University of Victoria

Institute for Integrated Energy Systems

Application of Triple Collocation Technique to Wave Resource Assessments and Wave Energy Converter Energy Production

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WCWI WEST COAST WAVE INITIATIVE

Presentation Overview

Motivation
- Improve the predictive ability of the SWAN model in Port Renfrew
- Gain familiarity with triple colocation method
- Introduction to the Wave Energy Converter (WEC) power prediction methodology

Measurements & Theory
- Location: Port Renfrew, British Columbia Canada
- Measurements: TriAXYS buoy, Nortek AWAC and SWAN Model
- Theory: Triple Collocation Technique

Application Regime
- Regime 1: Single Value Calibration
- Regime 2: Monthly Calibration
- Regime 3: Bivariate Distribution Calibration
- Regime 4: Spectral Calibration

Calibration Results
- Performance of differing calibration regimes
- Discussion on practicality and feasibility

Wave Energy Application
- Energy Period Calibration
- Wave Energy Converter (WEC) Power Production Variation
- WEC Mean Annual Energy Production Uncertainty

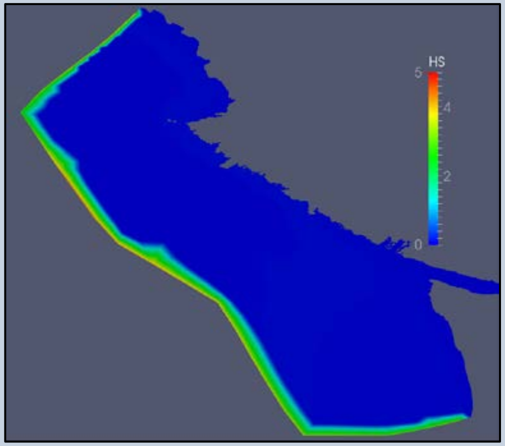
West Coast Wave Initiative @ UVic

Motivation | Measurements &Theory | Application Regime | Calibration Results | Wave Energy Application

"comprehensive wave-to-wire-washing machine modeling study"

Resource Assessment

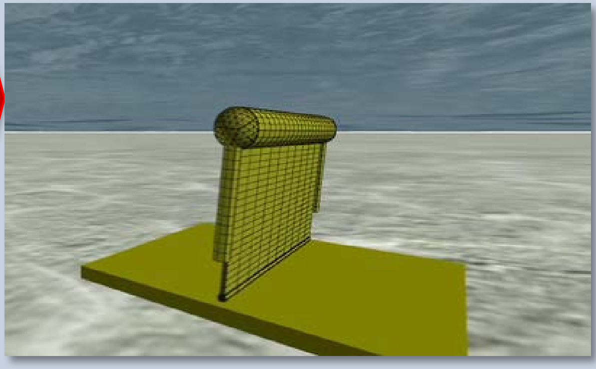
- Unstructured SWAN Model
- 4 Directional Wave Buoys
- 4km – 50m spatial resolution
- 11 yr Hindcast & 48 hr Forecast
- ECMWF wave / COAMPS wind



GROSS RESOURCE

Technology Modeling

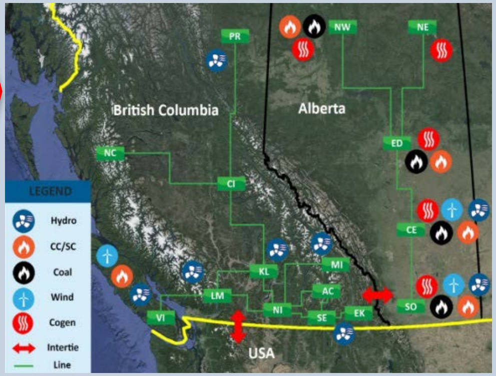
- Complete 6 DOF Motions
- Flexible time domain, fully coupled simulations.
- Mechanics, hydrodynamics, PTO feedback, moorings



NET RESOURCE

Grid Integration

- KW: Diesel offset / Remote Electrification
- MW: Energy Security / Small Markets
- Large: Carbon pricing, policy



