by many factors, including wave scattering from the stands and frames used to support the wave probes, and particularly by the quasi-stationary system imposed by the combination of incident and reflected waves. The spatial variability of the wave field is, therefore, an indication of the magnitude of such boundary effects.

For the wave calibration tests, the wave spatial variability can be characterized by the "near field" and "far field" conditions. The "near field" conditions can be represented by the measurements of the acoustic wave probes surrounding the nominal location of the WEC device. The "far field" conditions can be represented by the measurements of the in-line probe array located parallel to the wave machine.

Summarizing the results, the "near field" conditions indicate a variation relative to the target conditions of +/-10% in the wave height, +/-6% in the wave period (+/-0.1% for the monochromatic cases), and +/-20% for the wave energy flux. On the other hand, the "far field" conditions indicate a variation relative to the target conditions of +/-9% in the wave height, +/-0.7% in the wave period, and +/-17% for the wave energy flux.

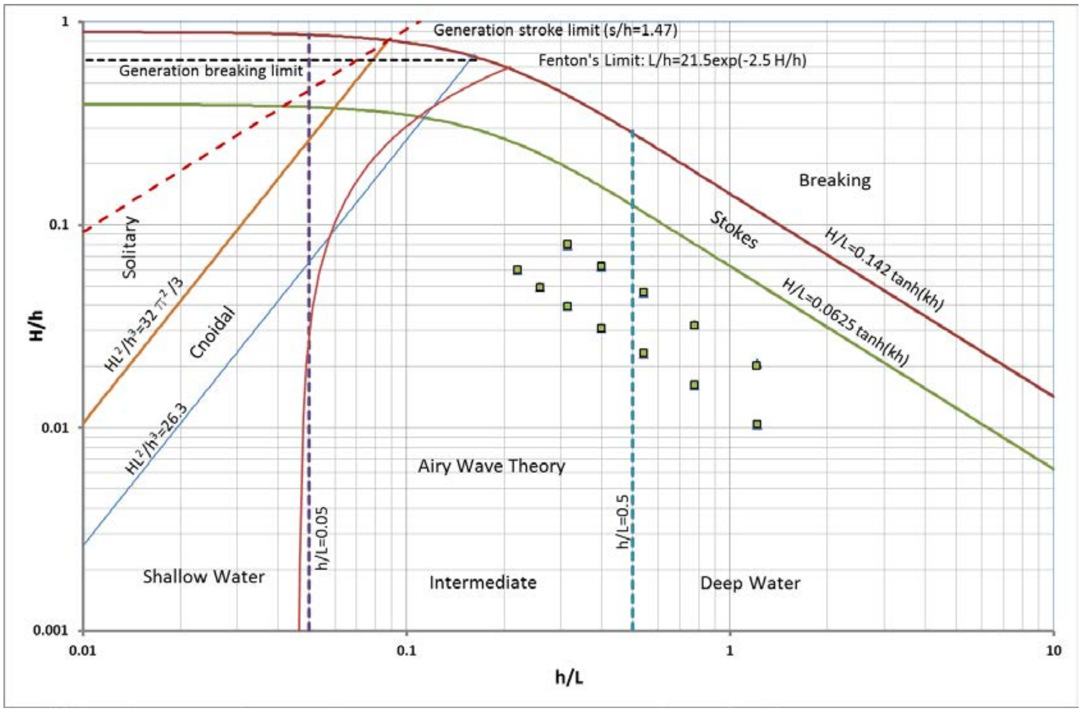

Figure 7. Measured (green square) and target (red triangle) regular wave conditions and its comparison to the validity ranges of different wave theories at the nominal location of the WEC device (wg6).

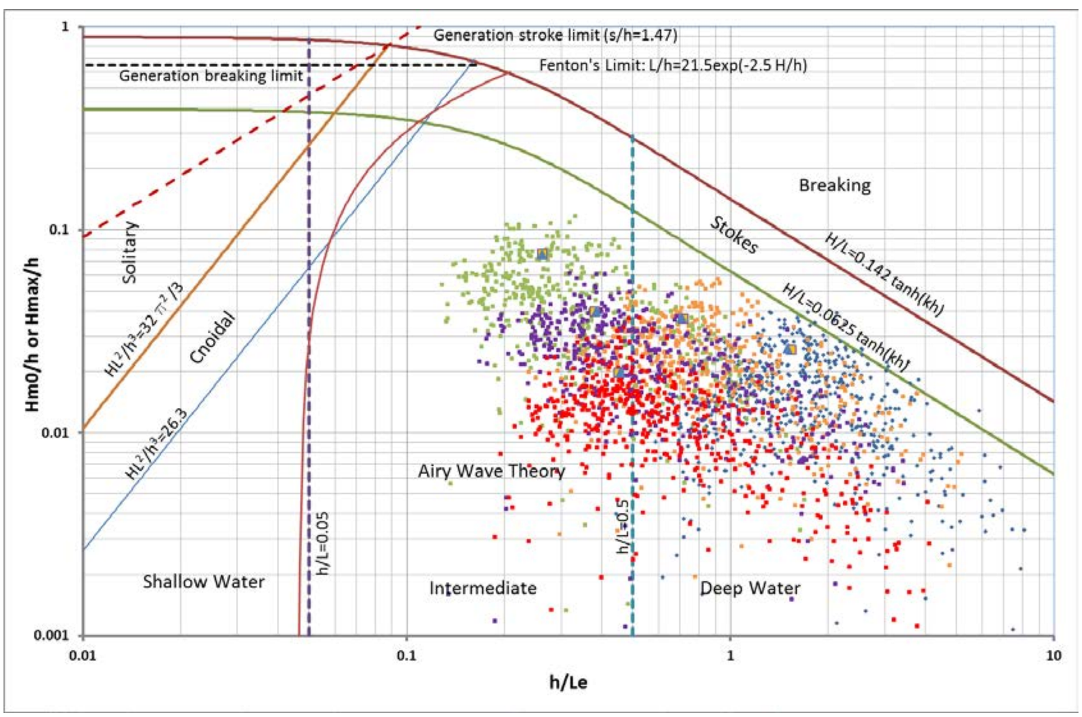

Figure 8. Measured (blue triangle) and target (orange square) irregular wave conditions and its comparison to the validity ranges of different wave theories at the nominal location of the WEC device (wg6). Measured wave conditions include individual waves from a standard zero-crossing analysis.

5. Principle Power ServerFloat Testing

Principle Power participates as one of the contestants of WEC-Prize by introducing the ServerFloat, a floating platform designed to harvest energy from waves by applying a modification of the Oscillating Water Column (OWC) concept.

The ServerFloat model was received at HWRL, measured and installed for testing in the DWB according to the test program as prescribed by the WEC-Prize. This chapter summarizes the model layout and instrumentation, and describes the structure of the raw and processed data submitted as part of the deliverables. Results of the data analysis is included in the SSTF submission report.

5.1 Model Description and Measurements

The ServerFloat model is a floating platform made of 8 vertical cylinders, interconnected and supported by rounded braces. The cylinders are arranged forming a square, along the perimeter. A flat horizontal plate at the upper part of the platform supports the PTO and control mechanisms. The nominal width of the platform is 70 m, center to center between columns, and 31 m high. Each column has a nominal diameter of 11.5 m. the draft of the structure is around 24.5 m, although this was changed depending on the wave conditions, as part of the configuration of the model.

An isometric view of the ServerFloat, is shown in Figure 9. An image of the ServerFloat model, ready for testing, is presented in Figure 10.

General dimensions and mass were measured as part of the model characterization procedures. Results of the measurements are summarized in Table 6. Principle Power decided not to measure the Center of Gravity and Moments of Inertia to avoid any possible damage to the model during this process. The 6DOF motions included as part of the SSTF submission report have been computed on the CoG indicated in the design drawings submitted by Principle Power as part of the TG2.

Table 6. General dimensions and mass of the ServerFloat (prototype scale).

Component	Nominal dimensions	Measured dimensions
Column diameter	11.5 m	10.95 m
Column height	31.0 m	30.7625 m
Center to center column width	70.0 m	71.525 m
Platform mass (includes PTO)	n/a	11,525 ton

Columns at the corners have an open bottom (shown in blue in Figure 10) thus the water level inside is subject to the hydrodynamic pressure variations and the air volume variations inside, while the other four columns are watertight, thus working as reservoirs of air to increase the pressure difference at the PTO (shown in white in Figure 10), and contribute to the platform buoyancy. Wave energy is harvested by applying the piston-type effect of the OWC to increase pressure on two of the vertical cylinders, while reducing pressure on the other two columns. The flow of air is controlled by a series of pipes and check-valves. Under power production mode, air flows from the high-pressure cylinders to the low-pressure cylinders through a control valve and a flow meter.

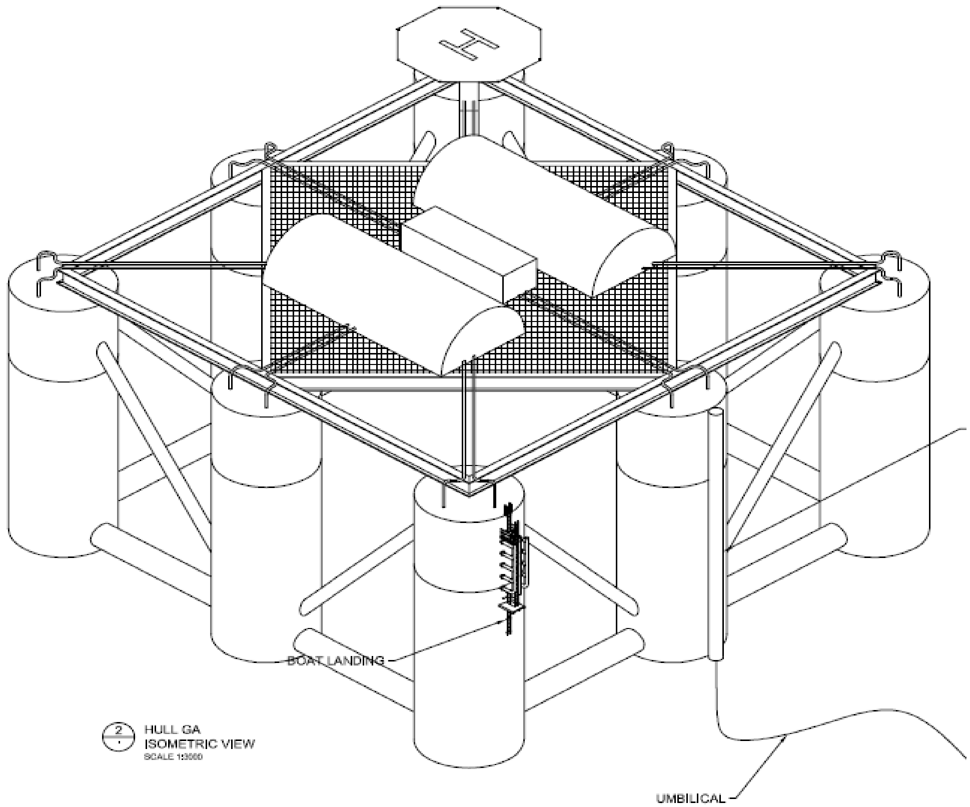

Figure 9. Isometric view of the ServerFloat (by Principle Power).

