Williwaw Engineering

November 2, 2015

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Subject: October 2015 Monthly Report – RCUH P.O. #Z10066105

Dear Luis,

The following constitutes my monthly report for the subject agreement for services associated with October 2015.

Work Completed under Task 3: Support HNEI in Device Performance Data Collection Throughout Development:

- Monitored the device regularly via remote connection to the NWEI host PC in Room 106, Battery French. Downloaded data from PC as necessary, and updated device control settings when necessary.

- Analyzed output power data to produce monthly power performance data plots; see Attachment 1 for results.

- Analyzed Azura float angle data using MATLAB to produce plots of 30 minute average float angle data for the deployment period. The data indicates that the Azura has not settled further in the water during the month of October. Also note that on October 29, the float went over the top to the offshore side and the device continued to operate with the float on the offshore side for the rest of the month. See Attachment 2 for results.

- Plotted daily humidity sensor data for the cRIO enclosure and drybox on board the Azura. The results continue to show that the drybox, which is entirely sealed from the Azura hull, has maintained very low humidity throughout the deployment period while humidity has slowly increased inside the cRIO enclosure since the June deployment. To date the humidity inside the cRIO enclosure is still well below levels that would cause condensing moisture and equipment damage. See Attachment 3 for a plot of these results.

- Analyzed data to calculate complex Response Amplitude Operators (RAOs). This analysis made use of water pressure data from a sensor mounted on the side of the Azura hull to calculate water surface elevation at the device. The complex RAO results include both magnitude and phase information. The RAO magnitudes generally compare well with earlier RAO magnitudes calculated using Waverider buoy data. The RAO phase results can't be calculated using Waverider buoy data because this buoy is located a distance from the device. The phase results are useful for checking against analytical model results. See Attachment 4 for these results

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- Analyzed data to calculate Relative Capture Width (RCW) with respect to wave frequency. These results, together with the annual average energy flux distribution for the wave site, can be used to estimate annual energy production. The results show that the power production of the half-scale Azura is poorly matched to the annual conditions at the WETS site with respect to wave period. See Attachment 5 for these results.

Please let me know if you have any questions or comments concerning this project.

Sincerely,

Terry Lettenmaier

Attachment 1: Azura power performance data plots

Attachment 2: Azura 30 minute average float angle data plots

Attachment 3: Azura cRIO enclosure and drybox humidity

Attachment 4: Azura Response Amplitude Operators (RAOs)

Attachment 5: Azura Relative Capture Width (RCW)

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Attachment 1

Azura power performance data plots

Azura Power Performance – October 2015

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Summary

- Plots of Oct 2015 data only are shown on Slides 2-8
- Plots of cumulative data for the entire deployment period June-Oct 2015 are shown on Slides 9-15
- Azura was operated (output connected to grid) for 729 hours in October (98% of month). Most of the down time was either due to either temporary shut downs after brief grid voltage interruptions or for brief, intentional shut downs while device data was recorded at no load. This no load data is useful for comparison to computer model results.
- Device operation was continued throughout most of October the same as in July and August, cycling between six different constant hydraulic motor displacement settings
  - Settings changed every 30 minutes
  - Constant displacement control is the simplest method possible and is expected to be useful for comparison to computer model results.
- During the last two days of October and continuing into early November, the device was operated at the highest load setting only, after the float rotated to the offshore side of the device in large seas. This high load setting was used to keep the float on the offshore side; data from this operation will be analyzed in November.

Azura Power Performance
Monthly Data October 2015

Azura Power Performance – October 2015

Data samples collected

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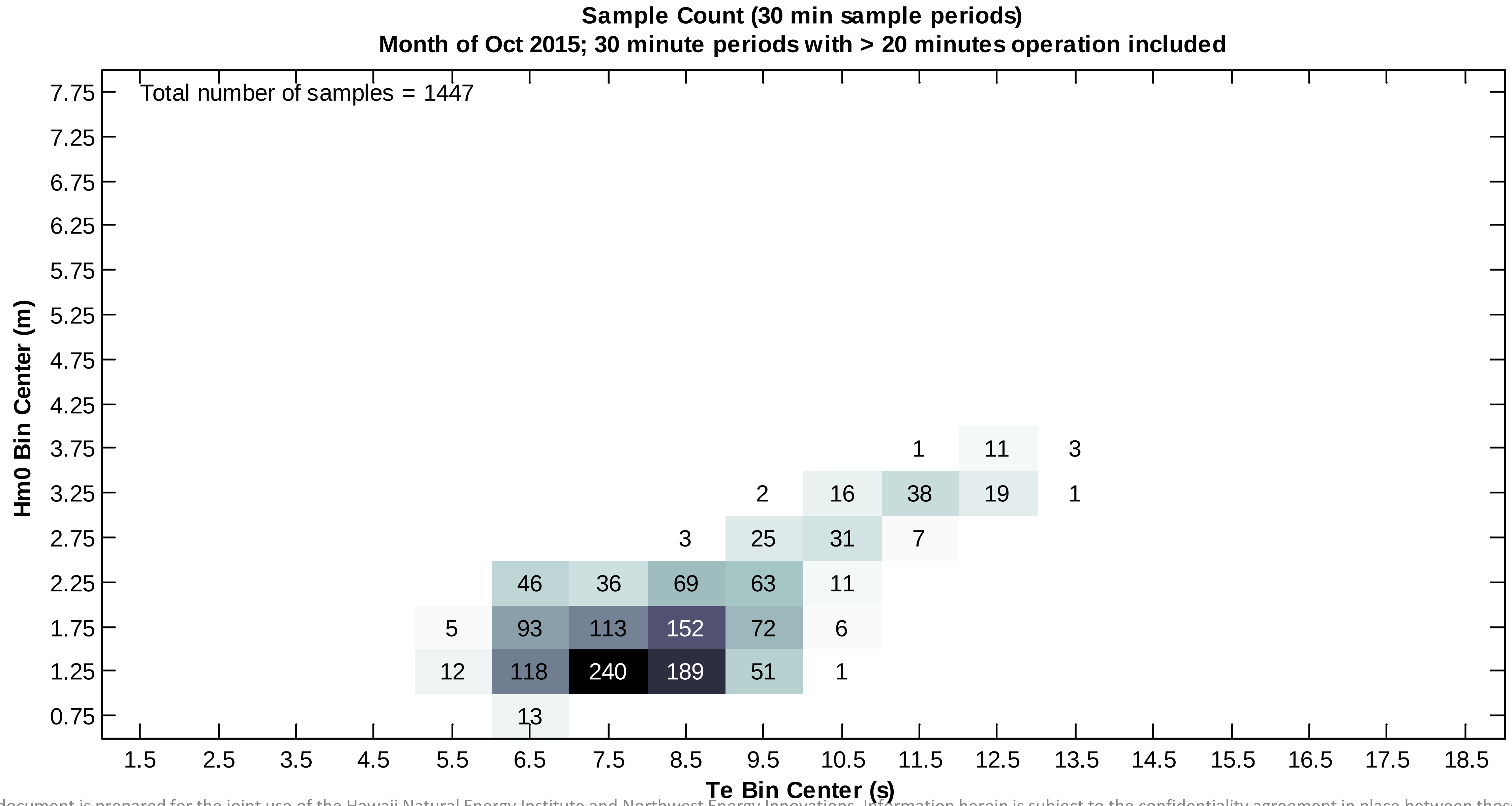

Azura Power Performance – October 2015

Mean power matrix

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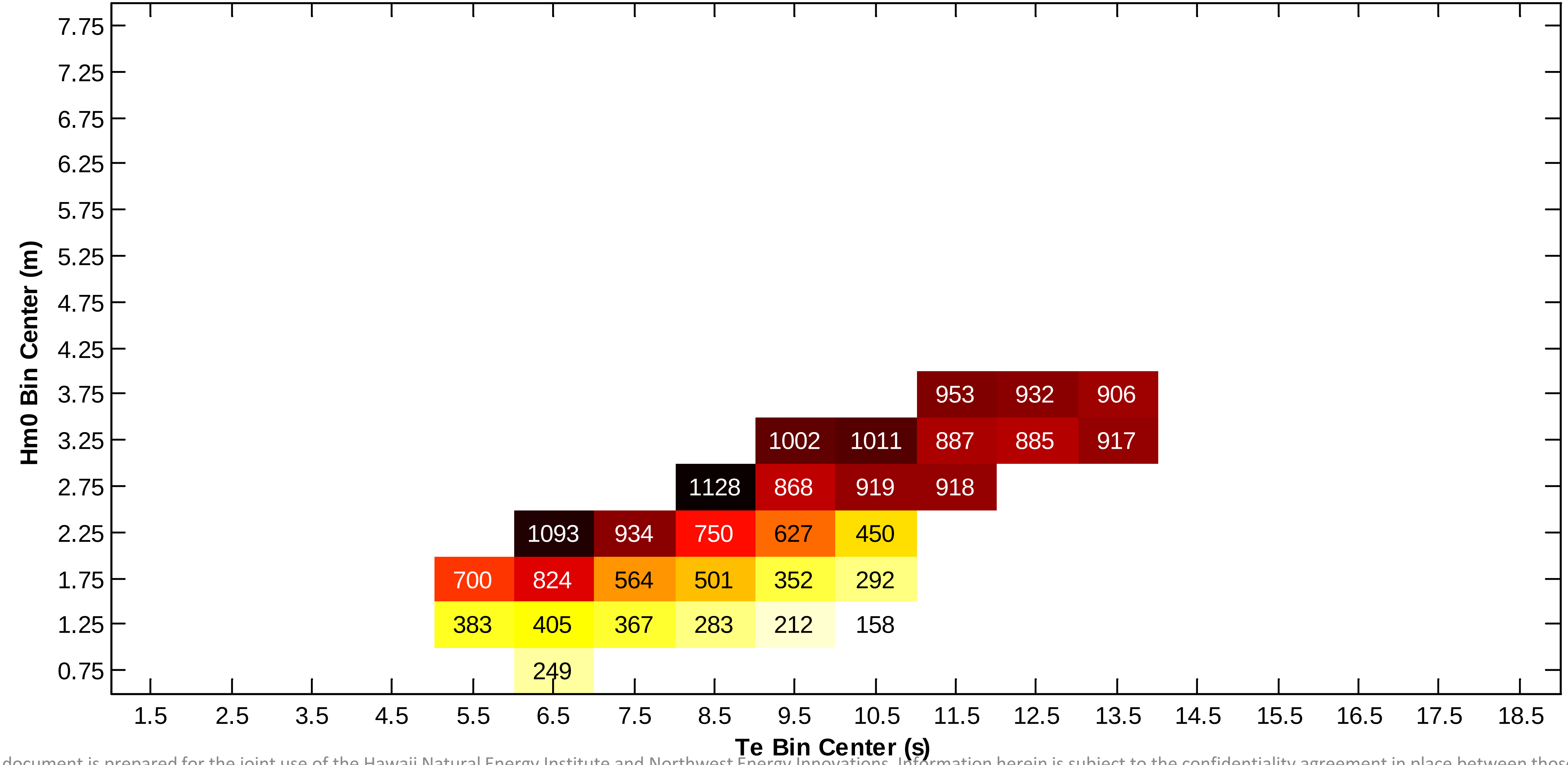
Mean Device Dc Output Power (W)
Month of Oct 2015; 30 minute periods with > 20 minutes operation included