USABLE RESOURCE

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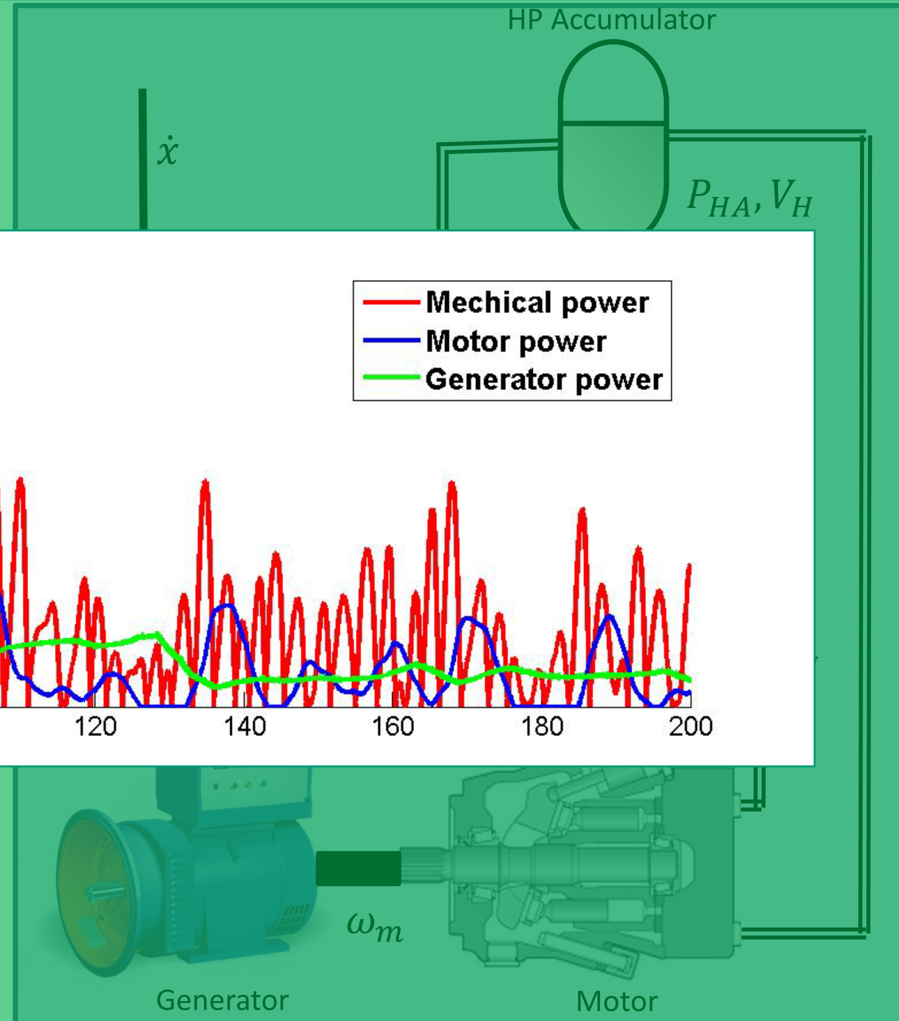
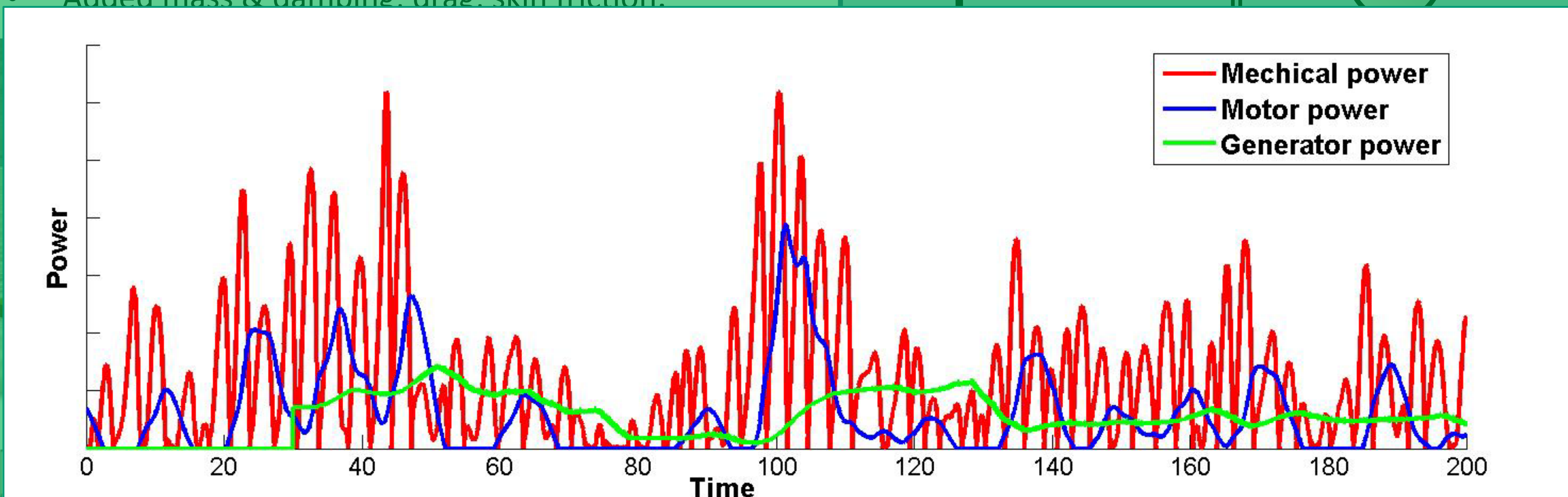
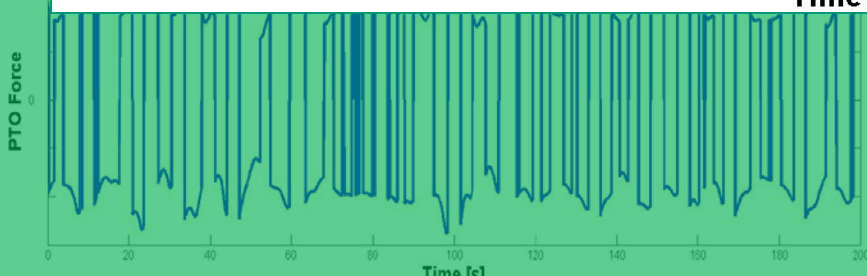
Wave Energy Conversion – PTO Modelling