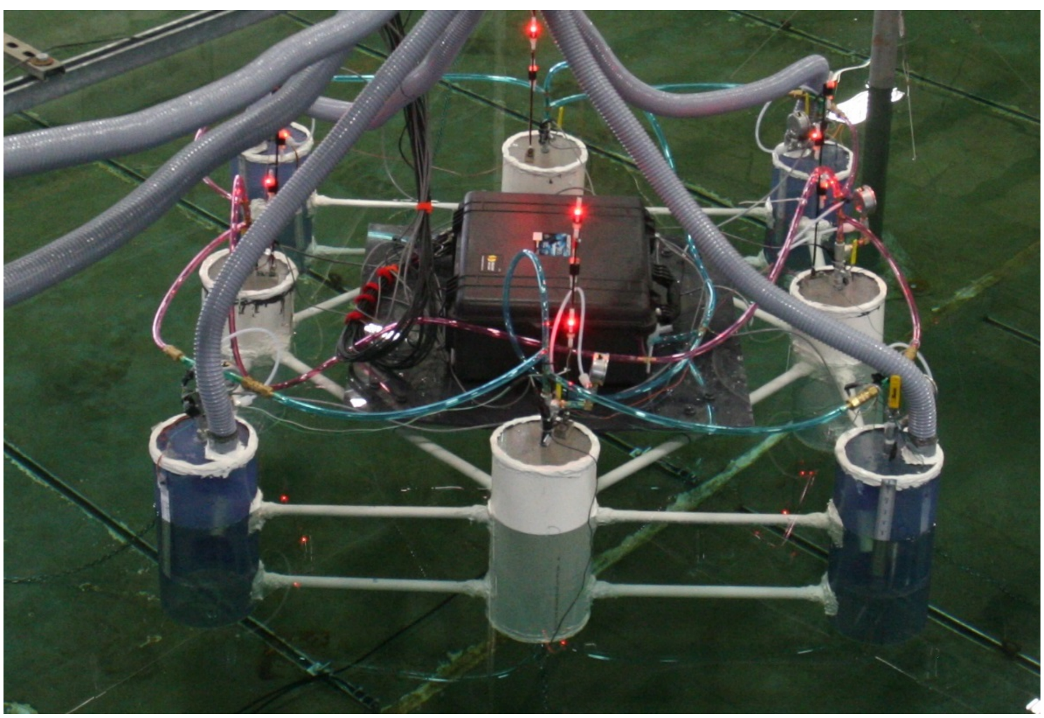

Figure 10. The ServerFloat model ready for testing.

Power can be assessed by the air flow rate and the pressure difference, using the following expression:

$$P = q\ \Delta p\ [W]$$

Where: q is the air flow rate in m^3/s, i.e. the kinematic part of the power,
Δp is the pressure differential in Pa (kg /ms^2), i.e. the dynamic part of the power.

The flow rate can also be computed by the pressure differential according to the TG2 representative PTO characterization submission, yielding:

$$q = R_{load}\ \Delta p\ [\mathrm{m}^3/\mathrm{s}]$$

And R_{load} is the resistive value obtained by Principle Power and represents the PTO setting for each testing. This value has been reported in the SSTF submission spreadsheet. The scaling is based on the assumption that the air flow is governed by Reynolds (i.e. viscous and inertia effects), and is therefore scaled by the cube of the geometrical scale (λ^3).

5.2 Test layout

The ServerFloat was installed at the center of the motion tracking frame in the DWB, approximately 17.5 m from the wave machine and 18.4 m from the shoreline. Once the wave calibration tests were executed, the DWB was drained and the wave gauge corresponding to the nominal location of the model (wg6) was removed. The rest of the instruments used during the wave calibration remained in place during the whole test program. The mooring system was installed and attached to the model according to the design layout. The first configuration corresponded to the normal incident, head on waves (0 degrees). The model layout and instrumentation in the DWB is shown in Figure 11.

The mooring system consisted of four chains in a squared arrangement, 275 m wide, as also shown in Figure 11. All mooring chains were similar and were fixed to four dead weights deployed on the basin floor. The length of the model mooring chains was 167.64 m (prototype scale). The chain used in the model tests was #2 straight link machine chain. The model chain weight was 1.73 N/m (216.25 kN/m, prototype scale).

As indicated above, testing of different wave directions was achieved by rotating the model. The procedure consisted on dragging the dead weights to previously marked locations on the basin floor, corresponding to the 0, 20 and 50 degrees.

An in-line load cell was installed at the attachment point of each mooring chain and the model, for measuring the dynamic loads during the tests. The load cell numbering and arrangement is shown in Figure 12.

The model 6DOF motions were measured with a PhaseSpace system of 8 cameras mounted on the frame and 4 rods with LED active markers attached to the model.

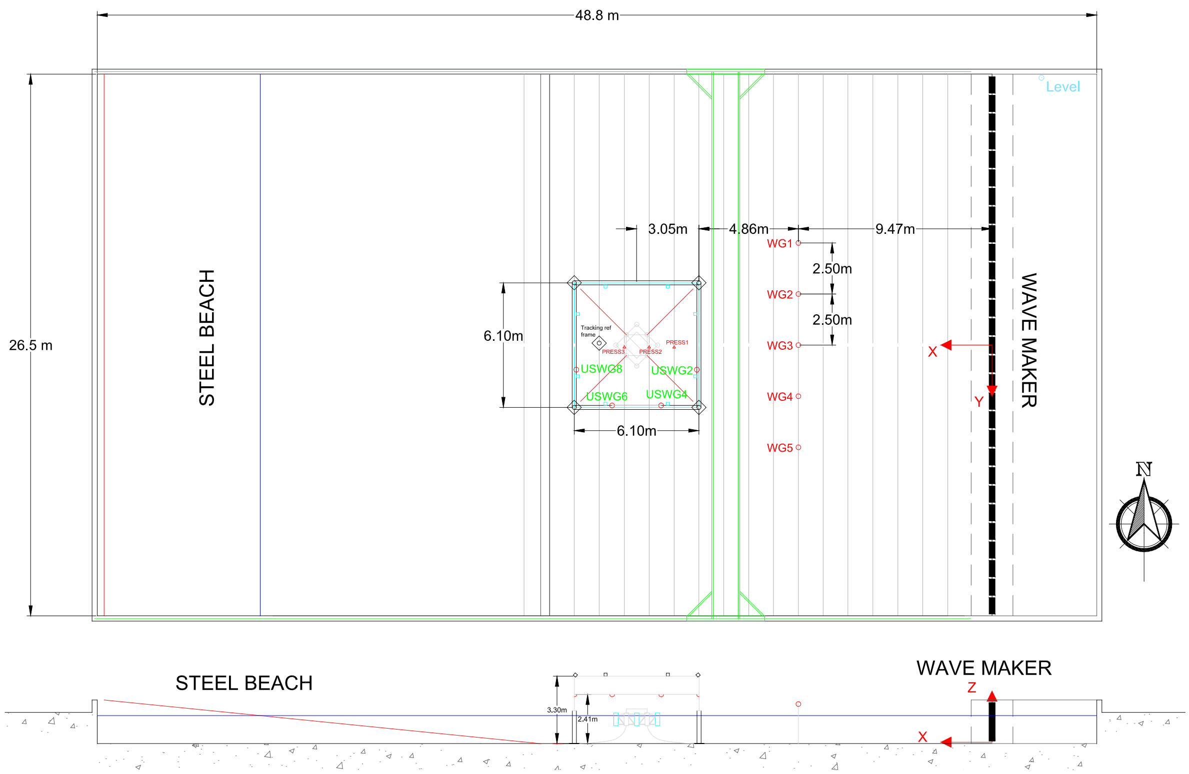

Figure 11. Model layout and instrumentation in the DWB.

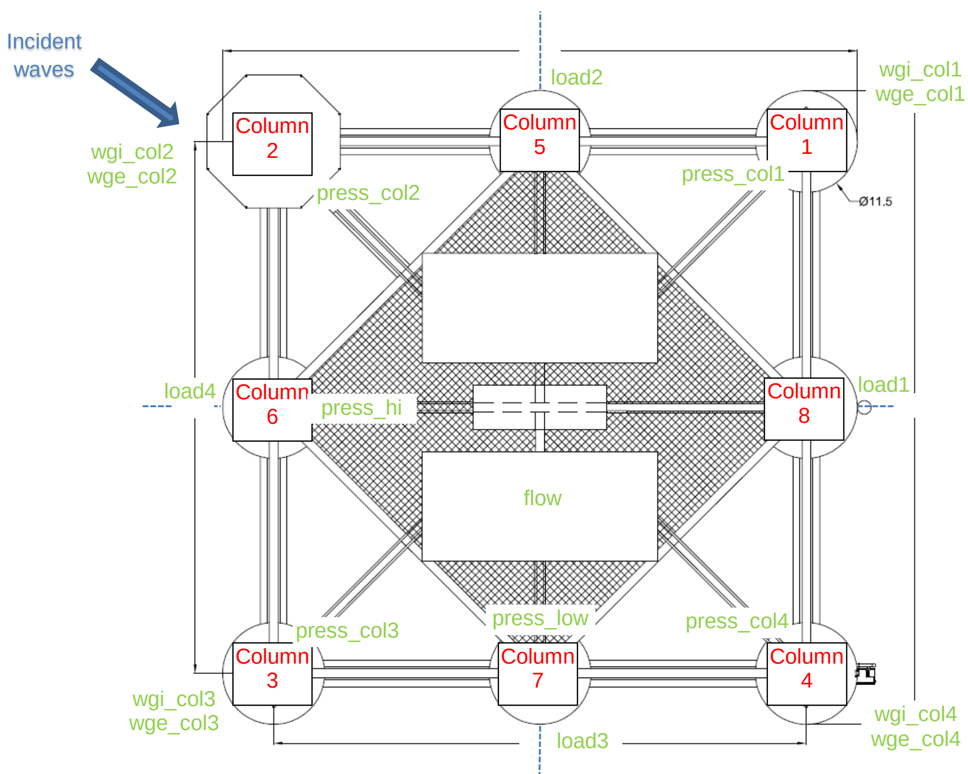

Figure 12. Detailed model layout and instrumentation in the DWB.