Azura Power Performance – October 2015

95th percentile power matrix

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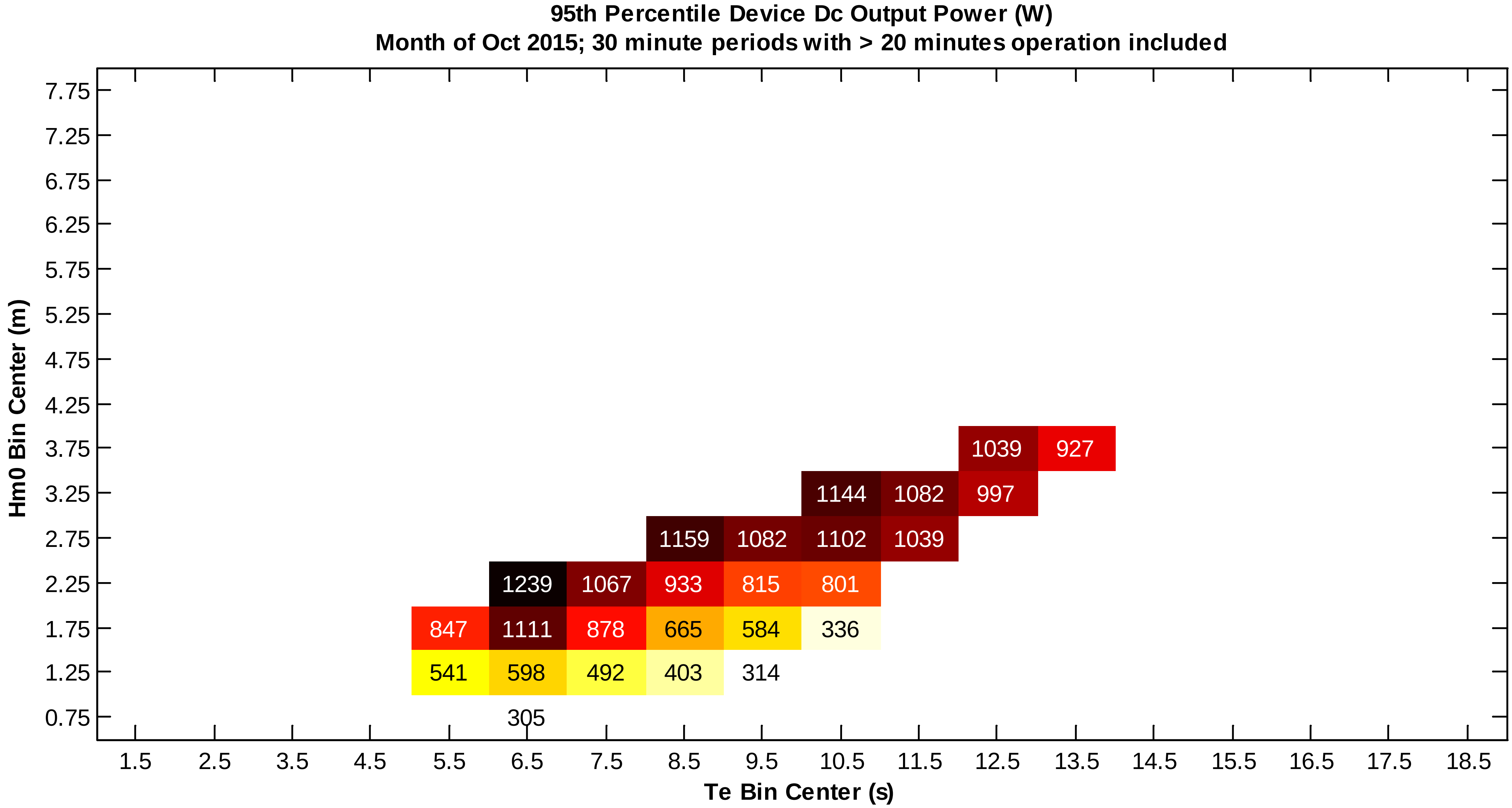

Azura Power Performance – October 2015

Standard deviation of power matrix

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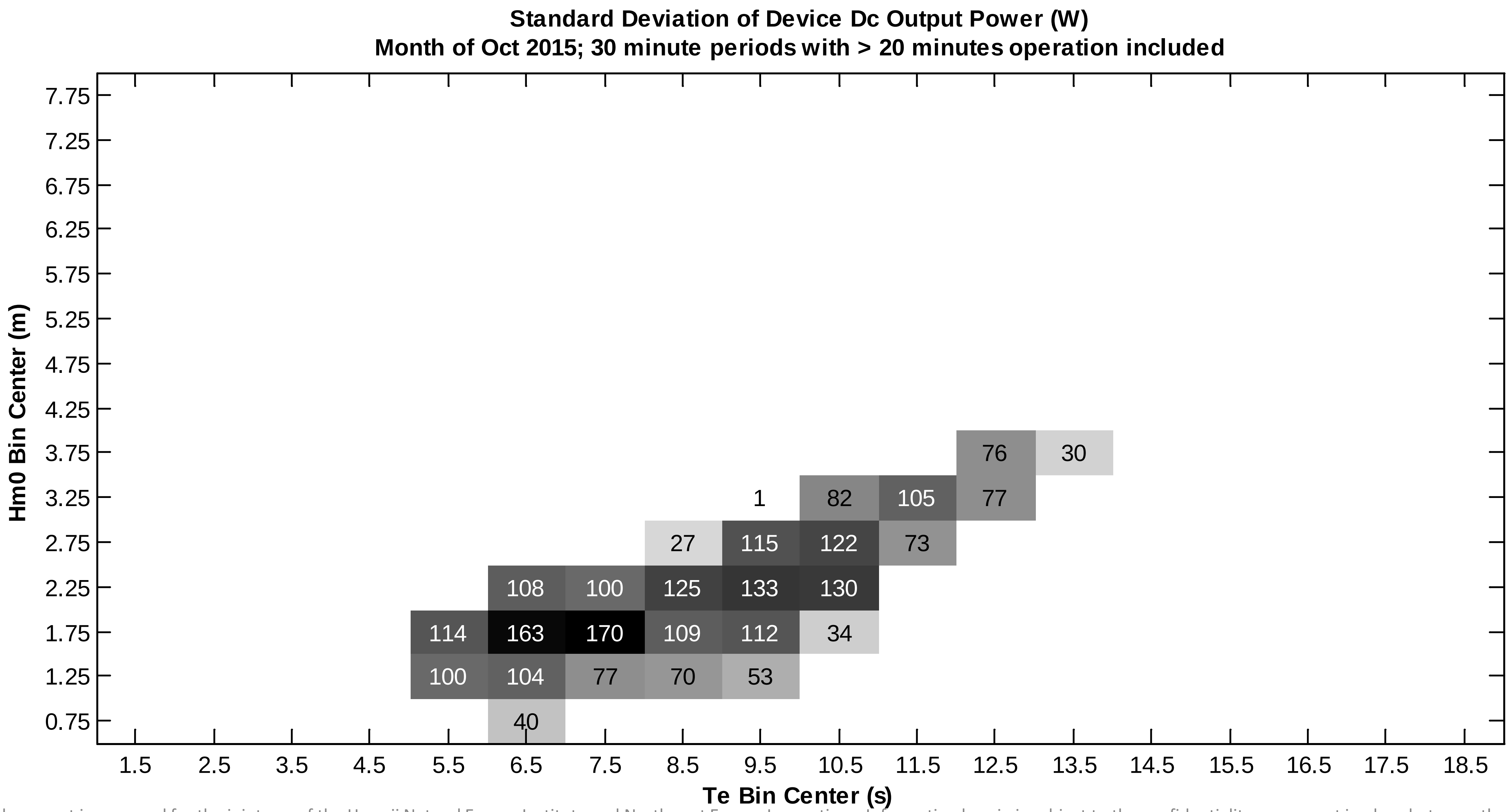

Azura Power Performance – October 2015

Mean capture length matrix

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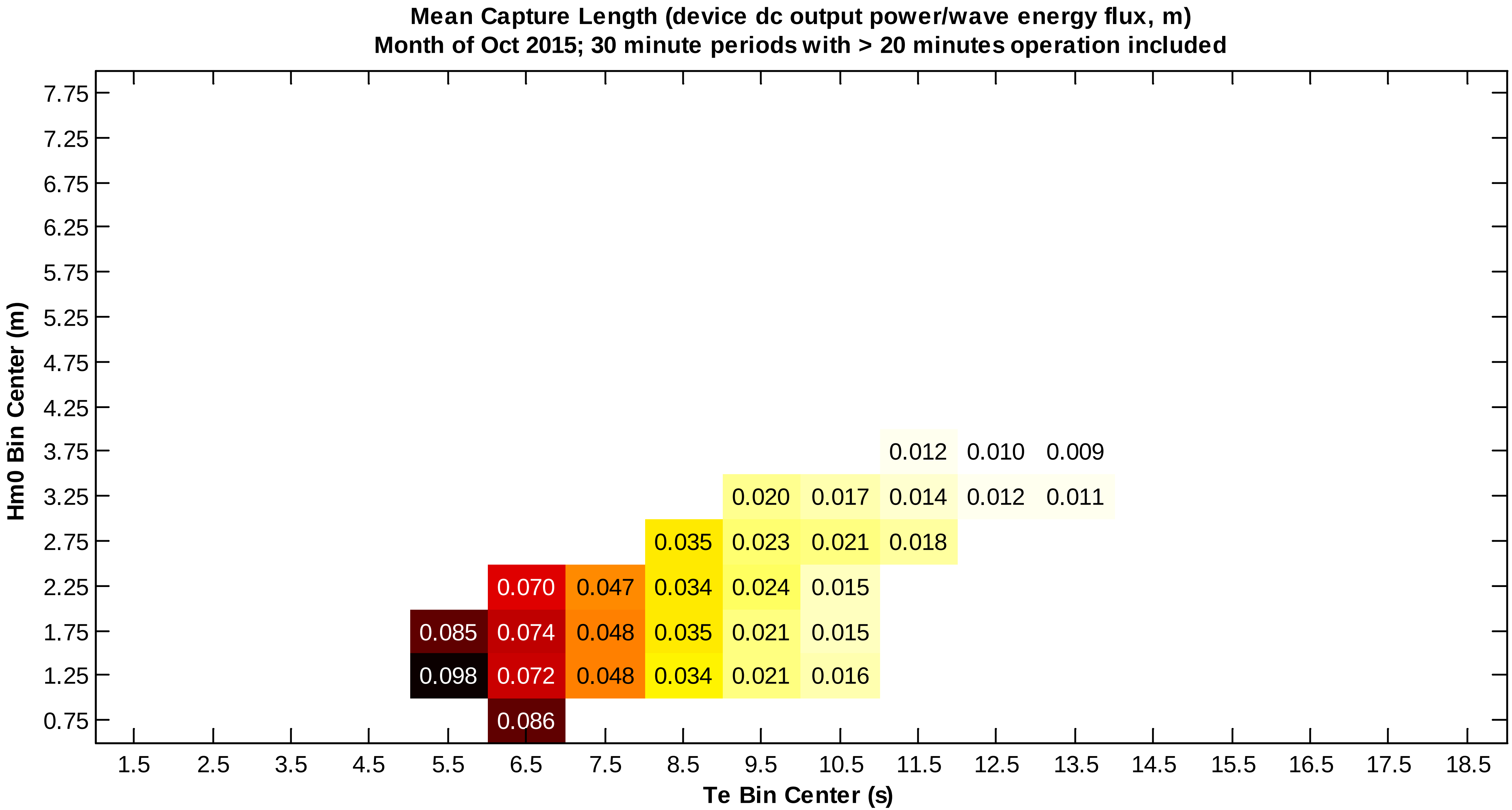