Proteus DS:

- Waves
- Wind, tides
- Mooring forces
- Added mass & damping, drag, skin friction,







Wave Energy Conversion – A Study in Parametrization

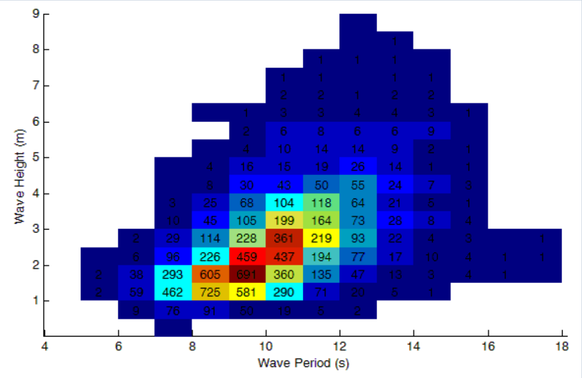
Motivation | Measurements &Theory | Application Regime | Calibration Results | Wave Energy Application

“comprehensive wave-to-wire-washing machine modeling study”

Resource Assessment

kW/m
Hours

$$T_e = \frac{m_{-1}}{m_0}$$



GROSS RESOURCE

Technology Modeling

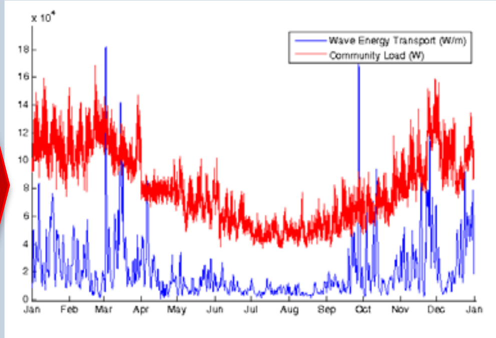
Device Width
Efficiency

Period	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
0.25	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	6	0	6	0	0	0	0
1.25	0	41	47	47	39	39	39	32	31	29	0
1.75	0	92	96	93	84	81	79	72	70	64	61