Further, on-board instruments by Principle Power included 8 pressure gauges, 6 water level sensors, and an air flow meter. Location and labelling of the on-board instruments is also indicated in Figure 12.

The power production in the model can be estimated with the flow rate as provided by the air flow meter, indicated as flow in Figure 12, and by computing the pressure differential by subtracting the pressure measurements, indicated as press_hi and press_low in Figure 12.

5.3 Wave Measurements

As indicated previously, wave heights were measured using resistance wave gauges and acoustic probes. The resistance gauges use the conductivity of the water between two parallel metal rods or wires. The electronics differentially drive the metal conductors with a 10 KHz signal, measuring the current as it responds to changes in the conductivity, which is the inverse of resistance, due to changing water height between the metal conductors. The electronics convert the current to voltages and amplify the results. The wave gauge electronics were designed by Terry Dibble (former electrical engineer at the HWRL) and built by ImTech.

Ultrasonic sensors, also called ultrasonic transducers, measure the distance to or the presence of a target object by sending a sound pulse, above the range of human hearing (ultrasonic), toward the target and then measuring the time it takes the sound echo to return. Knowing the speed of sound, the sensor determines the distance of the target and sets its outputs accordingly. The advantages are its resolution (~0.086 mm) and its non-intrusiveness. The acoustic probes used during the wave calibration tests for WEC-Prize were built by Senix, Inc.

The locations of the gauges as depicted in Figure 11 in the DWB coordinates are given in Table 7.

Table 7. Wave gauge locations during the model testing.

Wave Gauge	Basin x (m)	Basin y (m)
wg1	9.479	-5.002
wg2	9.490	-2.505
wg3	9.480	0.000
wg4	9.486	2.482
wg5	9.489	4.988
uswg2	14.150	1.235
uswg4	16.135	3.233
uswg6	18.661	3.229
uswg8	20.660	1.274

5.4 Water Level Measurements

A pressure sensor was used to determine the water depth. The DWB sensor is a model PDCR 10/FD made by Druck, which is now a subsidiary of GE Sensing. The PDCR 10/FD has a 5 psig (34.47 kPa) range, and has been calibrated with associated level enclosure for 34.05 cm of water per volt. This sensor has a combined non-linearity and hysteresis of 0.25% BSL. The PDCR 10/FD model has an integral 10.6 meter cable. The sensor is temperature compensated over a 0° to 30°C range. The water temperature during the tests varied from 7 to 12ºC.

The water level sensor is located in front of the wave machine paddles, on the southeast corner (see Figure 11). The coordinates of the water level sensor are indicated in Table 8.

Table 8. Water level sensor location.

Pressure Gauge	Basin x (m)	Basin y (m)
Level	2.136	12.895

5.5 Motion tracking measurements

Model 6DOF motions were measured using a PhaseSpace optical motion tracking system. The system has eight fixed cameras mounted on an overhead frame. The camera frame is a 6.1m x 6.1 m square. The height of the cameras above the bottom is 3.3 m. The cameras have an optical resolution of 3600 x 3600 pixels, with a 16-bit dynamic range and a 480 Hz sampling rate. The cameras are used to track active LED markers which are attached to the model (see Figure 10). Each LED has a particular light-pulse frequency which provides a unique identifier. There is a LED base station which is used to synchronize the LED controllers with the camera sever. The LED controller is a Radio Frequency (RF) transceiver used to turn particular LEDs or strings of LEDs off and on.

The camera server collects and processes data from the cameras outputting 3D position data. PhaseSpace states that the system is capable of sub millimeter accuracy. Tests conducted using the 6.1 m x 6.1 m HWRL frame indicate that the total system accuracy is approximately 4.1 mm and the precision is to within 0.8 mm at 480 Hz (Brown, 2010).

The system is calibrated by moving a calibration wand which has eight LEDs with known spacing throughout the test volume. The locations are referenced to a PhaseSpace coordinate axis definition square which is located in the field of view of the cameras (indicated as tracking ref frame in Figure 11).

Data are time stamped by the DAQ and triggered by the start and stop of the wavemaker. The 480 Hz data are down sampled to 50 Hz to match the sampling rate of the wave, pressure and load cell data. The data were filtered and then, using a spline, interpolated the 480 Hz data at 50 Hz.

The motions of the model are given in PhaseSpace coordinates for a point on the buoy located at the lower target light on Column #5 of the platform. The motions at this location were transferred to the model CoG and with the DWB coordinate system.

5.6 Mooring Line Force Measurements

Mooring line forces were measured using Futek Model LSB210 load cells. These are submersible, stainless steel, temperature compensated S-Beam load cells. The load cells in the four mooring lines were 50 pound range. The load cells had linear and stable calibrations, with a typical sensitivity of 10.5 lb/volt. The low level load cell signals were low-pass filtered at 15Khz and amplified using a Vishay 2120 signal conditioning unit. A second stage of filtering was applied to the signals using a National Instruments SCXI-1143 lowpass filter module incorporating an 8-pole Butterworth filter with a cutoff frequency of 25Hz. The signals were then sampled using a National Instruments PXI-6259 16bit analog to digital converter at 50 hz. The resolution is approximately 0.006% of the maximum range.

5.7 Near-bed Pressure Measurements

Three pressure sensors were installed at the basin floor, in-line with the incoming waves and at the nominal location of the WEC device. The pressure sensor is a model PDCR 830 made by Druck, which is now a subsidiary of GE Sensing. The PDCR 830 has a 15 psig (103.41 kPa) range. This sensor has a combined non-linearity and hysteresis of 0.1% BSL. The PDCR 830 model has an integral 10.6 meter cable. The sensor is temperature compensated over a 0° to 30°C range. The water temperature during the tests varied from 7 to 12°C.

The pressure sensors (indicated as press1, press2 and press3 in Figure 11) were located along the center axis of the basin, below the nominal location of the WEC device. The coordinates of the pressure sensors are indicated in Table 9.

Table 9. Near-bed pressure sensor location.

Pressure Gauge	Basin x (m)	Basin y (m)
Press1	15.568	-0.022
Press2	16.782	-0.017
Press3	18.003	-0.027

5.8 Videos

High definition video recordings were made of all wave runs. The camera was a JVC Everio with 1080p and 40x optical zoom. The camera was fixed on the instrumentation bridge, overlooking the WEC device. At the beginning of each test, the camera started and a sign specifying the wave conditions was located in front of the camera to keep track of the corresponding trial.

An LED was also fixed on the cameras field of view to mark events during the test. The RST event checklist is included as part of the deliverables. During an event, the LED is switched on for approximately 1 second, and an event signal is also recorded in file. The LED signal has been recorded simultaneously as the rest of the instruments, so direct correlation of the event and the wave conditions can be obtained. The event signal channel name is led.

Figure 13 presents an image of the WEC device during testing, where the location of the LED has been highlighted for reference.

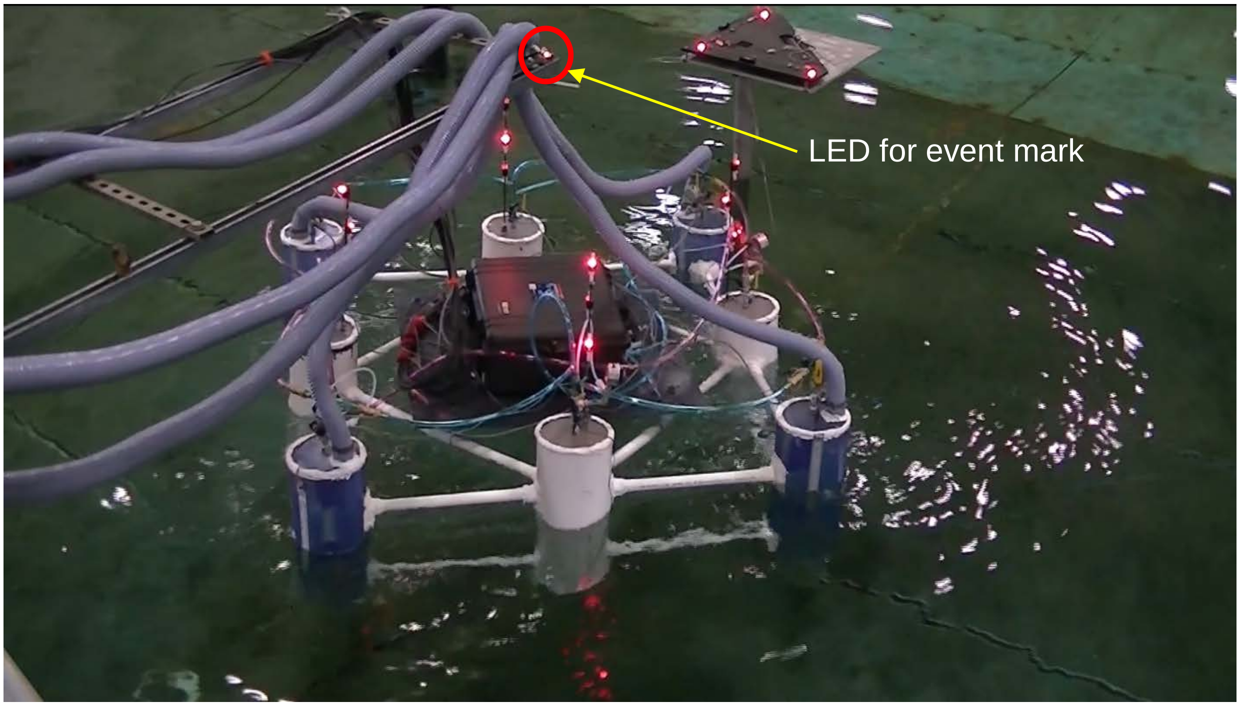

Figure 13. Image frame taken from the video file indicating the localization of the LED for event mark.

5.9 Data Acquisition System (DAQ)

The data acquisition system (DAQ) used at the HWRL runs on National Instruments PXI architecture computers. These computers use a real-time version of the LabVIEW programming environment. Each computer is installed in a PXI chassis along with accompanying PXI and or SCXI modules. Analog data acquisition for each DAQ is controlled by a NI PXI-6259 M-series 16-bit multifunction DAQ module. The DAQ module communicates via the PXI/SCXI backplane to SCXI-1143 Butterworth anti-aliasing filter modules in its containing PXI-1052 chassis. Each filter module is fronted with SCXI-1305 terminal blocks that take ±5V differential inputs from analog channels via 50Ω coaxial cable with BNC connectors. The SCXI-1143 Butterworth anti-aliasing filters are set with cutoff frequency at ½ the sampling rate. There are eight filter modules per PXI-1052 chassis and 8 channels per filter module, for a total of 64 channels of analog inputs per chassis. Synchronization of up to 3 independent chassis permits up to 192 synchronized analog input channels. The DAQ sampling rate is typically 50 Hz; the DAQ is capable of up to 5 KHz when sampling all 64 channels. The DAQ assumes that all input sources are floating; therefore it has a 100kΩ resistor to ground on the low (negative) side of each differential input. Testing at the HWRL has shown that the DAQ is accurate to within ±0.3mV when observing known voltages on NIST-traceably certified voltage standards.