Azura Power Performance – October 2015

Standard deviation of capture length matrix

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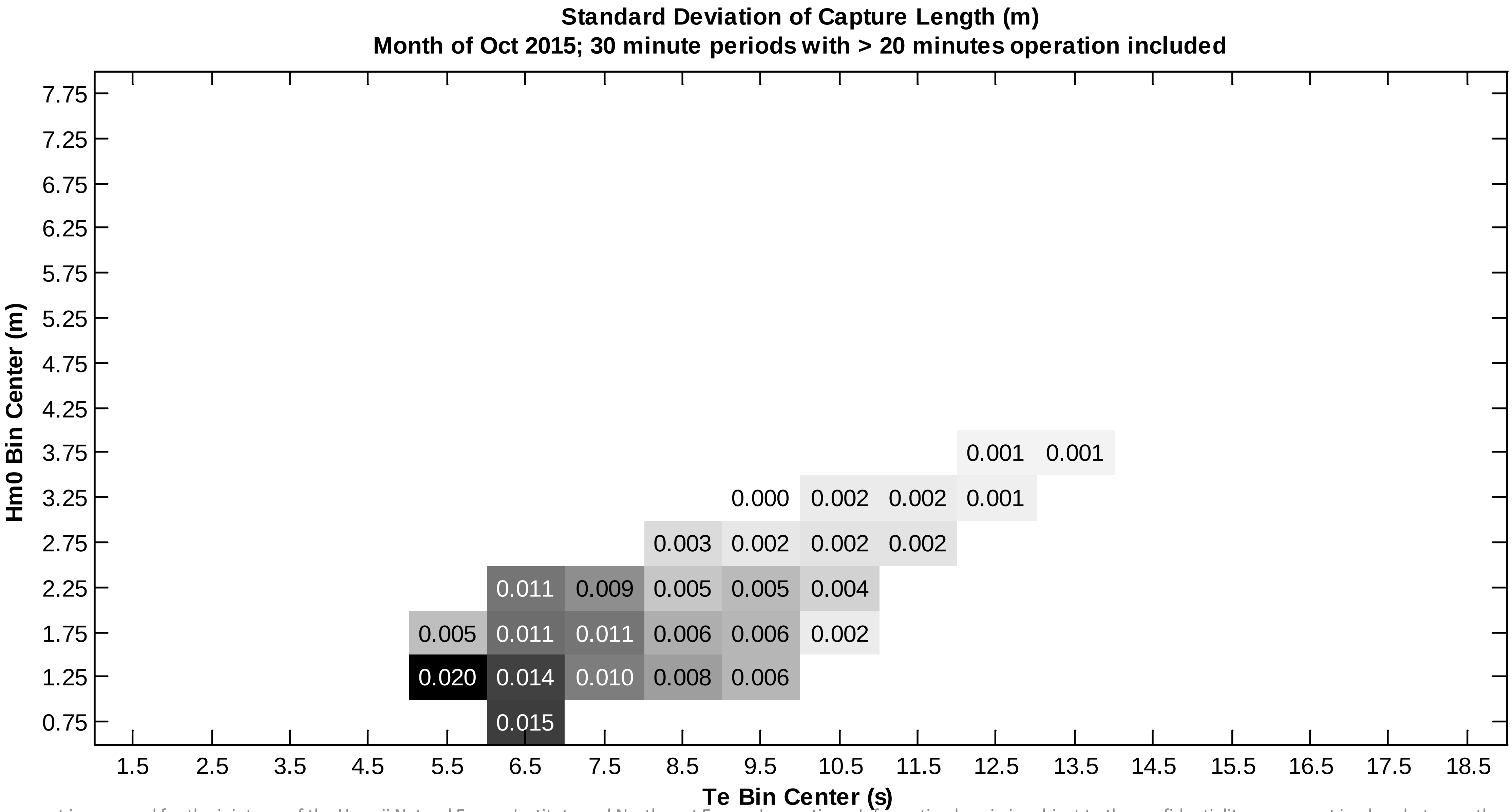

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Azura Power Performance
Cumulative Data June - October 2015

Azura Power Performance – June-October 2015

Data samples collected

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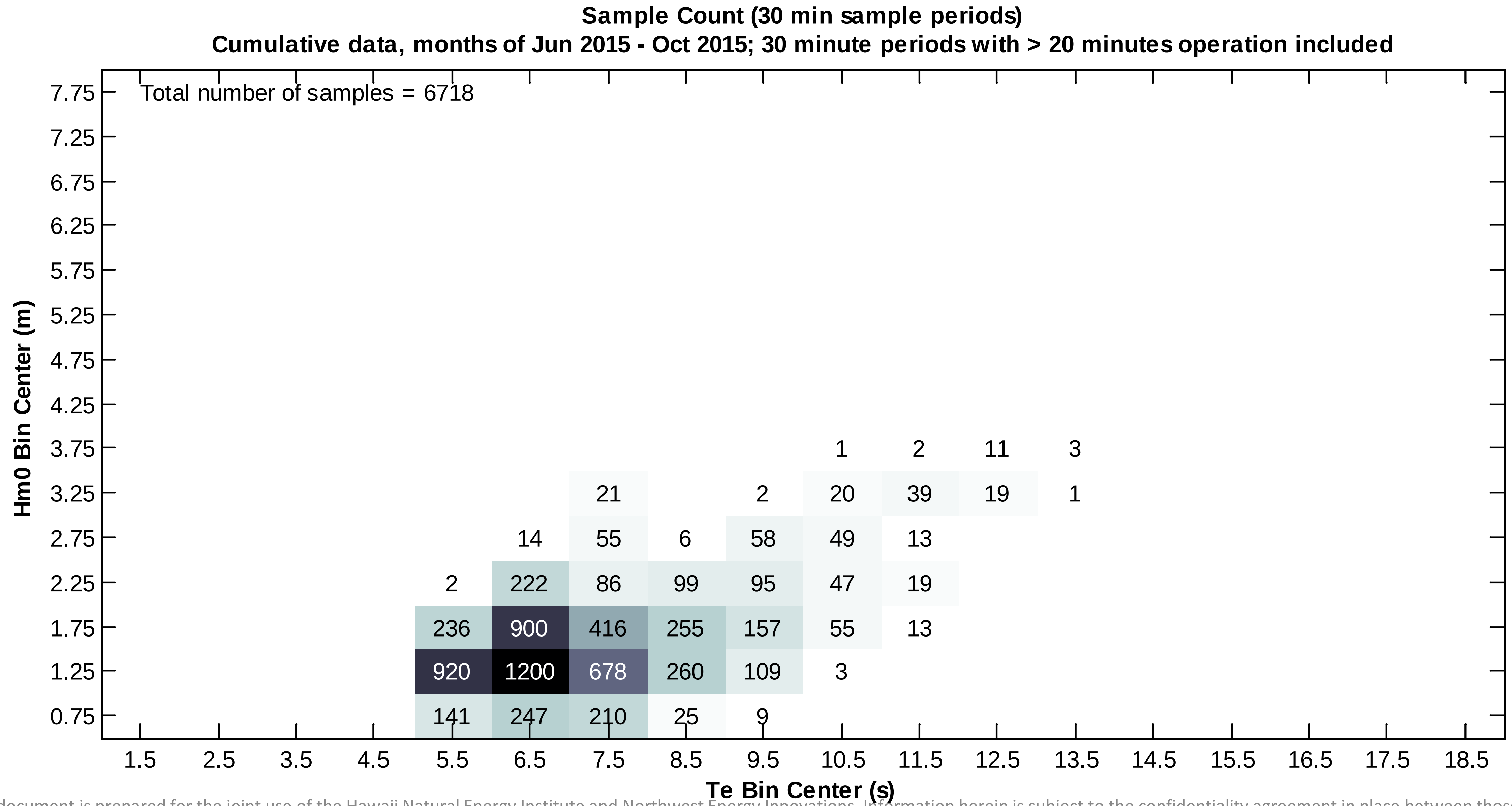

Azura Power Performance – June-October 2015

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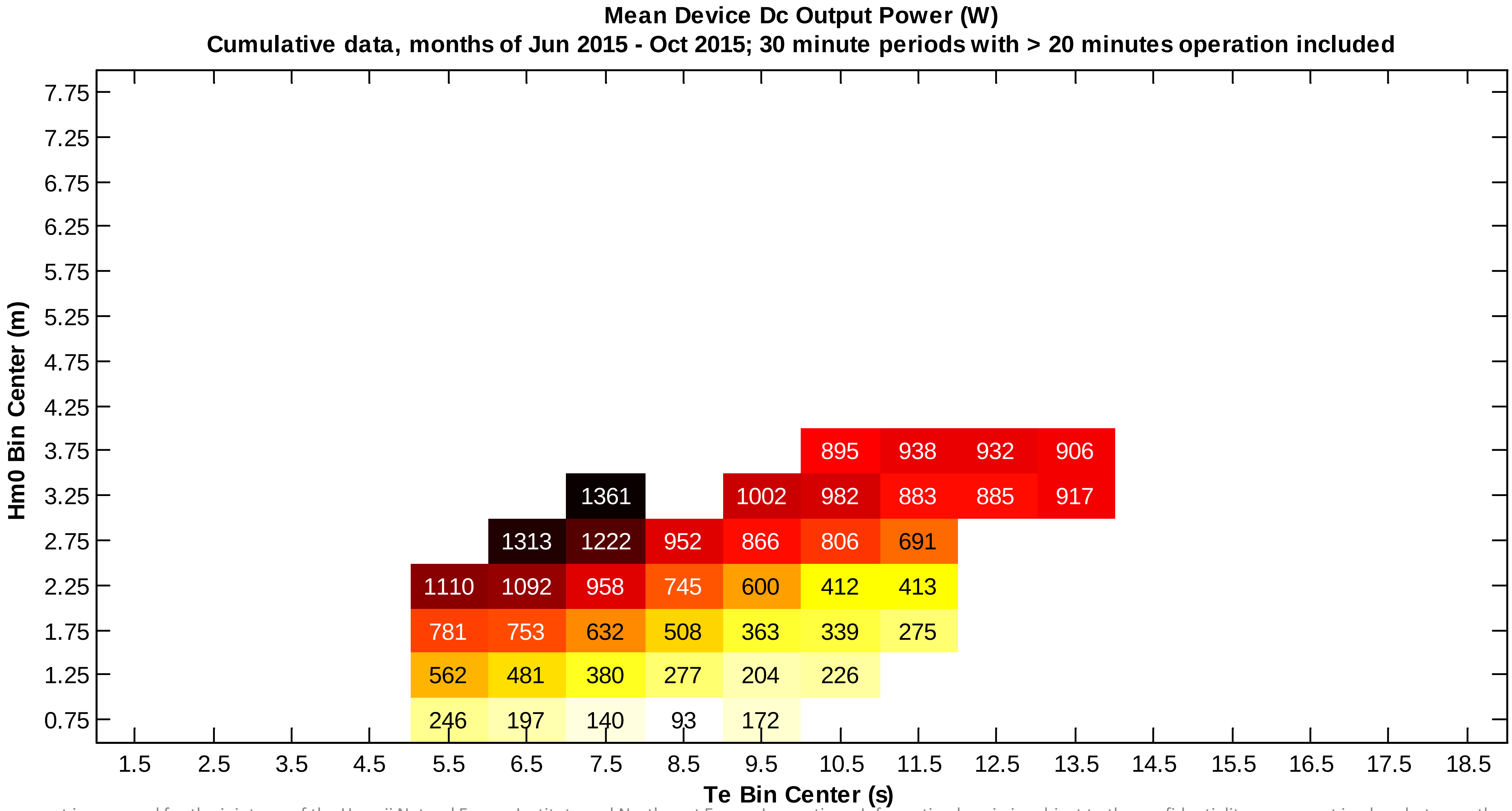
Mean power matrix



Azura Power Performance – June-October 2015

95th percentile power matrix

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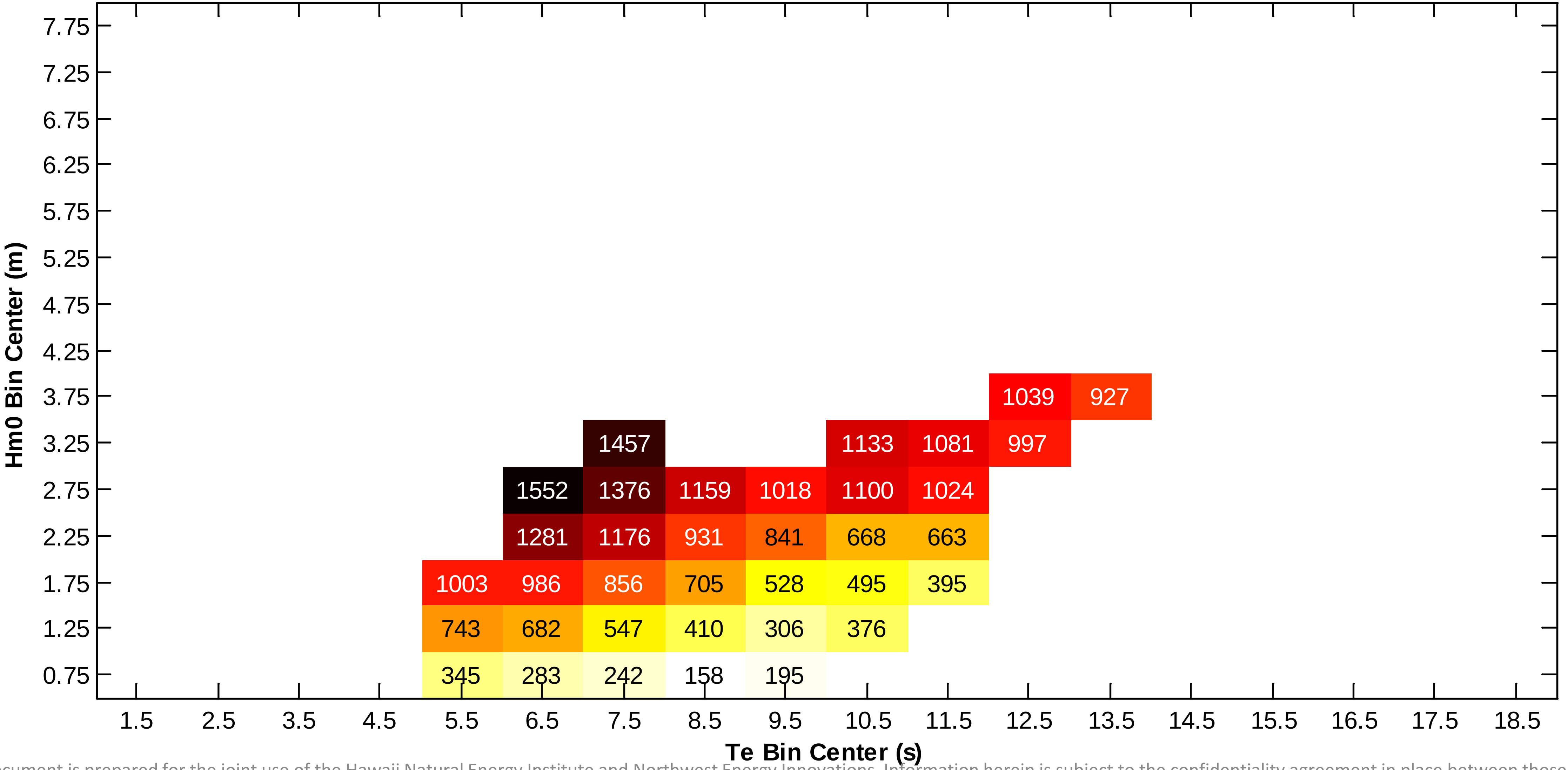
95th Percentile Device Dc Output Power (W)
Cumulative data, months of Jun 2015 - Oct 2015; 30 minute periods with > 20 minutes operation included