2.25	0	0	148	141	130	124	121	114	109	101	0
2.75	0	0	0	189	177	168	164	157	151	0	0
3.25	0	0	0	233	221	210	205	198	0	0	0
3.75	0	0	0	0	256	245	240	238	0	0	0
4.25	0	0	0	0	0	270	263	264	253	0	0
4.75	0	0	0	0	0	0	265	272	0	0	0
5.25	0	0	0	0	0	0	251	0	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	0
6.25	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0	0	0	0	0	0	0	0	0	0
Height											

NET RESOURCE

Grid Integration

KWhr



USABLE RESOURCE

Presentation Overview – Back to Triple Collocation

Motivation | Measurements &Theory | Application Regime | Calibration Results | Wave Energy Application

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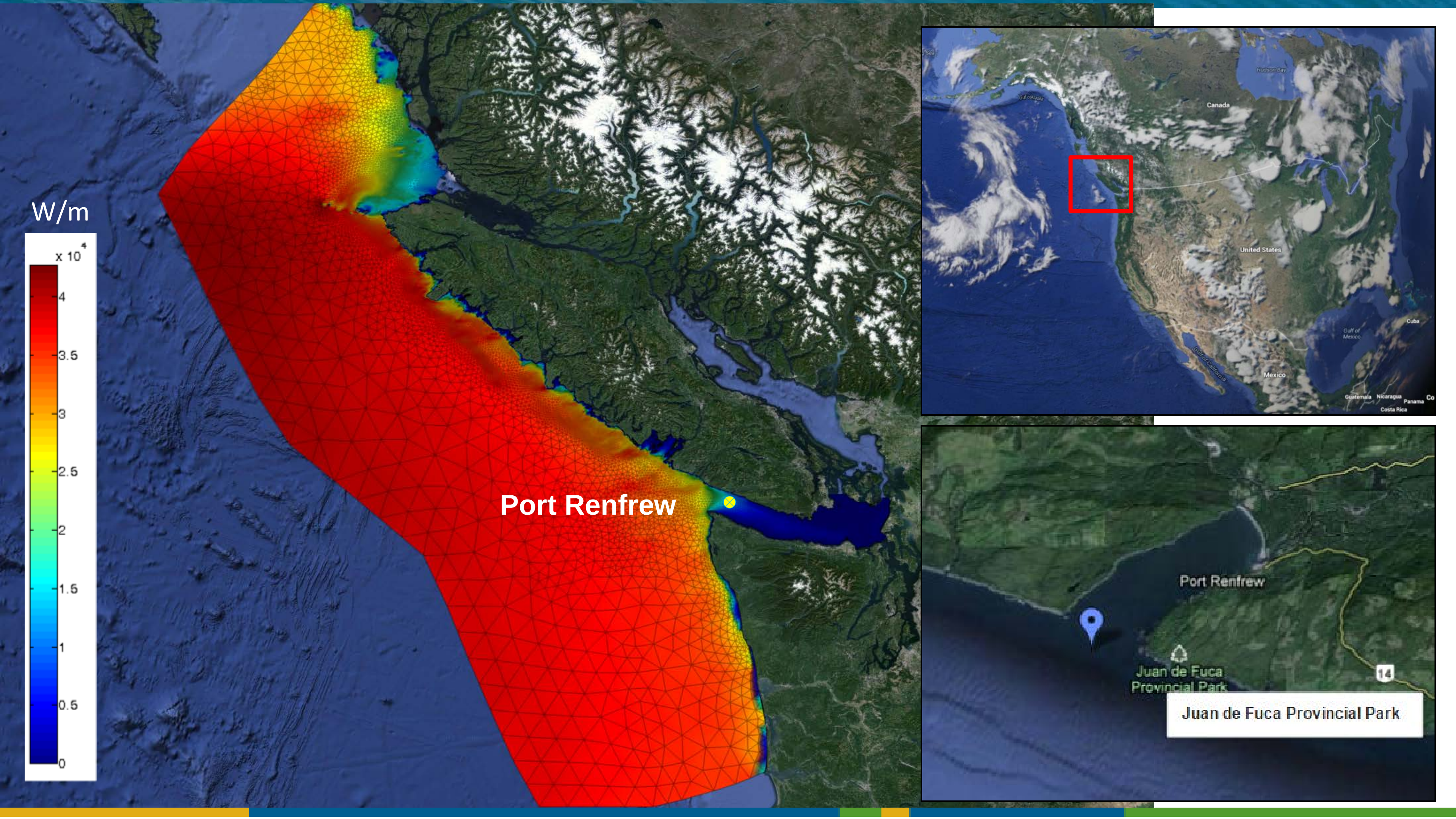
Port Renfrew, British Columbia