During the WEC device tests, two PXI modules were used. Sample coherency is maintained through the use of TTL pulses generated by one master DAQ and listened to by the other slave DAQ. The PhaseSpace motion tracking system at the HWRL is set up in sync mode and triggered by a wavemaker output 5V high at the start of operations and holds it high until after the board is stopped and current span has wound down to 0. This is called the wmstart signal. It is an analog output transmitted over 50Ω coaxial cable and recorded as an analog input channel on the HWRL DAQ, and it can be buffered and sent to other systems for simultaneous recording and then post-processed to align signals afterwards. The accuracy of this procedure is to within ±1 sample of the slowest-sampling system.

HWRL DAQ system clocks are synchronized to a grandmaster clock using the National Instruments NITimeSync implementation of the IEEE 1588-2008 Precision Time Protocol. The grandmaster clock is a dedicated PXI-based HWRL DAQ system with an NI-PXI-6682 timing and synchronization module connected to a Trimble Bullet III GPS antenna mounted on the roof of the HWRL. The GPS signal provides ±100ns accuracy relative to UTC. The grandmaster clock sends synchronization messages over the local firewalled HWRL DAQ network every 500ms. Testing shows that HWRL DAQ timestamps agree to within ±7ms when observing triggered coherent samples of the same analog signal.

During the WEC device testing, both PXI modules (master and slave) were configured with a sampling rate of 50 Hz, while the PhaseSpace system had a sampling rate of 480 Hz.

Figure 14 shows the master and slave PXI modules as deployed during the testing.

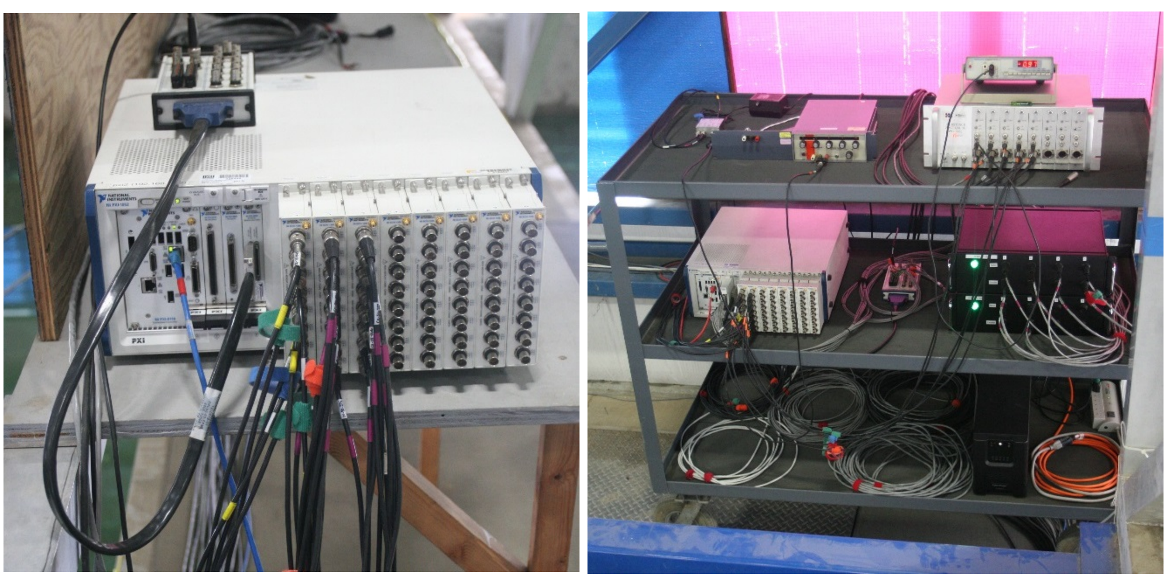

Figure 14. Master and slave DAQ PXI modules used during the WEC-Prize testing.

5.10 Raw Channel List

The data recorded during the WEC device tests have been organized as Raw and Processed Data Files. Raw Data is the original measured data, in physical units (model scale). The data have been included in two files:

1. A data file containing all instruments recorded by the master and slave DAQ PXI modules (wave gauges, pressure gauges, load cells, on-board instruments, LED for event mark, water level, wavemaker start pulse, wave board #15 displacement, and wave board #15 surface elevation) with a sampling rate of 50 Hz. The data file contains all the data taken from the DAQ start. The data file is a .csv table where the first row has the name of each channel, as described below.
2. A data file containing the 3D motions (Surge, Sway, Heave, Roll, Pitch, Yaw) of the platform, as measured by PhaseSpace at the top of Column #5 of the platform in the PhaseSpace coordinate system. The sampling rate is 480 Hz and the data sampling begins with the wave maker start pulse. PhaseSpace coordinate system and the DWB coordinate system are shown in Figure 15.

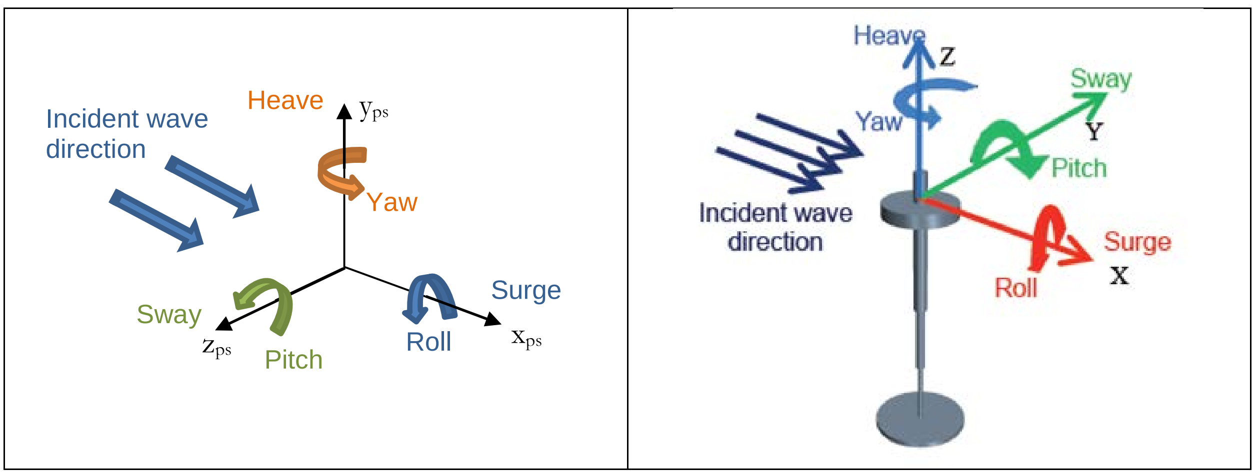

Figure 15. Definition sketch of PhaseSpace and DWB coordinate systems.

Raw data is submitted in a series of directories, containing the raw data of the instruments for each Wave_ID, and the raw data from PhaseSpace, indicated as Wave_ID_PS.

Table 10 presents the channel list of the raw data.

Table 10. Raw data channel list.

Data File	Channel Name	Description	Unit	Sensor	Sample Rate
R *Wave_ID* PrinciplePower.csv	time	time stamp	s	NI PXI-6259 system clock	50 Hz
R *Wave_ID* PrinciplePower.csv	press1	near-bed pressure gauge 1	Pa	Druck PDCR 830-6300	50 Hz
R *Wave_ID* PrinciplePower.csv	press2	near-bed pressure gauge 2	Pa	Druck PDCR 830-6301	50 Hz
R *Wave_ID* PrinciplePower.csv	press3	near-bed pressure gauge 3	Pa	Druck PDCR 830-3591	50 Hz
R *Wave_ID* PrinciplePower.csv	load1	load cell for mooring line at Column 8	N	Futek LSB 210-3299	50 Hz
R *Wave_ID* PrinciplePower.csv	load2	load cell for mooring line at Column 5	N	Futek LSB 210-3298	50 Hz
R *Wave_ID* PrinciplePower.csv	load3	load cell for mooring line at Column 7	N	Futek LSB 210-3301	50 Hz
R *Wave_ID* PrinciplePower.csv	load4	load cell for mooring line at Column 6	N	Futek LSB 210-3296	50 Hz
R *Wave_ID* PrinciplePower.csv	press_col1	pressure gauge at column 1	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	press_col2	pressure gauge at column 2	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	press_col3	pressure gauge at column 3	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	press_col4	pressure gauge at column 4	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	press_hi	pressure gauge at column 6 (hi pressure)	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	press_low	pressure gauge at column 7 (low pressure)	Pa	MPX4250A	50 Hz
R *Wave_ID* PrinciplePower.csv	flow	air flow rate	l/s	HAUFHT00204AXT	50 Hz
R *Wave_ID* PrinciplePower.csv	empty	n/a	-	-	50 Hz
R *Wave_ID* PrinciplePower.csv	wgi_col1	surface elevation inside column 1	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wgi_col2	surface elevation inside column 2	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wgi_col3	surface elevation inside column 3	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wgi_col4	surface elevation inside column 4	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wge_col1	surface elevation outside column 1	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wge_col2	surface elevation outside column 2	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wge_col3	surface elevation outside column 3	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	wge_col4	surface elevation outside column 4	m	eTape-12	50 Hz
R *Wave_ID* PrinciplePower.csv	led	LED signal for event mark	volts	-	50 Hz
R *Wave_ID* PrinciplePower.csv	standard	reference voltage	volts	VSTD-8241	50 Hz
R *Wave_ID* PrinciplePower.csv	wmstart	wave maker start signal	volts	-	50 Hz
R *Wave_ID* PrinciplePower.csv	depth	depth at the wave maker	m	TDG-TWM-0001	50 Hz
R *Wave_ID* PrinciplePower.csv	wmdisp15	displacement of wave board #15	m	TMPO-TWM-0015	50 Hz
R *Wave_ID* PrinciplePower.csv	wmwg15	surface elevation at wave board #15	m	RWG-TWM-0015	50 Hz
R *Wave_ID* PrinciplePower.csv	level	water level in the basin	m	Druck PDCR 10/FD	50 Hz
R *Wave_ID* PrinciplePower.csv	wg1	surface elevation at gauge 1	m	RWG-2265-01	50 Hz
R *Wave_ID* PrinciplePower.csv	wg2	surface elevation at gauge 2	m	RWG-2265-02	50 Hz
R *Wave_ID* PrinciplePower.csv	wg3	surface elevation at gauge 3	m	RWG-2265-03	50 Hz
R *Wave_ID* PrinciplePower.csv	wg4	surface elevation at gauge 4	m	RWG-2265-04	50 Hz
R *Wave_ID* PrinciplePower.csv	wg5	surface elevation at gauge 5	m	RWG-2265-05	50 Hz
R *Wave_ID* PrinciplePower.csv	uswg2	surface elevation at acoustic probe 2	m	Senix DS-6555	50 Hz
R *Wave_ID* PrinciplePower.csv	uswg4	surface elevation at acoustic probe 4	m	Senix DS-6665	50 Hz
R *Wave_ID* PrinciplePower.csv	uswg6	surface elevation at acoustic probe 6	m	Senix DS-6664	50 Hz
R *Wave_ID* PrinciplePower.csv	uswg8	surface elevation at acoustic probe 8	m	Senix DS-6662	50 Hz
Data File	**Channel Name**	**Description**	**Unit**	**Sensor**	**Sample Rate**
R *Wave_ID* PrinciplePower.csv	time	time stamp	s	PhaseSpace system clock	480 Hz
R *Wave_ID* PrinciplePower.csv	surge	linear displacement	mm	LED and processor	480 Hz
R *Wave_ID* PrinciplePower.csv	sway	linear displacement	mm	LED and processor	480 Hz
R *Wave_ID* PrinciplePower.csv	heave	linear displacement	mm	LED and processor	480 Hz
R *Wave_ID* PrinciplePower.csv	roll	angular displacement	degrees	LED and processor	480 Hz
R *Wave_ID* PrinciplePower.csv	pitch	angular displacement	degrees	LED and processor	480 Hz
R *Wave_ID* PrinciplePower.csv	yaw	angular displacement	degrees	LED and processor	480 Hz