Azura Power Performance – June-October 2015

Standard deviation of power matrix

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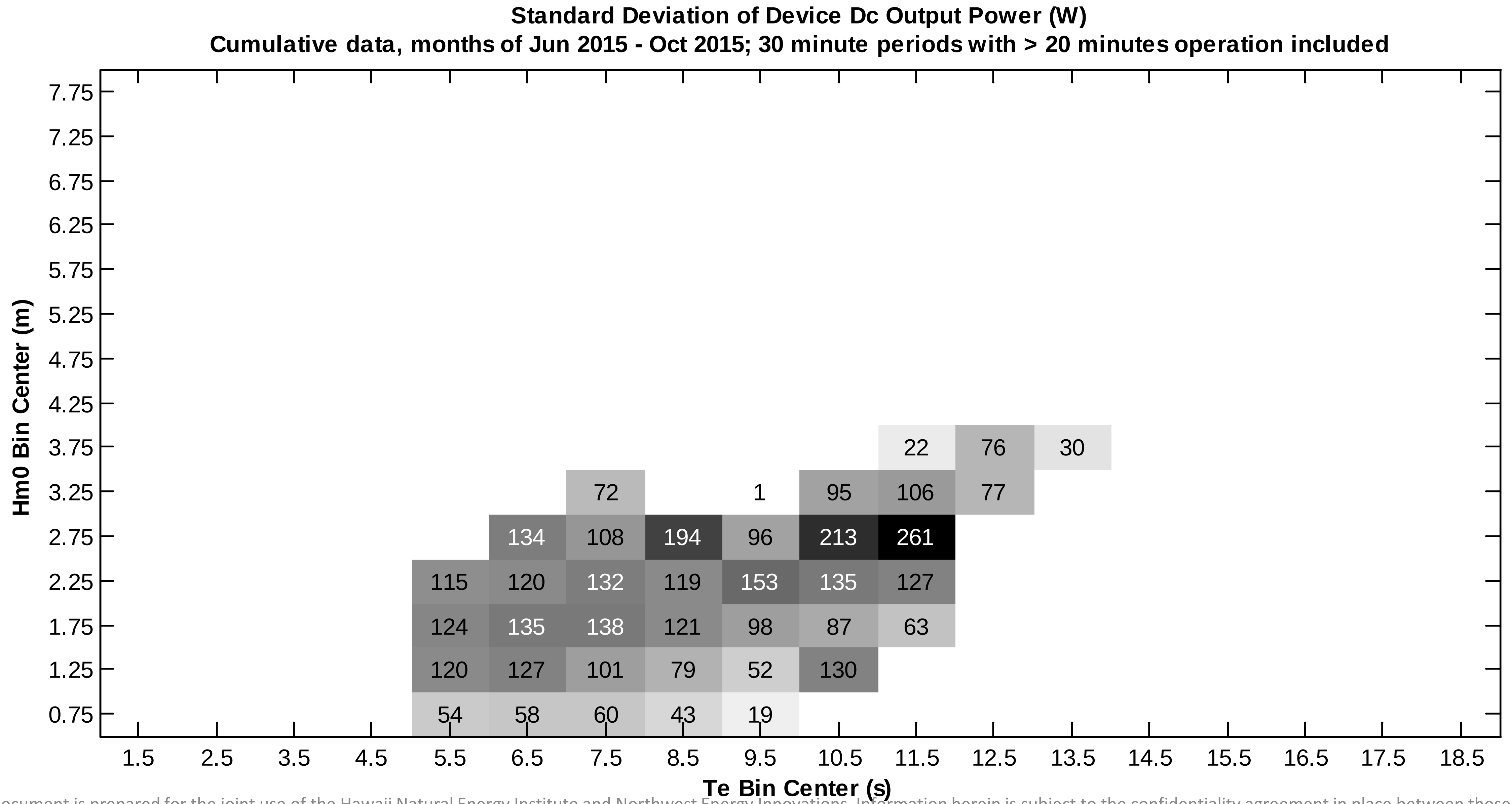

Azura Power Performance – June-October 2015

Mean capture length matrix

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Mean Capture Length (device dc output power/wave energy flux, m)
Cumulative data, months of Jun 2015 - Oct 2015; 30 minute periods with > 20 minutes operation included

Hm0 Bin Center (m) \ Te Bin Center (s)	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
7.75																		
7.25																		
6.75																		
6.25																		
5.75																		
5.25																		
4.75																		
4.25																		
3.75										0.012	0.011	0.010	0.009					
3.25							0.035		0.020	0.017	0.014	0.012	0.011					
2.75						0.051	0.041	0.030	0.022	0.018	0.014							
2.25					0.089	0.068	0.048	0.034	0.023	0.014	0.013							
1.75					0.100	0.078	0.054	0.036	0.022	0.017	0.015							
1.25					0.115	0.084	0.055	0.033	0.024	0.021								
0.75					0.100	0.074	0.051	0.036	0.037									

Azura Power Performance – June-October 2015

Standard deviation of capture length matrix

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Standard Deviation of Capture Length (m)

Cumulative data, months of Jun 2015 - Oct 2015; 30 minute periods with > 20 minutes operation included

Hm0 Bin Center (m) \ Te Bin Center (s)	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
7.75																		
7.25																		
6.75																		
6.25																		
5.75																		
5.25																		
4.75																		
4.25																		
3.75											0.001	0.001	0.001					
3.25							0.003		0.000	0.002	0.002	0.001						
2.75						0.009	0.004	0.006	0.003	0.005	0.005							
2.25					0.015	0.011	0.007	0.005	0.006	0.004	0.004							
1.75					0.013	0.012	0.010	0.007	0.006	0.005	0.003							
1.25					0.020	0.017	0.012	0.008	0.006	0.008								
0.75					0.020	0.017	0.013	0.010	0.002									

Attachment 2

Azura 30 minute average float angle data plots

Azura 30 minute average float angle data – October 2015

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Summary

- See following slide for plot of June-Oct 2015 data
- Average float angle remained at approximately 10° above horizontal throughout October
- On October 29 at 12:30 UTC, the float went over the top to the offshore side
- At this time, the device was at no load and sea conditions were H_{m0} = 2.2 m and T_e = 9 s
- Shortly after, device operation was resumed and the PTO setting was adjusted to maximum load (motor displacement 30 cc/rev) to keep the float on the offshore side for data collection with this configuration.

Azura 30 min average float angle data through Oct 2015

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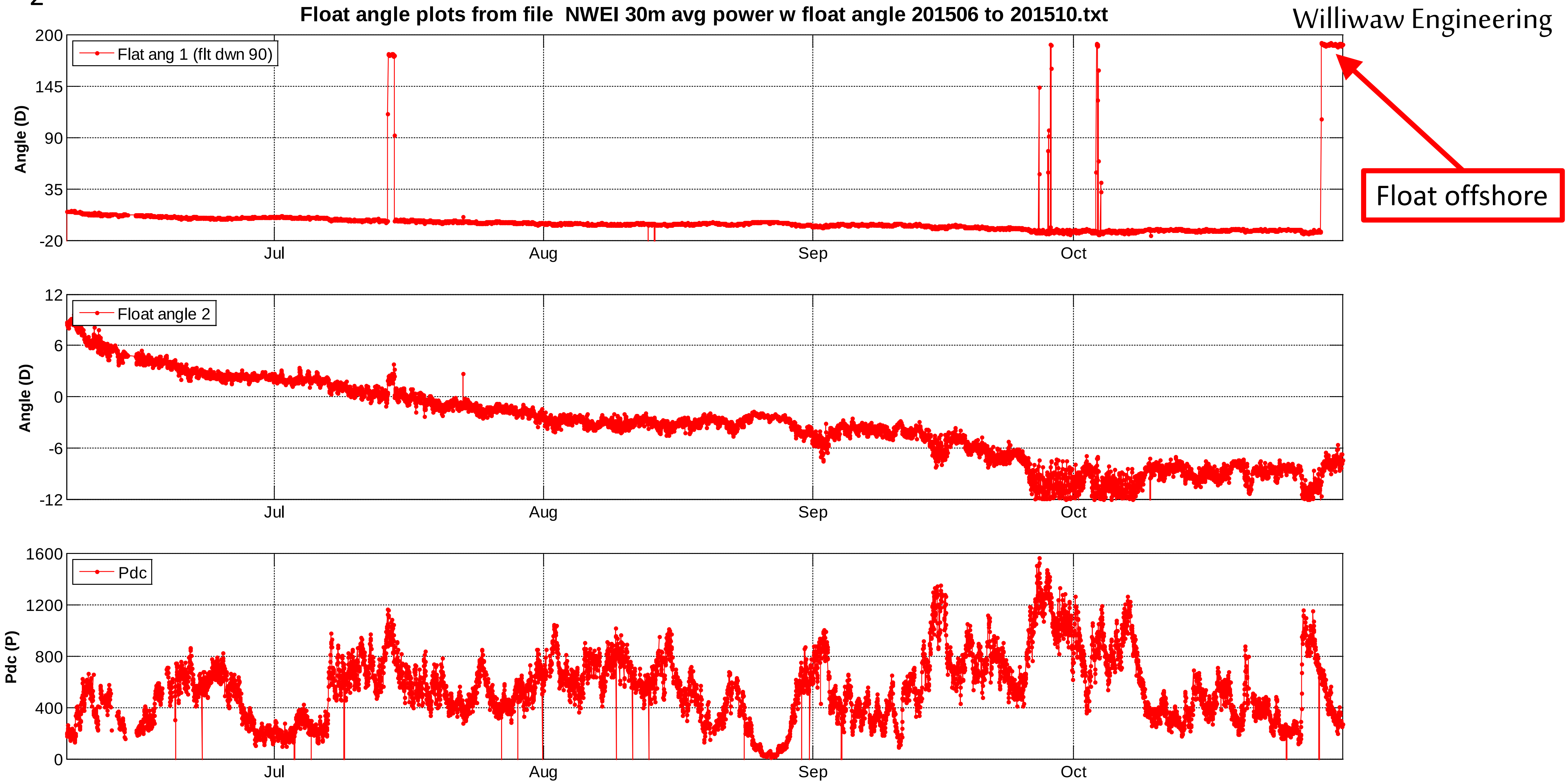