WCWI Buoys, AWAC and SWAN Model

<u>SWAN Model:</u>

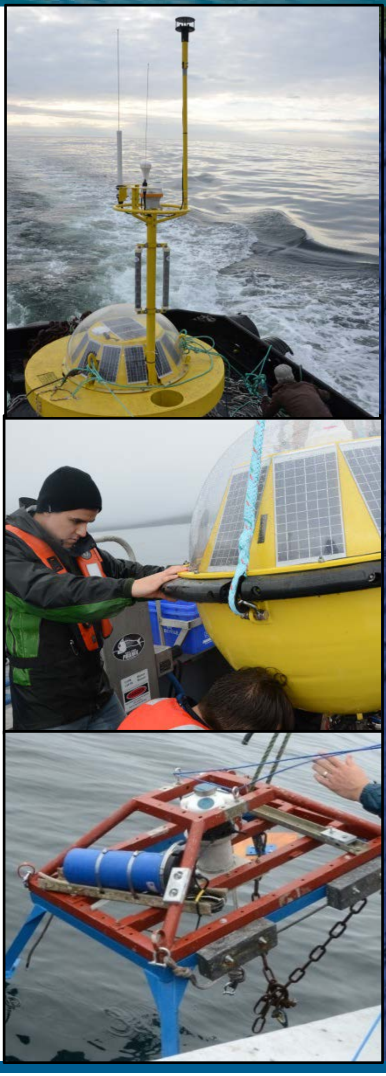
- Unstructured grid with 50m nearshore resolution
- Grid resolution dependent on slope and depth
- Sensitivity Study: ECMWF / COAMPS boundary conditions
- 11 year hindcast @ 3 hr resolution
- 36 freq. & 10° wave spectrum.
- Validated against NDBC, EC and WCWI buoys