5.11 Processed Channel List

The Processed data includes the time series of the relevant measurements for analysis. Post-processing and further analysis is included in the SSTF submission spreadsheet.

The Raw data firstly is cropped according to the wavemaker start signal. Previous data is used to compute the still water level for each of the wave gauges. Acoustic probes are also filtered to eliminate spikes and false data. Further, a secondary bandpass filter is applied on the surface elevation signals (wg and uswg) as well as on the mooring line loads (load). Finally, the PhaseSpace data (3D motions) are also filtered, down sampled to 50 Hz, and the coordinate system is transformed to the DWB system and translated to the center of gravity of the platform.

Since the instrument data and PhaseSpace data have now the same time stamp, and the same sample frequency, the processed data is stored in a single csv file.

Processed data is in physical units, model scale.

Table 11 presents the channel list of the processed data.

Table 11. Processed data channel list.

Data File	Channel Name	Description	Unit	Sensor	Sample Rate
P *Wave_ID* Principle Power.csv	time	time stamp	s	NI PXI-6259 system clock	50 Hz
P *Wave_ID* Principle Power.csv	flow	air flow rate	m3/s	HAUFHT00204AXT	50 Hz
P *Wave_ID* Principle Power.csv	heave	linear displacement	m	LED and processor	50 Hz
P *Wave_ID* Principle Power.csv	led	LED signal for event mark	volts	-	50 Hz
P *Wave_ID* Principle Power.csv	load1	load cell for mooring line at Column 8	N	Futek LSB 210-3299	50 Hz
P *Wave_ID* Principle Power.csv	load2	load cell for mooring line at Column 5	N	Futek LSB 210-3298	50 Hz
P *Wave_ID* Principle Power.csv	load3	load cell for mooring line at Column 7	N	Futek LSB 210-3301	50 Hz
P *Wave_ID* Principle Power.csv	load4	load cell for mooring line at Column 6	N	Futek LSB 210-3296	50 Hz
P *Wave_ID* Principle Power.csv	pitch	angular displacement	rad	LED and processor	50 Hz
P *Wave_ID* Principle Power.csv	press1	near-bed pressure gauge 1	Pa	Druck PDCR 830-6300	50 Hz
P *Wave_ID* Principle Power.csv	press2	near-bed pressure gauge 2	Pa	Druck PDCR 830-6301	50 Hz
P *Wave_ID* Principle Power.csv	press3	near-bed pressure gauge 3	Pa	Druck PDCR 830-3591	50 Hz
P *Wave_ID* Principle Power.csv	press_col1	pressure gauge at column 1	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	press_col2	pressure gauge at column 2	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	press_col3	pressure gauge at column 3	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	press_col4	pressure gauge at column 4	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	press_hi	pressure gauge at column 6 (hi pressure)	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	press_low	pressure gauge at column 7 (low pressure)	Pa	MPX4250A	50 Hz
P *Wave_ID* Principle Power.csv	roll	angular displacement	rad	LED and processor	50 Hz
P *Wave_ID* Principle Power.csv	surge	linear displacement	m	LED and processor	50 Hz
P *Wave_ID* Principle Power.csv	sway	linear displacement	m	LED and processor	50 Hz
P *Wave_ID* Principle Power.csv	uswg2	surface elevation at acoustic probe 2	m	Senix DS-6555	50 Hz
P *Wave_ID* Principle Power.csv	uswg4	surface elevation at acoustic probe 4	m	Senix DS-6665	50 Hz
P *Wave_ID* Principle Power.csv	uswg6	surface elevation at acoustic probe 6	m	Senix DS-6664	50 Hz
P *Wave_ID* Principle Power.csv	uswg8	surface elevation at acoustic probe 8	m	Senix DS-6662	50 Hz
P *Wave_ID* Principle Power.csv	wg1	surface elevation at gauge 1	m	RWG-2265-01	50 Hz
P *Wave_ID* Principle Power.csv	wg2	surface elevation at gauge 2	m	RWG-2265-02	50 Hz
P *Wave_ID* Principle Power.csv	wg3	surface elevation at gauge 3	m	RWG-2265-03	50 Hz
P *Wave_ID* Principle Power.csv	wg4	surface elevation at gauge 4	m	RWG-2265-04	50 Hz
P *Wave_ID* Principle Power.csv	wg5	surface elevation at gauge 5	m	RWG-2265-05	50 Hz
P *Wave_ID* Principle Power.csv	wge_col1	surface elevation outside column 1	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wge_col2	surface elevation outside column 2	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wge_col4	surface elevation outside column 4	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wgi_col1	surface elevation inside column 1	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wgi_col2	surface elevation inside column 2	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wgi_col4	surface elevation inside column 4	m	eTape-12	50 Hz
P *Wave_ID* Principle Power.csv	wmdisp15	displacement of wave board #15	m	TMPO-TWM-0015	50 Hz
P *Wave_ID* Principle Power.csv	wmwg15	surface elevation at wave board #15	m	RWG-TWM-0015	50 Hz
P *Wave_ID* Principle Power.csv	yaw	angular displacement	rad	LED and processor	50 Hz

Appendix A. Calibration Sheets and Data

A.1 Wave gauges

All wave gauges and acoustic probes are calibrated when changing the tank water level (filling and draining). Fill and drain calibration methods are the same. While the water level is slowly changing, the HWRL DAQ observes all analog inputs over a sample period, typically sampling at 50Hz for a 1-minute duration. Sampling of analog inputs is typically done every 5 minutes for an entire fill or drain, which can take up to 9 hours. The mean voltage of every input channel is estimated for each sample period. Mean voltage estimates are then put into a wave gauge calibration spreadsheet that calculates a linear least-squares fit between the observed wave gauge voltages and the calibrated water depth observations from a NIST traceably-calibrated pressure sensor, referred to as level in the HWRL DAQ. The latest calibration results for wave gauges and acoustic probes is shown in Table 12.

Table 12. Calibration results for wave gauges and acoustic probes on January 12, 2016.

Wave Gauge	Calibration coefficient	Units	Correlation coefficient
Wg1	0.2544	m/V	99.70%
Wg2	0.2446	m/V	99.72%
Wg3	0.2491	m/V	99.65%
Wg4	0.2449	m/V	99.53%
Wg5	0.2498	m/V	99.56%
Uswg2	-0.1723	m/V	99.96%
Uswg4	-0.1768	m/V	99.85%
Uswg6	-0.1722	m/V	99.85%
Uswg8	-0.1899	m/V	99.54%

A.2 Pressure gauges and water level sensors

Pressure gauges and water level sensors are calibrated in-house and following NIST standards, using traceable calibration equipment. The calibration constants for all pressure gauges and water level sensors ae included in Table 13. Calibration certificates are included in Section A.6.

Table 13. Calibration results for pressure gauges and water level sensors.

Pressure Gauge	Calibration coefficient	Units
Press1	21070	Pa/V
Press2	20891	Pa/V
Press3	20864	Pa/V
Depth	0.4	m/V
Level	0.486	m/V

A.3 Load cells

Load cell calibration constants are based on independent calibration certificates, included in Section A.6. The calibration constants for all load cells are shown in Table 14.

Table 14. Calibration results for the load cells.

Load cell	Calibration coefficient	Units
Load1	44.50	N/V
Load2	44.76	N/V
Load3	44.79	N/V
Load4	44.85	N/V

A.4 Wave machine sensors

Each wave board has a wave gauge attached for active wave absorption, and each actuator has a position transducer to ensure the quality on following the drive signal. Both set of sensors are automatically calibrated by the wave machine control system. The calibration constants for the wave paddle #15 position transducer and wave gauge are presented in Table 15.

Table 15. Calibration constants for the position transducer and wave gauge of paddle #15.

Sensor	Calibration coefficient	Units
Wmdisp15	0.23	m/V
Wmwg15	0.20	m/V

A.5 On-board sensors (by Principle Power)

The ServerFloat on-board instruments were installed and calibrated by Principle Power. The calibration constants for all on-board instruments are included in Table 16. These constants were also applied on the measured data to obtain the Raw and Processed time series in physical units, and used to elaborate the SSTF submission spreadsheet.

Table 16. Calibration constants for the on-board instruments installed by Principle Power.