Attachment 3

Azura cRIO enclosure and drybox humidity plots

Azura cRIO enclosure and drybox humidity Oct 2015

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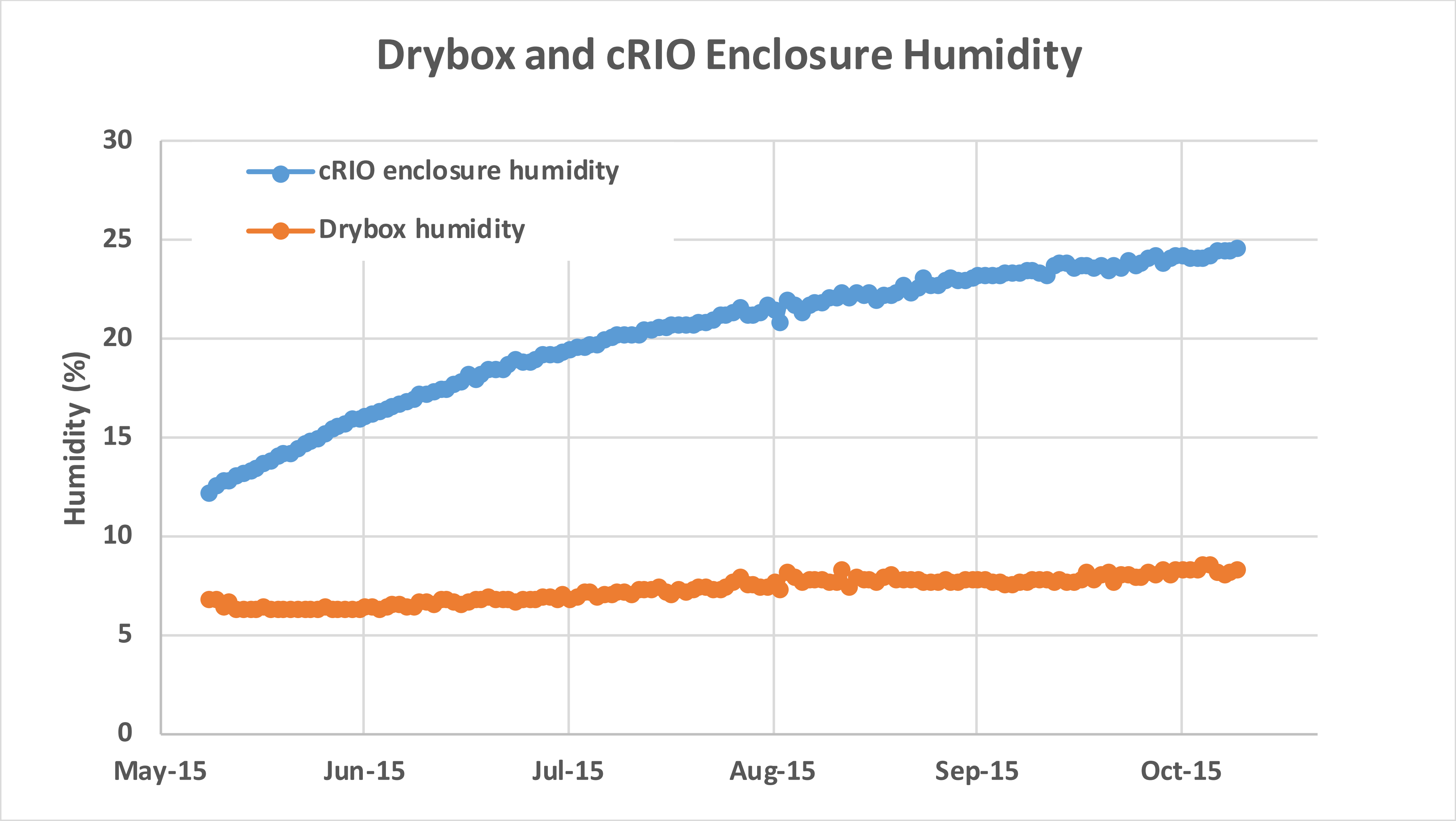

Attachment 4

Azura Response Amplitude Operators (RAOs)

Calculations of Azura Response Amplitude Operators (RAOs) from water pressure data

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Notes:

- Previous experimental Response Amplitude Operators (RAOs) were calculated using wave elevation data from a Waverider buoy located a short distance from the half-scale Azura as follows:

  $$|H(\omega)|^2 = \frac{S_{yy}(\omega)}{S_{xx}(\omega)}$$ where $S_{xx}(\omega)$ is the wave spectrum and $S_{yy}(\omega)$ is the response spectrum

  The above method can only be used to calculate RAO magnitudes (wave measurement not at device).

- Complex RAOs with both magnitude and phase information were calculated using wave elevation at the device, which was calculated from water pressure measured at the hull:

  $$H(\omega) = \frac{S_{xy}(\omega)}{S_{xx}(\omega)}$$ where $S_{xy}(\omega)$ is the cross-spectrum of wave elevation and device response

- Wave elevation at the device was calculated from water pressure and heave data as follows:

  $$\eta = \left(\frac{pressure}{\rho g} + heave\right) / \left(\frac{\cosh(k(heave+h+z))}{\cosh(kh)}\right)$$ where h=depth (30m), z=sensor depth (6m), k=wavenumber

  - The wavenumber k was calculated from the 30 minute energy period T_e using the dispersion relation.
  - Pressure was measured with a sensor mounted 6m below waterline on the hull.
  - Heave was measured with a dynamic motion sensor mounted on the top of the PowerPod.

- Wave elevation calculated from water pressure is expected to be less accurate than the Waverider data, but since it is measured at the device it can be used to calculate valuable RAO phase information.

Data used – results are average of all data for each PTO setting

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Date_time	Op_min	Pdc_W	Pgen_W	Damping recorded	WR_DateTime	Te_s	Hm0_m	MotDisp	Rdc_inv		Data period (NREL/NWEI data)	Data period (Waverider)	Mean wave direction 4-7s (degrees true)	Mean Azura heading (degrees true)
No load 1m/7s														
20150820_0800	0	NA	NA	NA	20150820_0806	6.97	1.02	80	NA		20150820_0800	20150820_0806	62	26
20150820_0830	0	NA	NA	NA	20150820_0836	7.04	1.02	80	NA		20150820_0830	20150820_0836	60	25
20150820_0900	0	NA	NA	NA	20150820_0906	7.22	0.98	80	NA		20150820_0900	20150820_0906	56	25
20150820_0930	0	NA	NA	NA	20150820_0936	7.13	1.06	80	NA		20150820_0930	20150820_0936	59	25
20150820_1000	0	NA	NA	NA	20150820_1006	7.12	1.04	80	NA		20150820_1000	20150820_1006	57	25
20150820_1030	0	NA	NA	NA	20150820_1036	7.04	1.03	80	NA		20150820_1030	20150820_1036	59	25
20150820_1100	0	NA	NA	NA	20150820_1106	7.09	0.99	80	NA		20150820_1100	20150820_1106	58	26
20150820_1130	0	NA	NA	NA	20150820_1136	6.79	0.87	80	NA		20150820_1130	20150820_1136	55	25
20150820_1200	0	NA	NA	NA	20150820_1206	6.78	0.88	80	NA		20150820_1200	20150820_1206	58	26
20150820_1230	0	NA	NA	NA	20150820_1236	7.13	0.88	80	NA		20150820_1230	20150820_1236	57	27
1.3m/5.5s														
20150730_0600	30	463	492	21.1	20150730_0606	5.56	1.42	30	20		20150730_0600	20150730_0606	72	24
20150730_0830	30	598	631	21.6	20150730_0836	5.59	1.35	80	20		20150730_0830	20150730_0836	71	25
1.3/6 s														
20150729_0600	30	468	497	21.1	20150729_0606	5.63	1.33	30	20		20150729_0600	20150729_0606	70	25
20150729_0830	30	633	667	21.6	20150729_0836	5.88	1.35	80	20		20150729_0830	20150729_0836	70	25
2m/6.5s														
20150714_0000	30	1052	1109	21.1	20150714_0006	6.79	2.02	30	20		20150714_0000	20150714_0006	58	26
20150714_0230	30	984	1039	21.6	20150714_0236	6.84	2.01	80	20		20150714_0230	20150714_0236	57	25
1.6m/7.5s														
20150807_1200	30	581	615	21.1	20150807_1206	7.59	1.64	30	20		20150807_1200	20150807_1206	26	26
20150807_1430	30	500	529	21.6	20150807_1436	7.55	1.67	80	20		20150807_1430	20150807_1436	34	26
2.5m/9s														
20150807_0000	30	764	810	21.1	20150807_0006	8.96	2.4	30	20		20150807_0000	20150807_0006	47	27
20150807_0230	30	796	843	21.6	20150807_0236	8.98	2.62	80	20		20150807_0230	20150807_0236	40	26

Comparison of water pressure & Waverider RAO results

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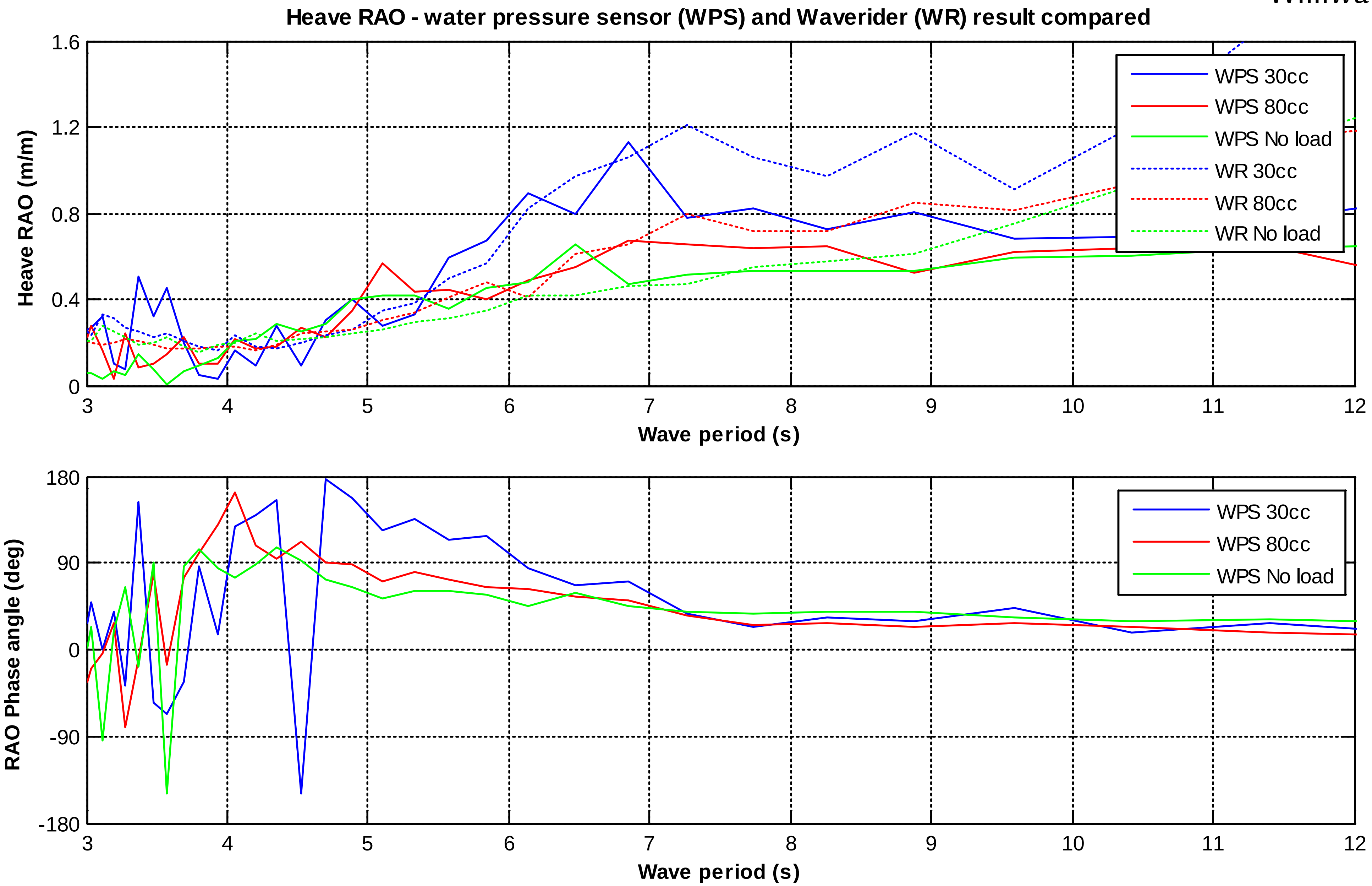