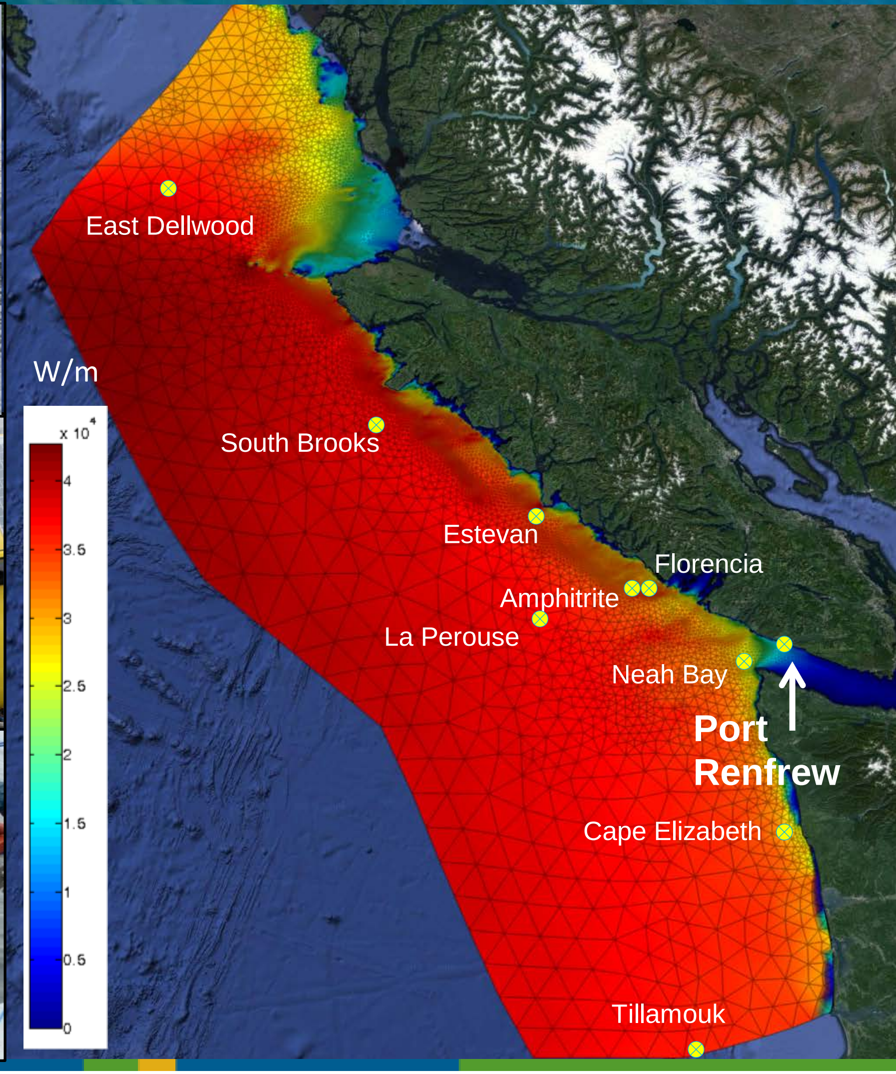
<u>TriAxys Wave Buoy:</u>

- ~27m deep (shallow)
- 1 yr w/ hourly measurements
- 0.005 Hz and 3° resolution
- SE Validation point for SWAN numerics.

<u>Nortek AWAC:</u>

- Collocated with buoy (~27m)
- Sept – Dec 2014
- Hourly data
- 0.01 Hz and 2° resolution





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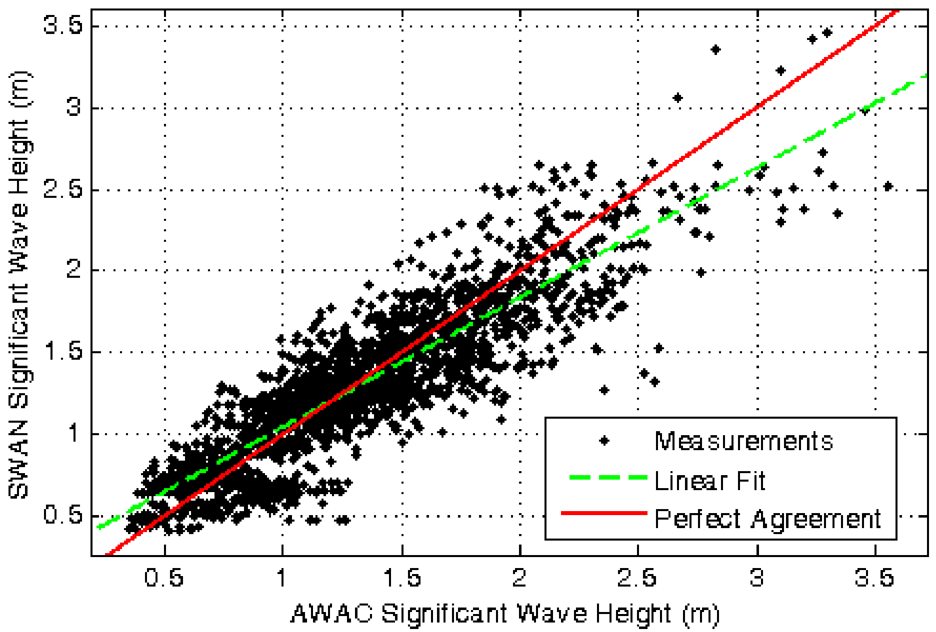