Sensor	Calibration coefficient	Units
Press_col1	49020	Pa/V
Press_col2	49020	Pa/V
Press_col3	49020	Pa/V
Press_col4	49020	Pa/V
Press_hi	49020	Pa/V
Press_low	49020	Pa/V
Flow	0.152	L/s/V
Wgi_col1	0.055	m/V
Wgi_col2	0.058	m/V
Wgi_col3	n/a	-
Wgi_col4	0.061	m/V
Wge_col1	0.054	m/V
Wge_col2	0.058	m/V
Wge_col3	n/a	-
Wge_col4	0.056	m/V

A.6 Calibration certificates

O.H. Hinsdale Wave Research Laboratory
3550 SW Jefferson Way
Corvallis OR 97331

Certificate of Calibration CAL-BETA10G-9163157-20150219

MARTEL ELECTRONICS

BETA CALIBRATORS

REPORT OF CALIBRATION

This instrument is calibrated and tested to verify compliance with Martel's test specifications for all ranges and parameters required to meet 1 year performance specifications. The calibration uses measurement standards traceable to the National Institute of Standards and Technology (NIST). This calibration complies with the requirements of ANSI/NCSL Z540-1-1994 part 2. Calibration and verification are performed at an ambient temperature of 23 ± 5°C and relative humidity of > 20% to < 70%.

Any test uncertainty (TUR) less than 4:1 appears under the TUR heading on the data record. Where the TUR meets or exceeds 4:1, the TUR field is blank.

Tom Fatur
Tom Fatur
President

Florin Visuian
Calibrated By
Florin Visuian

Manufacturer:	Martel Corporation	**Cal Date:**	February 19, 2015
Model:	BetaPort 10G	**Report Date:**	February 19, 2015
Serial Number:	9163157	**Temperature:**	21.7°C
		Relative Humidity:	31 %
Calibration Procedure:	Beta 0-10psi yellow module: (1 year) AT/FN 7010 C		
Procedure Revision:	2.1		

Standards Used

Asset	Manufacturer	Model Number	Description	Cal. Date	Due Date
48221	Ruska	7010D0015S10	CALIBRATOR	6-Nov-14	20-Feb-15

Test Data

PARAMETER	RESULT	ACCEPTANCE LIMITS LOW	HIGH		TUR
As Found Pressure Read Verification					
0.000psi	0.000	-0.005	0.005	PASS	
2.500psi	2.500	2.495	2.505	PASS	
5.000psi	5.001	4.995	5.005	PASS	
7.500psi	7.501	7.495	7.505	PASS	
10.000psi	10.002	9.995	10.005	PASS	
7.500psi	7.501	7.495	7.505	PASS	
5.000psi	5.001	4.995	5.005	PASS	
2.500psi	2.501	2.495	2.505	PASS	
0.000psi	0.002	-0.005	0.005	PASS	
As Left Pressure Read Verification					
0.000psi	0.000	-0.005	0.005	PASS	
2.500psi	2.498	2.495	2.505	PASS	
5.000psi	4.999	4.995	5.005	PASS	
7.500psi	7.499	7.495	7.505	PASS	
10.000psi	9.999	9.995	10.005	PASS	
7.500psi	7.499	7.495	7.505	PASS	
5.000psi	4.999	4.995	5.005	PASS	
2.500psi	2.499	2.495	2.505	PASS	
0.000psi	0.000	-0.005	0.005	PASS	

MET/CAL RunTime Report: Calibration Results

Page 1 of 1

Calibration Report Number: 02064702192015 9163157

3 Corporate Park Drive, Derry, NH 03038 (603) 434-8179 (800) 821-0023 FAX (603) 434-1653 www.martelcorp.com

O.H. Hinsdale Wave Research Laboratory
3550 SW Jefferson Way
Corvallis OR 97331

Certificate of Calibration DVM-7420-20150223

Certificate of Calibration

Certificate Number: **584953**

JJ Calibrations, Inc.
7007 SE Lake Rd
Portland, OR 97267-2105
Phone 503.786.3005
FAX 503.786.2994

Oregon State University - Hindsdale Wave Research
3550 SW Jefferson Way
Corvallis, OR 97331

PO: 2458-18022015
Order Date: 02/18/2015
Authorized By: N/A

Property #: N/A
User: N/A
Department: N/A
Make: Agilent
Model: 34401A
Serial #: MY44007420
Description: Bench Meter, 6.5 Digit
Procedure: DCN 400706
Accuracy: Refer to Mfg. Specs.

Calibrated on: 02/23/2015
*Recommended Due: 02/23/2016
Environment: 20 °C 27 % RH
As Received: Within Tolerance
As Returned: Within Tolerance
Action Taken: Calibrated
Technician: 112

Remarks: * Many factors may cause the unit to drift out of calibration before the recommended due date. Any reported error is the absolute value between the reference and the unit.

Standards Used

Std ID	Manufacturer	Model	Nomenclature	Due Date	Trace ID
397A	Fluke	5700A	Calibrator	08/08/2015	568031
427A	Fluke	5500A-SC300	Calibrator W/300MHz	02/04/2016	582108

Measurement Data

Parameter / Measurement Description	Range Unit	Reference	Min	Max	*Error	UUT
Before/After						
AC Voltage						
@ 1KHz	100 mV	100.0000	99.900	100.100	0.007	100.007 mV
@ 50KHz	100 mV	100.00000	99.8300	100.1700	0.0763	99.9237 mV
@ 1KHz	1 V	1.0000000	0.999100	1.000900	0.000015	1.000015 V
@ 50KHz	1 V	1.0000000	0.998300	1.001700	0.000688	0.999312 V
@ 1KHz	10 V	10.000000	9.99100	10.00900	0.00018	10.00018 V
@ 50KHz	10 V	10.000000	9.98300	10.01700	0.00419	9.99581 V
@ 1KHz	100 V	100.00000	99.9100	100.0900	0.0087	99.9913 V
@ 50KHz	100 V	100.00000	99.8300	100.1700	0.0664	99.9336 V
@ 50KHz	750 V	195.0000	194.583	195.417	0.265	194.735 V
@ 1KHz	750 V	750.0000	749.325	750.675	0.178	749.822 V
AC Current						
@ 1KHz	1 A	1.0000000	0.998600	1.001400	0.000056	0.999944 A
@ 1KHz	2 A	2.000000	1.99520	2.00480	0.00076	1.99924 A
DC Voltage						
	100 mV	100.00000	99.9915	100.0085	0.0005	99.9995 mV
	1 V	1.0000000	0.999530	1.000470	0.000009	1.000009 V
	10 V	10.000000	9.99600	10.00400	0.00003	10.00003 V
	100 V	100.00000	99.9949	100.0051	0.0005	100.0005 V
	1000 V	1000.0000	999.945	1000.055	0.002	1000.002 V
DC Current						
	10 mA	10.000000	9.99300	10.00700	0.00002	10.00002 mA
	100 mA	100.00000	99.9450	100.0550	0.0006	99.9994 mA
	1 A	1.0000000	0.998900	1.001100	0.000051	0.999949 A
	2 A	2.000000	1.99700	2.00300	0.00028	1.99972 A
Frequency						
@ 10mVrms	100 Hz	100.000000	99.90000	100.10000	0.00052	99.99948 Hz
@ 1Vrms	100 kHz	100.00000	99.9900	100.0100	0.0004	100.0004 kHz
Resistance (4 Wire)						
	100 Ohm	99.994670	99.98067	100.00867	0.00223	99.99690 Ohm
	1 kOhm	0.99991310	0.9998031	1.0000231	0.0000139	0.9999270 kOhm
	10 kOhm	9.9994640	9.998364	10.000564	0.000166	9.999630 kOhm
	100 kOhm	99.99770	99.9867	100.0087	0.0021	99.9998 kOhm
	1 MOhm	0.99993070	0.9998207	1.0000407	0.0000183	0.9999490 MOhm

Certificate: 584953 Page 1 of 2

O.H. Hinsdale Wave Research Laboratory
3550 SW Jefferson Way
Corvallis OR 97331

Certificate of Calibration DVM-7420-20150223

Parameter		Measurement Data				
Measurement Description	Range Unit					UUT
Before/After		Reference	Min	Max	*Error	
Resistance (4 Wire)	10 MOhm	9.999950	9.99585	10.00405	0.00069	9.99926 MOhm

JJ Calibrations, Inc. certifies that this instrument has been calibrated in accordance with the JJ Calibrations Quality Assurance Manual with the stated procedure using standards that are traceable to the National Institute of Standards and Technology (NIST), or other National Measurement Institutes (NMI's), or by using natural physical constants, intrinsic standards or ratio calibration techniques. The quality system and this certificate are in compliance with ANSI/NCSL Z540-1-1994, ISO/IEC 17025-2005, ISO 10012-1, the ISO 9000 family and QS 9000. The expanded uncertainties of measurements for this calibration are based upon 95% (2 sigma) confidence limits. Unless otherwise stated, a test accuracy ratio (TAR) of 4:1, if achievable, is maintained. The results reported herein apply only to the calibration of the item described above. This report may not be reproduced, except in full, without prior written consent of JJ Calibrations, Inc.
JJ Calibrations, Inc. quality system has been assessed and accredited to ISO/IEC 17025:2005.

Reviewer — Issued 02/24/2015 — Rev # 15 — Inspector

Certificate of Calibration

Certificate Number **1111070023**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Sensor Info:

S/N .... 423301 **Model** LSB210
Item # .... QSH00256 **Capacity** .... 50 lb

Description: LSB210, 50 lb, JR. S-Beam Load Cell, Submersible Version, Material - 17-4 PH S.S., #4-40-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 5 ft Long

Calibration Procedure OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter:

HP Model: **Agilent 34401A**, *S/N:* **US36135067**

Dead Weight(s):

1-10 lb, *Traceability No:* **622978**

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request.

This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: ***Angel Mendoza***
Issue Date: 11/7/2011 **Re-Calibration Date:** One Year After Issue Date

Futek Advanced Sensor Technology Inc. 10 Thomas Irvine CA. 92618 USA • Tel: (949) 465-0900 Fax: (949) 465-0905
www.futek.com

Certificate Number...... **1111070023**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Single Channel Item

CALIBRATION DATA

Test Temp ... 72.7 °F (22.6 °C)	**Relative Humidity** ... 50.2 %
Input Resistance .... 351 Ω	**Output Resistance** .... 352 Ω
Excitation .... 4.99 Vdc	**Zero Balance** .... 0.0126 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
10	0.4545	-0.046
20	0.9105	-0.025
30	1.3656	-0.045
40	1.8211	-0.047
50	2.2777	0.000
0	0.0006	

SHUNT CALIBRATION

Tension

Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load
60.4	(-Exc) & (-S)	1.4550	31.940 lb

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www.futek.com

Page 2 of 2

Certificate of Calibration

Certificate Number **1111070021**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Sensor Info:

S/N 423299
Item # QSH00256

Model LSB210
Capacity .... 50 lb

Description: LSB210, 50 lb, JR. S-Beam Load Cell, Submersible Version, Material - 17-4 PH S.S., #4-40-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 5 ft Long

Calibration Procedure OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter:

HP Model: **Agilent 34401A**, *S/N:* **US36135067**

Dead Weight(s):

1-10 lb, *Traceability No:* **622978**

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request.