Comparison of water pressure & Waverider RAO results

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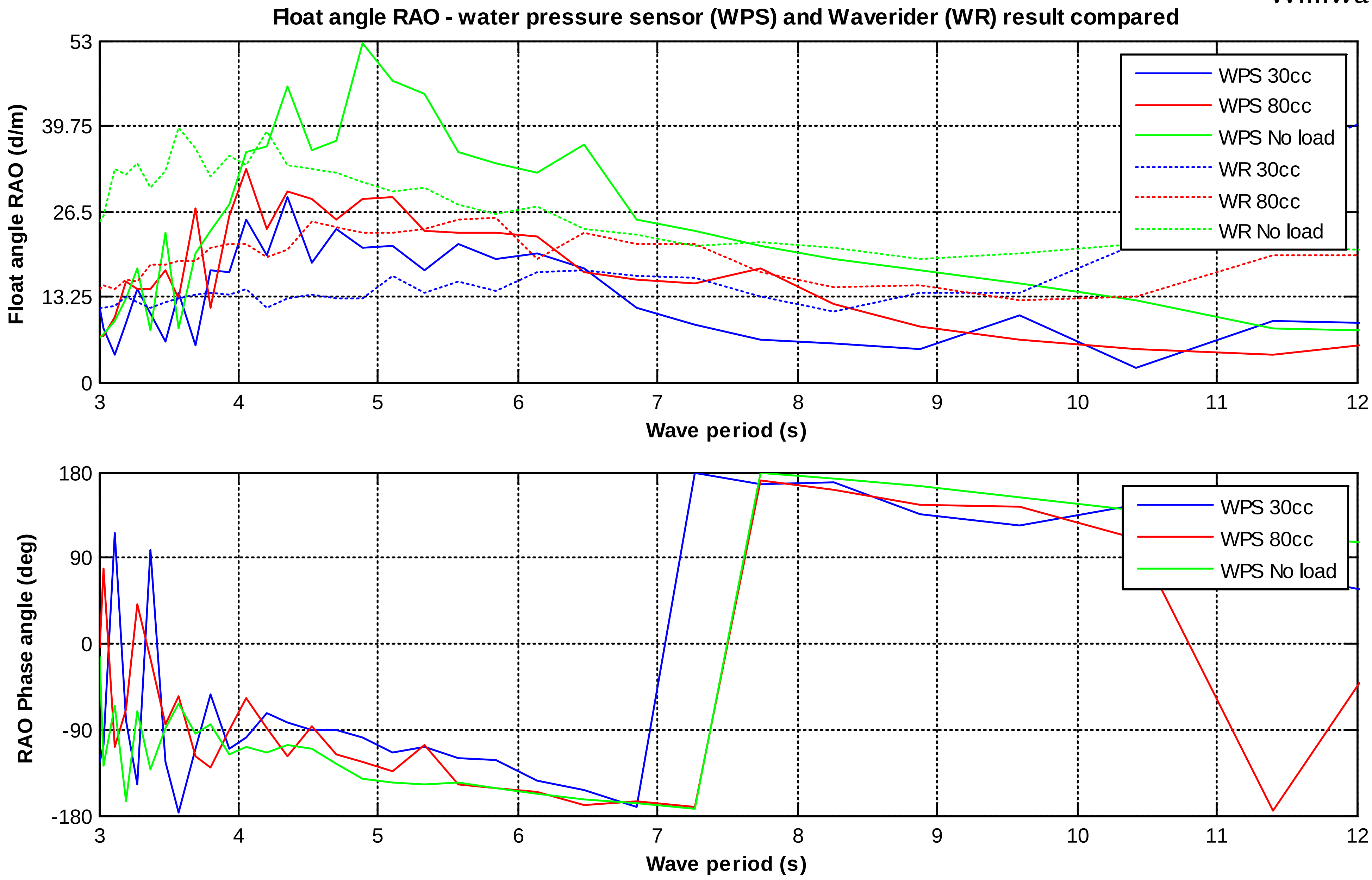

Comparison of water pressure & Waverider RAO results

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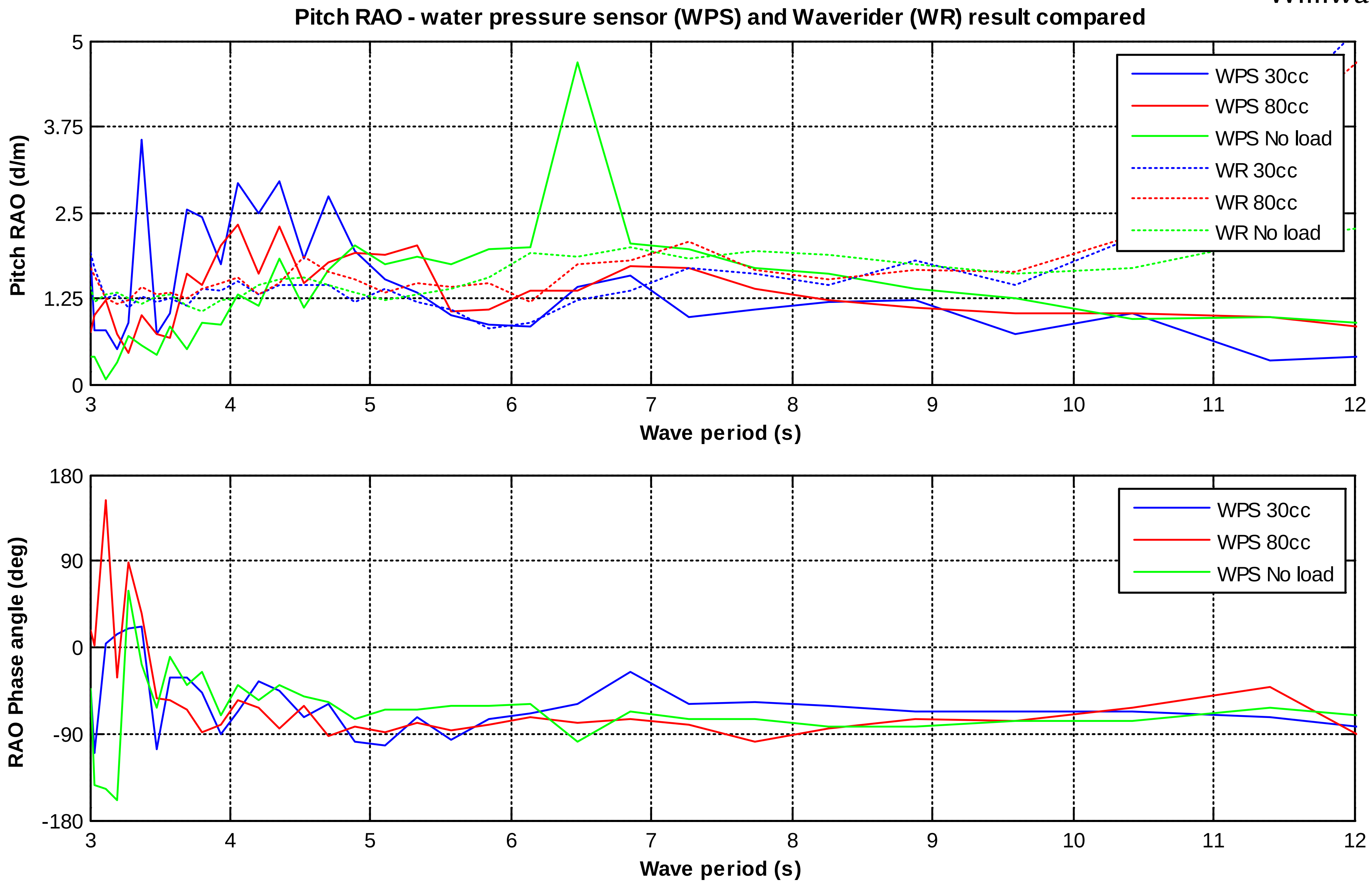