This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: ***Angel Mendoza***
Issue Date: 11/7/2011 **Re-Calibration Date:** One Year After Issue Date

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www.futek.com

Certificate Number **1111070021**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Single Channel Item

CALIBRATION DATA

Test Temp ... 73.2 °F (22.9 °C) **Relative Humidity** ... 52.8 %

Input Resistance .... 351 Ω **Output Resistance** .... 352 Ω

Excitation .... 4.99 Vdc **Zero Balance** .... -0.0050 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
10	0.4537	-0.030
20	0.9077	-0.047
30	1.3622	-0.041
40	1.8169	-0.027
50	2.2719	0.000
0	0.0007	

SHUNT CALIBRATION

Tension

Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load
60.4	(-Exc) & (-S)	1.4553	32.027 lb

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www.futek.com

Certificate of Calibration

Certificate Number **1111070020**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Sensor Info:

S/N 423298
Model LSB210
Item # QSH00256
Capacity .... 50 lb

Description: LSB210, 50 lb, JR. S-Beam Load Cell, Submersible Version, Material - 17-4 PH S.S., #4-40-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 5 ft Long

Calibration Procedure OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter:

HP Model: **Agilent 34401A**, *S/N:* **US36135067**

Dead Weight(s):

1-10 lb, *Traceability No:* **622978**

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request.

This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: ***Angel Mendoza***
Issue Date: 11/7/2011 **Re-Calibration Date:** One Year After Issue Date

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www.futek.com

Certificate Number **1111070020**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Single Channel Item

CALIBRATION DATA

Test Temp ... 73.6 °F (23.1 °C)	**Relative Humidity** ... 52.4 %
Input Resistance .... 352 Ω	**Output Resistance** .... 352 Ω
Excitation .... 4.99 Vdc	**Zero Balance** .... 0.0082 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
10	0.4815	-0.037
20	0.9637	-0.046
30	1.4459	-0.054
40	1.9286	-0.041
50	2.4120	0.000
0	0.0008	

SHUNT CALIBRATION

Tension

Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load
60.4	(-Exc) & (-S)	1.4552	30.165 lb

Futek Advanced Sensor Technology Inc. 10 Thomas Irvine CA. 92618 USA • Tel: (949) 465-0900 Fax: (949) 465-0905
www.futek.com

Certificate of Calibration

Certificate Number **1111070018**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Sensor Info:

S/N .... 423296 **Model** LSB210
Item # .... QSH00256 **Capacity** .... 50 lb

Description: LSB210, 50 lb, JR. S-Beam Load Cell, Submersible Version, Material - 17-4 PH S.S., #4-40-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 5 ft Long

Calibration Procedure OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter:

HP Model: **Agilent 34401A**, *S/N:* **US36135067**

Dead Weight(s):

1-10 lb, *Traceability No:* **622978**

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request.
This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: ***Angel Mendoza***
Issue Date: 11/7/2011 **Re-Calibration Date:** One Year After Issue Date

Futek Advanced Sensor Technology Inc. 10 Thomas Irvine CA. 92618 USA • Tel: (949) 465-0900 Fax: (949) 465-0905
www.futek.com

Page 1 of 2

Certificate Number **1111070018**

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Single Channel Item

CALIBRATION DATA

Test Temp ... 72.7 °F (22.6 °C) **Relative Humidity** ... 53.5 %

Input Resistance .... 351 Ω **Output Resistance** .... 352 Ω

Excitation .... 4.99 Vdc **Zero Balance** .... 0.0075 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
10	0.4632	-0.009
20	0.9257	-0.049
30	1.3896	-0.028
40	1.8530	-0.029
50	2.3171	0.000
0	0.0007	

SHUNT CALIBRATION

Tension

Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load
60.4	(-Exc) & (-S)	1.4540	31.375 lb

O.H. Hinsdale Wave Research Laboratory
3550 SW Jefferson Way
Corvallis OR 97331

Certificate of Calibration CALIBRATOR-9221486-20150224

MARTEL ELECTRONICS

BETA CALIBRATORS

REPORT OF CALIBRATION

This instrument is calibrated and tested to verify compliance with Martel's test specifications for all ranges and parameters required to meet 1 year performance specifications. The calibration uses measurement standards traceable to the National Institute of Standards and Technology (NIST). This calibration complies with the requirements of ANSI/NCSL Z540-1-1994 part 2. Calibration and verification are performed at an ambient temperature of 23 ± 5°C and relative humidity of > 20% to < 70%.

Any test uncertainty (TUR) less than 4:1 appears under the TUR heading on the data record. Where the TUR meets or exceeds 4:1, the TUR field is blank.

Tom Fatur
Tom Fatur
President

Nancy Fligg
Calibrated By
Nancy Fligg

Manufacturer:	Martel Corporation	**Cal Date:**	February 24, 2015
Model:	M2001	**Report Date:**	February 24, 2015
Serial Number:	9221486	**Temperature:**	21.9°C
		Relative Humidity:	31 %
Calibration Procedure:	2001:(90 day)FINAL RS-232/5520,1281,742,1521 C		
Procedure Revision:	1.0	**Data Type:**	AS-LEFT

Standards Used

Asset	Manufacturer	Model Number	Description	Cal. Date	Due Date
43681-1281	Wavetek-Datron	1281	Multimeter	19-Oct-14	19-Oct-15
7675001	Fluke Corporation	5520A	Calibrator	8-Jan-15	8-Jan-16
1982011	Fluke Corporation	742A-10	Resistance Standard	20-May-14	20-May-16
2029006	Fluke Corporation	742A-100	Resistance Standard	19-May-14	19-May-16
2029005	Fluke Corporation	742A-10K	Resistance Standard	17-May-14	17-May-16
3022085	Fluke Corporation	1524	Reference Thermometer	14-Jan-15	14-Apr-15
B4C0309	Fluke Calibration	5610	Thermistor Probe	21-Dec-14	21-Dec-16

Test Data

PARAMETER	RESULT	ACCEPTANCE LIMITS LOW	HIGH		TUR
Low Ohm Read Verification					
0.000 Ohm	0.000	-0.003	0.003	PASS	
25.000 Ohm	25.000	24.996	25.004	PASS	
75.000 Ohm	75.000	74.995	75.005	PASS	
95.000 Ohm	95.001	94.994	95.006	PASS	
105.000 Ohm	105.001	104.993	105.007	PASS	
150.000 Ohm	149.998	149.992	150.008	PASS	
300.000 Ohm	299.994	299.986	300.014	PASS	
400.000 Ohm	399.991	399.983	400.017	PASS	
High Ohm Read Verification					
0.00 Ohm	0.00	-0.03	0.03	PASS	

MET/CAL RunTime Report: Calibration Results

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Calibration Report Number: 09344102242015 9221486

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3550 SW Jefferson Way
Corvallis OR 97331

Certificate of Calibration CALIBRATOR-9221486-20150224

MARTEL ELECTRONICS

BETA CALIBRATORS

PARAMETER	RESULT	ACCEPTANCE LIMITS LOW	HIGH		TUR
250.00 Ohm	250.00	249.96	250.04	PASS	
750.00 Ohm	749.98	749.95	750.05	PASS	
1500.00 Ohm	1500.00	1499.92	1500.08	PASS	
3000.00 Ohm	3000.01	2999.86	3000.14	PASS	
4000.00 Ohm	4000.02	3999.83	4000.17	PASS	
mV Source Verification					
0.0000mV	-0.0004	-0.0030	0.0030	PASS	
35.0000mV	35.0004	34.9961	35.0039	PASS	
65.0000mV	65.0011	64.9954	65.0046	PASS	
100.0000mV	100.0021	99.9945	100.0055	PASS	
1V Source Verification					
0.000000V	-0.000001	-0.000020	0.000020	PASS	
0.350000V	0.350004	0.349971	0.350029	PASS	
0.650000V	0.650009	0.649964	0.650036	PASS	
1.000000V	1.000023	0.999955	1.000045	PASS	
10V Source Verification					
0.00000V	-0.00007	-0.00020	0.00020	PASS	
3.50000V	3.50000	3.49971	3.50029	PASS	
6.50000V	6.49999	6.49964	6.50036	PASS	
10.00000V	10.00002	9.99955	10.00045	PASS	
100V Source Verification					
0.0000V	-0.0006	-0.0020	0.0020	PASS	
35.0000V	35.0004	34.9971	35.0029	PASS	
65.0000V	65.0011	64.9964	65.0036	PASS	
100.0000V	100.0023	99.9955	100.0045	PASS	
100mA Source Verification					
0.000000mA	0.000100	-0.002000	0.002000	PASS	
35.000000mA	35.001033	34.995025	35.004975	PASS	
65.000000mA	65.001200	64.992475	65.007525	PASS	
100.000000mA	100.002600	99.989500	100.010500	PASS	
Low Ohm Source Verification					
5.000 Ohm	5.004	4.970	5.030	PASS	
100.000 Ohm	100.005	99.970	100.030	PASS	
200.000 Ohm	200.001	199.970	200.030	PASS	
400.000 Ohm	400.002	399.970	400.030	PASS	
High Ohm Source Verification					
5.00 Ohm	4.97	4.70	5.30	PASS	
1000.00 Ohm	1000.01	999.70	1000.30	PASS	
2000.00 Ohm	1999.97	1999.70	2000.30	PASS	
4000.00 Ohm	4000.03	3999.70	4000.30	PASS	
Thermocouple Read Verification - mV					
-10.000mV	-9.999	-10.003	-9.997	PASS	
15.000mV	15.000	14.997	15.003	PASS	
35.000mV	35.000	34.996	35.004	PASS	
55.000mV	55.000	54.996	55.004	PASS	
75.000mV	75.000	74.996	75.004	PASS	
Thermocouple Source Verification - mV					
-10.000mV	-10.001	-10.003	-9.997	PASS	
15.000mV	15.000	14.997	15.003	PASS	
35.000mV	35.000	34.996	35.004	PASS	
55.000mV	55.000	54.996	55.004	PASS	

MET/CAL RunTime Report: Calibration Results

Calibration Report Number: D93441022420159221486

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Certificate of Calibration CALIBRATOR-9221486-20150224

MARTEL ELECTRONICS

BETA CALIBRATORS

PARAMETER	RESULT	ACCEPTANCE LIMITS LOW	HIGH		TUR
75.000mV	75.000	74.996	75.004	PASS	3.8
Thermocouple Read Verification - Type J					
21.56degC	21.56	21.40	21.72	PASS	

End of Test Data

MET/CAL RunTime Report Calibration Results — Page 3 of 3

Calibration Report Number: 09344102242015 9221486

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Certificate of Calibration PRES-3591-20150825

Instrument
Type: Strain Gage based Pressure Sensor
Manufacturer: GE/Druck Sensing
Model: PDCR 830
Serial Number: 2993591
Lab ID: PRES-3591
Calibration Date: 2015/08/25
Calibration Due Date: 2016/08/25 or as needed
Environment: 24 °C ± 0.5 °C
Calibration Coefficient(s): 3.026 psig/V
Accuracy: ± 0.011 psig/V
Calibration Uncertainty U (k=2): ±0.37%
Raw data file name(s): 237.9314_hwrldaq01_pressure_off.txt to 237.9451_hwrldaq01_pressure_off.tx

Test Equipment
Standard Model: M2001
Standard Serial Number: 9221486
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/24
Calibration Report Number: 09344102242015 9221486
NIST Traceable: Yes

Standard Accessories Model: BetaPort 10G
Accessory Serial Number: 9163157
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/19
Calibration Report Number: 02064702192015 9163157
NIST Traceable: Yes

Standard Accessories Model: RTD (21530-1-14-60)
Accessory Serial Number: 06094961
Standard Manufacturer: Martel Corporation
Calibration Date: 2006/10/03
Calibration Report Number: 20765
NIST Traceable: Yes

Data Acquisition Card Model: PCI-6259
Card Serial Number: DF3281
Standard Manufacturer: National Instruments
Calibration Date: 2015/07/12
Calibration Report Number: 1257365.1
NIST Traceable: Yes

Notes
All equipment was allowed to warm up or equilibrate for a time equal to or greater than 2 hours.

PRES-3591 in Channel 3 of SG-SC-9957

Symbol	Source of Uncertainty	Value (%)	Distribution	Divisor	Uncertainty
U1	Sensor spec. nonlinearity, hysteresis, repeatability	0.100	R	sqrt 3	0.058
U2	Sensor spec. temperature error (-2°C to 30°C)	0.300	R	sqrt 3	0.173
U3	SG-SC-9957 10V excitation uncertainty ±1mV	0.010	R	sqrt 3	0.006
U4	Observed uncertainty and nonlinearity of calibration fits*	0.021	N	1	0.021
UR	Observed repeatability of random sources**	0.029	N	1	0.029
UC	Combined Uncertainty				0.186
U	Expanded Uncertainty (k=2)				0.372

* Includes std. err. of linear regression, spec. equipment uncertainty, observed input uncertainty; c.f. pres3591_20150825.xlsx
** Based on 10 tests by one operator

Technician Signature: Tony B. Mady Date: 2015/08/25

ONSITE CERTIFICATE OF CALIBRATION PRES-5573-20151221

O.H. Hinsdale Wave Research Laboratory
3550 SW Jefferson Way
Corvallis OR 97331

<u>Instrument</u>

Type: Strain Gage based Pressure Sensor
Manufacturer: GE/Druck Sensing
Model: PDCR 1830
Serial Number: 3405573
Lab ID: PRES-5573
Calibration Date: 2015/12/21
Calibration Due Date: 2016/12/21 or as needed
Environment: 20.9 ^{0}C ± 0.1 ^{0}C
Calibration Coefficient(s): 0.6908 psif/V
Accuracy: ± 0.0025 psif/V
Calibration Uncertainty U (k=2): ±0.37%
Raw data file name(s): 40894.9343_hwrldaq01_pressure_off.txt to 40894.9502_hwrldaq01_pressure_off.txt

<u>Test Equipment</u>

Standard Model: M2001
Standard Serial Number: 9221486
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/24
NIST Traceable: Yes
Calibration Report Number: 09344102242015 9221486

Standard Accessories Model: BetaPort 10G
Accessory Serial Number: 9163157
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/19
NIST Traceable: Yes
Calibration Report Number: 02064702192015 9163157

Standard Accessories Model: RTD (21530-1-14-60)
Accessory Serial Number: 06094961
Standard Manufacturer: Martel Corporation
Calibration Date: 03 October 2006
NIST Traceable: Yes
Calibration Report Number: 20765

Data Acquisition Card Model: PCI-6259
Card Serial Number: DF3281
Standard Manufacturer: National Instruments
Calibration Date: 2015/07/12
NIST Traceable: Yes
Calibration Report Number: 1257365.1

Notes: Sensor calibrated in SG-SC-0001. All test and under test equipment were allowed to warm up or equilibrate for a time greater than 24 hours.

Technician Signature: ____________ Date: 2015/12/21 ____________

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ONSITE CERTIFICATE OF CALIBRATION PRES-5573-20151221

PRES-5573 in Channel 1 of SG-SC-0001

Symbol	Source of Uncertainty	Value (%)	Distribution	Divisor	Uncertainty
U1	Sensor spec. nonlinearity, hysteresis, repeatability	0.060	R	sqrt 3	0.035
U2	Sensor spec. temperature error (-2°C to 30°C)	0.300	R	sqrt 3	0.173
U3	Observed uncertainty and nonlinearity of calibration fits*	0.030	N	1	0.030
UR	Observed repeatability of random sources**	0.042	N	1	0.042
UC	Combined Uncertainty				0.184
U	Expanded Uncertainty (k=2)				0.368

* Includes std. err. of linear regression, spec. equipment uncertainty, observed input uncertainty; c.f. pres5573_20151221.xlsx
** Based on 10 tests by one operator

Technician Signature: Tony B. Moore Date: 2015/12/21 Page 2 of 2

O.H. Hinsdale Wave Research Laboratory
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Corvallis OR 97331

Certificate of Calibration PRES-6301-20150825

<u>Instrument</u>

Type: Strain Gage based Pressure Sensor
Manufacturer: GE/Druck Sensing
Model: PDCR 830
Serial Number: 2996301
Lab ID: PRES-6301
Calibration Date: 2015/08/25
Calibration Due Date: 2016/08/25 or as needed
Environment: 24 °C ± 0.5 °C
Calibration Coefficient(s): 3.030 psig/V
Accuracy: ± 0.011 psig/V
Calibration Uncertainty U (k=2): ±0.37%
Raw data file name(s): 237.8873_hwrldaq01_pressure_off.txt to 237.9033_hwrldaq01_pressure_off.txt

<u>Test Equipment</u>

Standard Model: M2001
Standard Serial Number: 9221486
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/24
Calibration Report Number: 09344102242015 9221486
NIST Traceable: Yes

Standard Accessories Model: BetaPort 10G
Accessory Serial Number: 9163157
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/19
Calibration Report Number: 02064702192015 9163157
NIST Traceable: Yes

Standard Accessories Model: RTD (21530-1-14-60)
Accessory Serial Number: 06094961
Standard Manufacturer: Martel Corporation
Calibration Date: 2006/10/03
Calibration Report Number: 20765
NIST Traceable: Yes

Data Acquisition Card Model: PCI-6259
Card Serial Number: DF3281
Standard Manufacturer: National Instruments
Calibration Date: 2015/07/12
Calibration Report Number: 1257365.1
NIST Traceable: Yes

<u>Notes</u>

All equipment was allowed to warm up or equilibrate for a time equal to or greater than 2 hours.

PRES-6301 in Channel 2 of SG-SC-9957

Symbol	Source of Uncertainty	Value (%)	Distribution	Divisor	Uncertainty
U1	Sensor spec. nonlinearity, hysteresis, repeatability	0.100	R	sqrt 3	0.058
U2	Sensor spec. temperature error (-2°C to 30°C)	0.300	R	sqrt 3	0.173
U3	SG-SC-9957 10V excitation uncertainty ±1mV	0.010	R	sqrt 3	0.006
U4	Observed uncertainty and nonlinearity of calibration fits*	0.020	N	1	0.020
UR	Observed repeatability of random sources**	0.024	N	1	0.024
UC	Combined Uncertainty				0.185
U	Expanded Uncertainty (k=2)				0.371

* Includes std. err. of linear regression, spec. equipment uncertainty, observed input uncertainty; c.f. pres6301_20150825.xlsx
** Based on 10 tests by one operator

Technician Signature: ____________________ Date: 2015/08/25

O.H. Hinsdale Wave Research Laboratory
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Certificate of Calibration PRES-6300-20150825

Instrument

Type: Strain Gage based Pressure Sensor
Manufacturer: GE/Druck Sensing
Model: PDCR 830
Serial Number: 2996300
Lab ID: PRES-6300
Calibration Date: 2015/08/25
Calibration Due Date: 2016/08/25 or as needed
Environment: 24 °C ± 0.5 °C
Calibration Coefficient(s): 3.056 psig/V
Accuracy: ± 0.011 psig/V
Calibration Uncertainty U (k=2): ±0.38%
Raw data file name(s): 237.8471_hwrldaq01_pressure_off.txt to 237.8632_hwrldaq01_pressure_off.txt

Test Equipment

Standard Model: M2001
Standard Serial Number: 9221486
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/24
Calibration Report Number: 09344102242015 9221486
NIST Traceable: Yes

Standard Accessories Model: BetaPort 10G
Accessory Serial Number: 9163157
Standard Manufacturer: Martel Corporation
Calibration Date: 2015/02/19
Calibration Report Number: 02064702192015 9163157
NIST Traceable: Yes

Standard Accessories Model: RTD (21530-1-14-60)
Accessory Serial Number: 06094961
Standard Manufacturer: Martel Corporation
Calibration Date: 2006/10/03
Calibration Report Number: 20765
NIST Traceable: Yes

Data Acquisition Card Model: PCI-6259
Card Serial Number: DF3281
Standard Manufacturer: National Instruments
Calibration Date: 2015/07/12
Calibration Report Number: 1257365.1
NIST Traceable: Yes

Notes

All equipment was allowed to warm up or equilibrate for a time equal to or greater than 2 hours.

PRES-6300 in Channel 1 of SG-SC-9957

Symbol	Source of Uncertainty	Value (%)	Distribution	Divisor	Uncertainty
U1	Sensor spec. nonlinearity, hysteresis, repeatability	0.100	R	sqrt 3	0.058
U2	Sensor spec. temperature error (-2°C to 30°C)	0.300	R	sqrt 3	0.173
U3	SG-SC-9957 10V excitation uncertainty ±1mV	0.010	R	sqrt 3	0.006
U4	Observed uncertainty and nonlinearity of calibration fits*	0.022	N	1	0.022
UR	Observed repeatability of random sources**	0.036	N	1	0.036
UC	Combined Uncertainty				0.187
U	Expanded Uncertainty (k=2)				0.375

* Includes std. err. of linear regression, spec. equipment uncertainty, observed input uncertainty; c.f. pres6300_20150825.xlsx
** Based on 10 tests by one operator

Technician Signature: ____________ Date: 2015/08/25