Comparison of water pressure & Waverider RAO results

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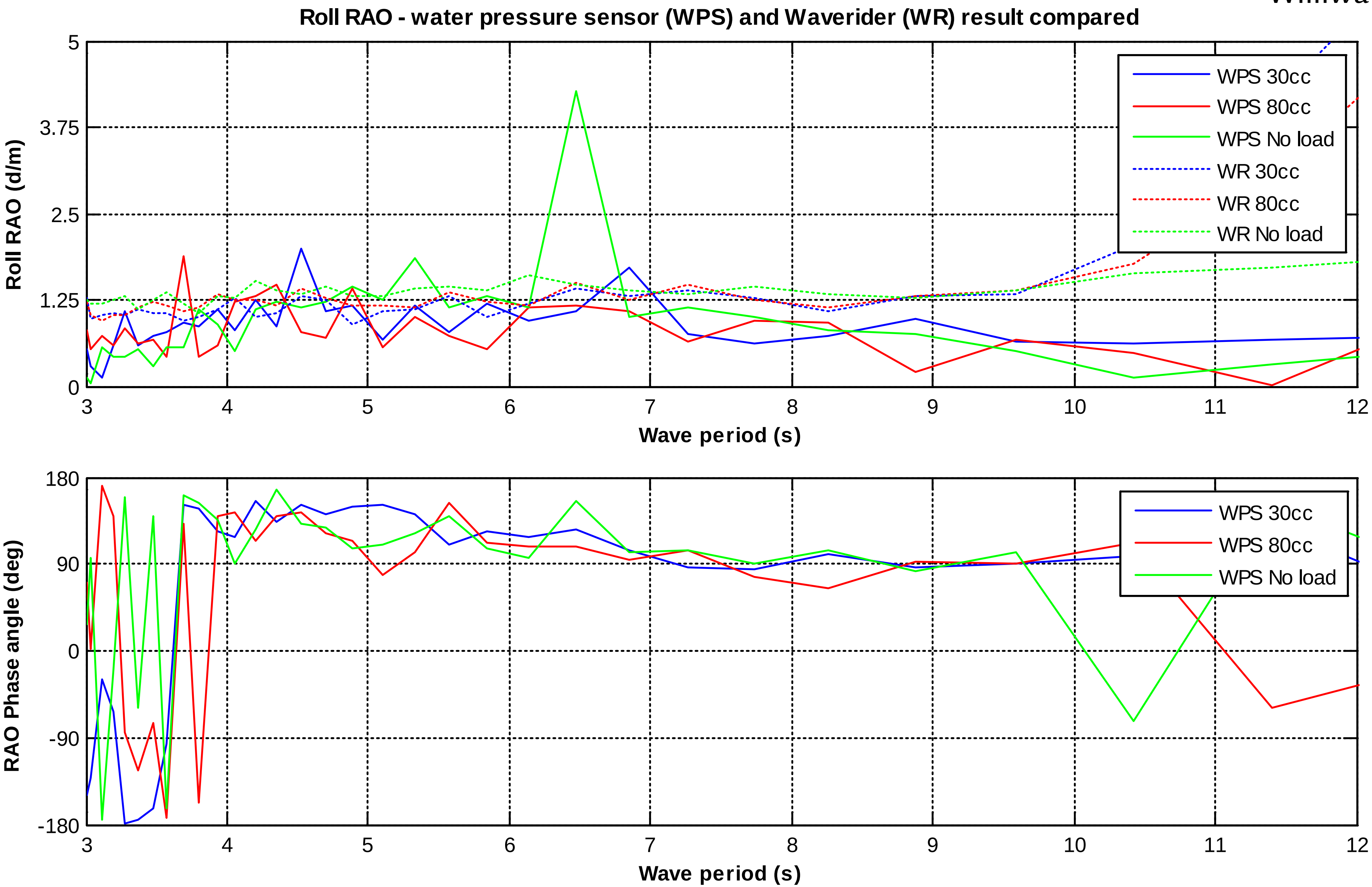
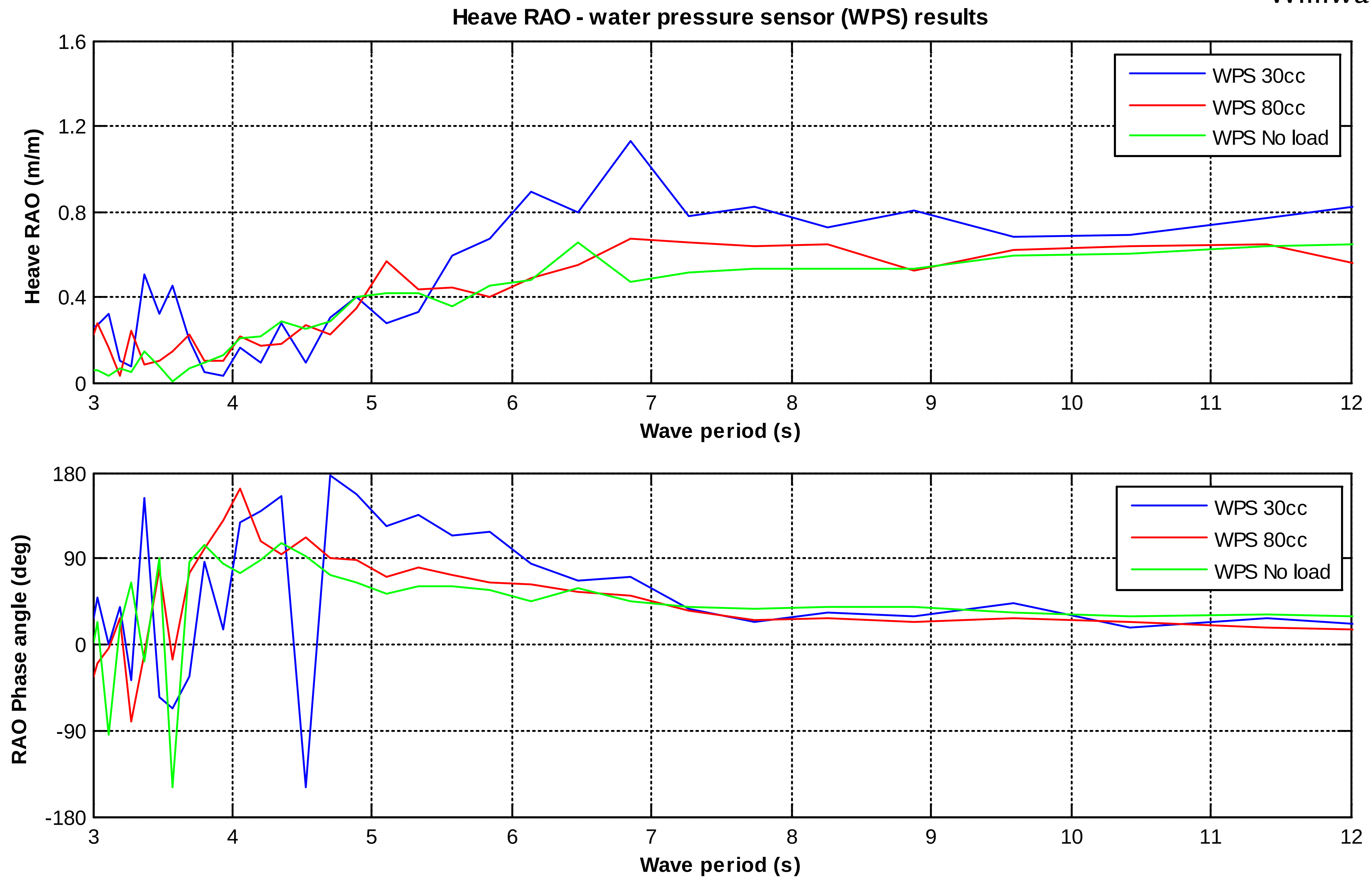
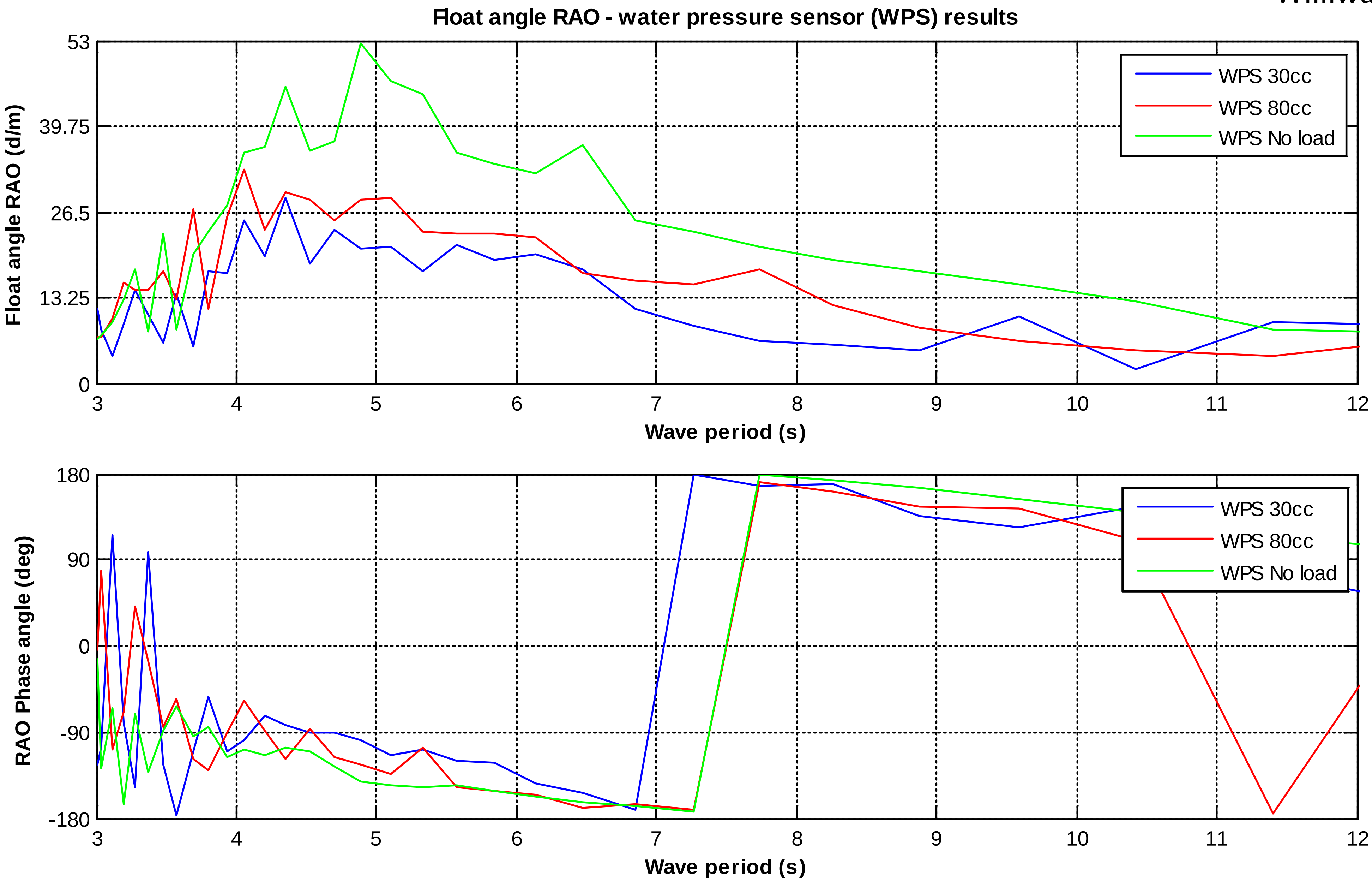


RAO results water pressure sensor data



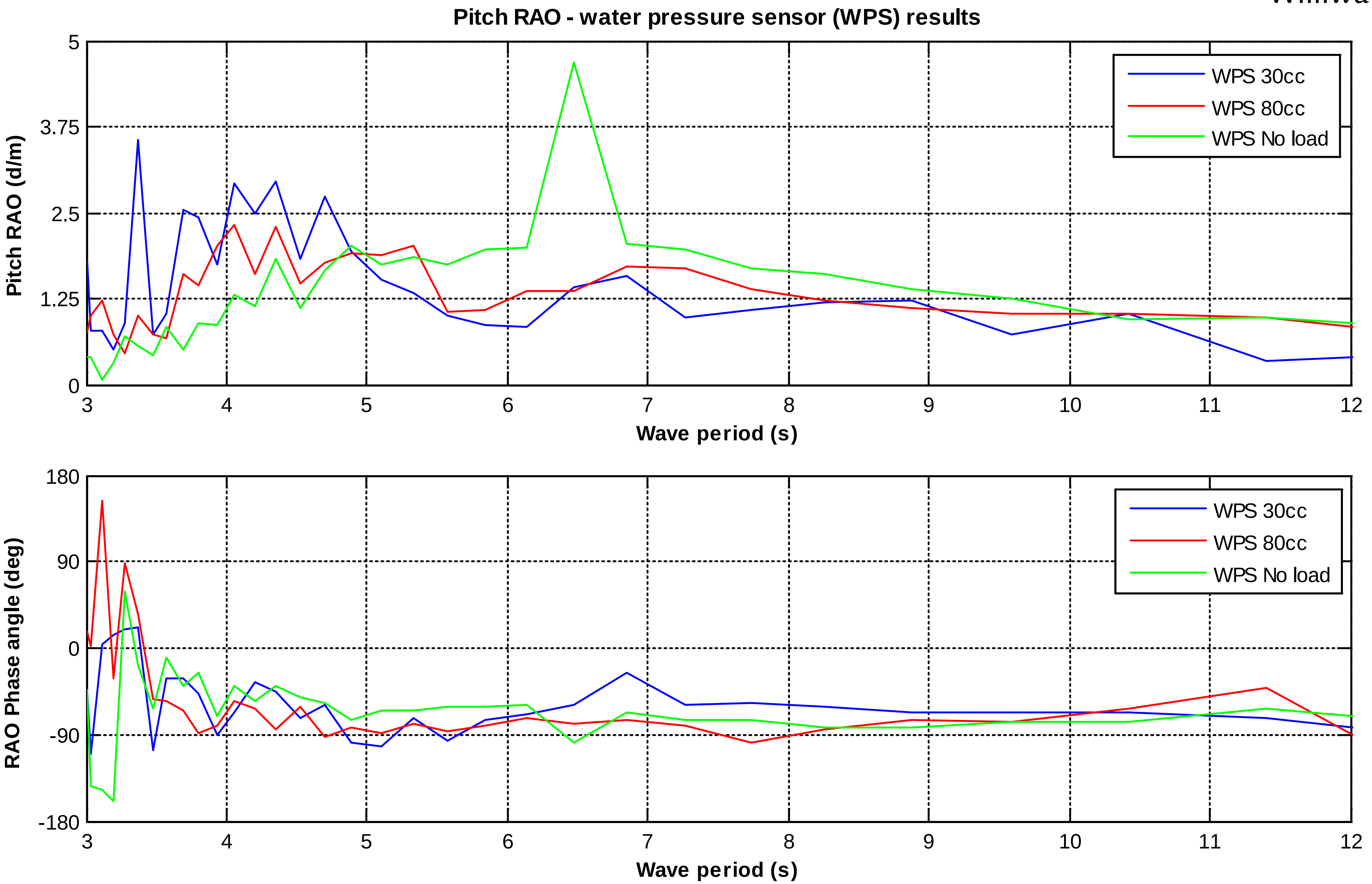
RAO results water pressure sensor data

Williwaw Engineering



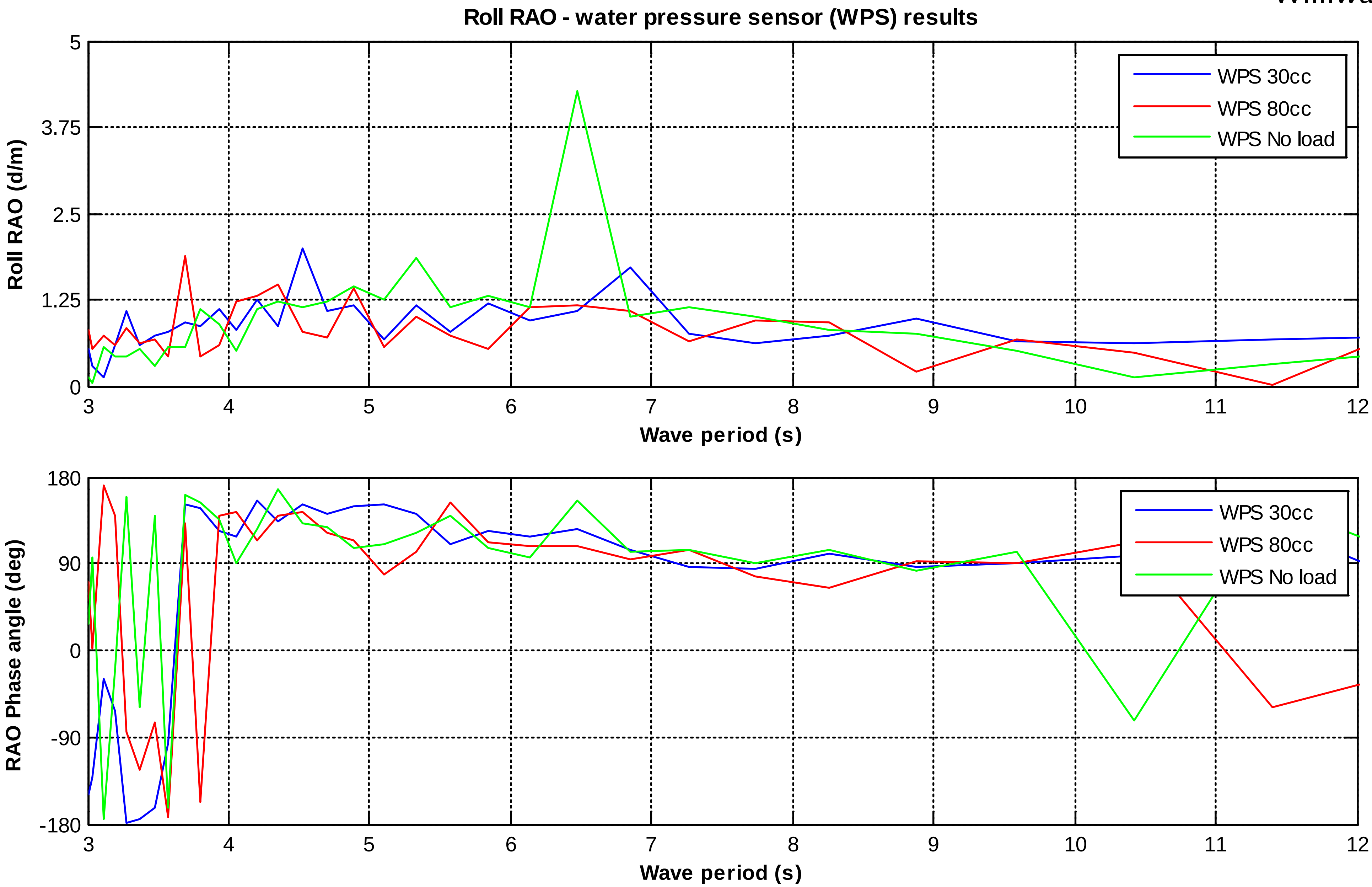
RAO results water pressure sensor data

Williwaw Engineering



RAO results water pressure sensor data

Williwaw Engineering



Attachment 5

Azura Relative Capture Width (RCW)

Calculations of Azura Relative Capture Width (RCW) with respect to wave period

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- The Azura PTO input power spectra were calculated for multiple 30 minute data periods as follows:

$$P(\omega) = \frac{2\,dt^2}{T} * \text{ fft(cylinder pressure) .* conj(fft(cylinder flow))}$$

where cylinder flow and pressure are alternating hydraulic pressure and flow at the PTO input. While cylinder pressure is directly measured, cylinder flow is calculated from rectified flow and sign of cylinder pressure.

- Relative Capture Width (RCW) was calculated from the power and wave spectra for each 30 minute data period as follows:

$$RCW(\omega) = real\left(\frac{P(\omega)}{J(\omega)}\right) * float\ width$$ where *J(ω)* is the wave energy flux spectra:

$$J(\omega) = \rho\ g\ C_g(\omega)\ S(\omega)$$ where ρ is water density, g acceleration of gravity, $C_g(\omega)$ is wave group velocity, and S(ω) the wave spectra measured by the Waverider buoy

- Note that results are for PTO input power so don't include PTO efficiency (approximately 60%). The calculation can't be directly done with PTO output power because frequency information is lost due to PTO rectification and power smoothing.

- Kaneohe Bay energy flux distribution was calculated by first averaging two years of Waverider buoy spectral data, calculating the corresponding average wave energy flux, multiplying by frequency spacing then normalizing so that the sum of spectral components is 1.

Relative Capture Width (RCW) results

(Plotted with Kaneohe Bay annual energy flux distribution)

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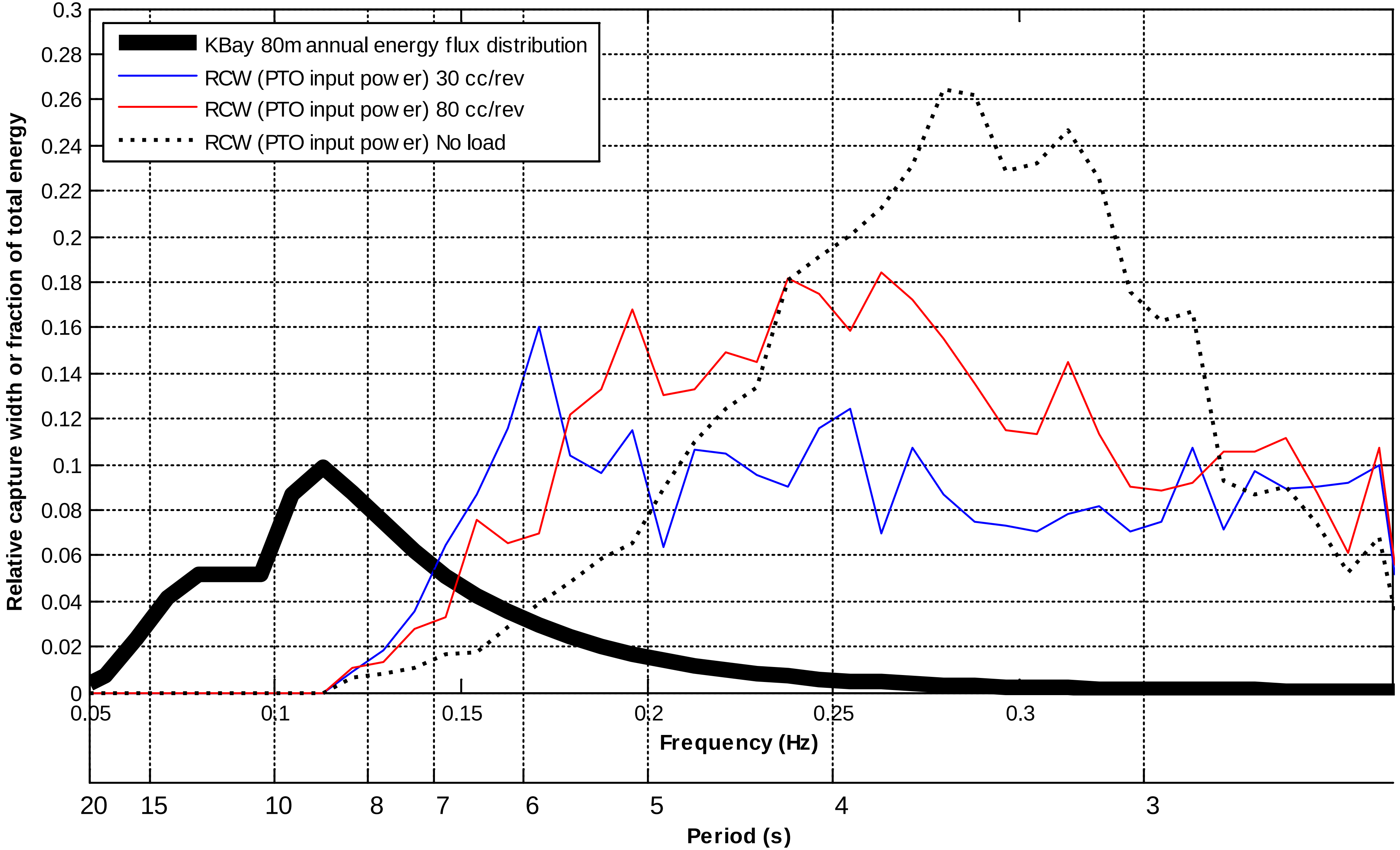

Data used – results are average of all data for each PTO setting

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Date_time	Op_min	Pdc_W	Pgen_W	Damping recorded	WR_DateTime	Te_s	Hm0_m	MotDisp	Rdc_inv		Mean wave direction 4-7s (degrees true)	Mean Azura heading (degrees true)
No load												
20150820_0800	0	NA	NA	NA	20150820_0806	6.97	1.02	80	NA		62	26
20150820_0830	0	NA	NA	NA	20150820_0836	7.04	1.02	80	NA		60	25
20150820_0900	0	NA	NA	NA	20150820_0906	7.22	0.98	80	NA		56	25
20150820_0930	0	NA	NA	NA	20150820_0936	7.13	1.06	80	NA		59	25
20150820_1000	0	NA	NA	NA	20150820_1006	7.12	1.04	80	NA		57	25
20150820_1030	0	NA	NA	NA	20150820_1036	7.04	1.03	80	NA		59	25
20150820_1100	0	NA	NA	NA	20150820_1106	7.09	0.99	80	NA		58	26
20150820_1130	0	NA	NA	NA	20150820_1136	6.79	0.87	80	NA		55	25
20150820_1200	0	NA	NA	NA	20150820_1206	6.78	0.88	80	NA		58	26
20150820_1230	0	NA	NA	NA	20150820_1236	7.13	0.88	80	NA		57	27
20151021_0500	0	NA	NA	NA	20151021_0509	6.3	1.51	80	NA		68	26
20151021_0530	0	NA	NA	NA	20151021_0539	6.4	1.47	80	NA		68	26
20151021_0600	0	NA	NA	NA	20151021_0609	6.11	1.48	80	NA		65	26
20151021_0630	0	NA	NA	NA	20151021_0639	6.08	1.57	80	NA		70	26
20151021_0700	0	NA	NA	NA	20151021_0709	6.12	1.52	80	NA		70	26
20151021_0730	0	NA	NA	NA	20151021_0739	6.31	1.58	80	NA		69	25
20151021_0800	0	NA	NA	NA	20151021_0809	6.18	1.55	80	NA		69	26
20151021_0830	0	NA	NA	NA	20151021_0839	6.38	1.49	80	NA		66	26
20151021_0900	0	NA	NA	NA	20151021_0909	6.4	1.52	80	NA		62	27
20151021_0930	0	NA	NA	NA	20151021_0939	6.28	1.39	80	NA		61	27
20151021_1000	0	NA	NA	NA	20151021_1009	6.38	1.4	80	NA		65	27
20151021_1030	0	NA	NA	NA	20151021_1039	6.24	1.35	80	NA		61	26
20151021_1100	0	NA	NA	NA	20151021_1109	6.2	1.41	80	NA		63	26
20151021_1130	0	NA	NA	NA	20151021_1139	6.34	1.4	80	NA		64	27
20151021_1200	0	NA	NA	NA	20151021_1209	6.36	1.36	80	NA		62	26
20151021_1230	0	NA	NA	NA	20151021_1239	6.49	1.45	80	NA		60	26
20151021_1300	0	NA	NA	NA	20151021_1309	6.68	1.42	80	NA		57	26
20151021_1330	0	NA	NA	NA	20151021_1339	6.35	1.32	80	NA		59	26
80 cc/rev												
20150924_0230	30	576	611	21.6	20150924_0236	5.73	1.46	80	20		53	26
20150924_0300	30	569	604	21.6	20150924_0306	5.86	1.33	80	20		54	25
20150924_0830	30	509	539	21.6	20150924_0836	5.58	1.28	80	20		60	26
20150924_0900	30	514	545	21.6	20150924_0906	5.53	1.34	80	20		61	25
20150924_1430	30	516	546	21.6	20150924_1436	5.17	1.22	80	20		53	26
20150924_1500	30	507	537	21.6	20150924_1506	5.25	1.28	80	20		52	26
20150924_2030	30	634	672	21.6	20150924_2036	5.35	1.29	80	20		53	27
30 cc/rev												
20150924_0000	30	505	539	21.1	20150924_0006	5.75	1.38	30	20		46	27
20150924_0530	30	462	492	21.1	20150924_0536	5.78	1.33	30	20		57	26
20150924_0600	30	518	551	21.1	20150924_0606	5.54	1.26	30	20		54	25
20150924_1130	30	411	438	21.1	20150924_1136	5.37	1.27	30	20		55	27
20150924_1200	30	470	501	21.1	20150924_1206	5.28	1.24	30	20		54	26
20150924_1730	30	502	533	21.1	20150924_1736	5.27	1.38	30	20		60	25
20150924_1800	30	533	566	21.1	20150924_1806	5.33	1.29	30	20		63	26