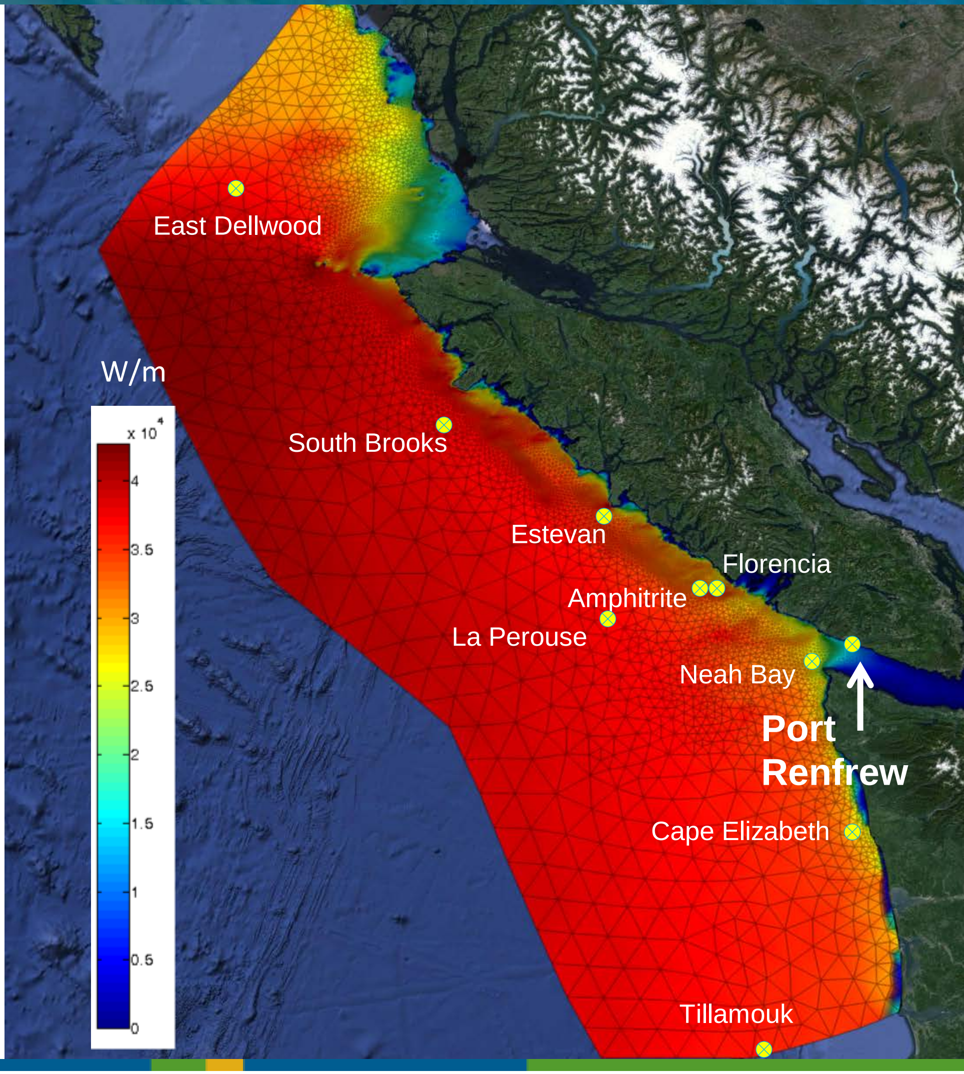

Triple Collocation Technique:

- Applied to many problems - only applying in differing regimes and to a different problem.
    - Caires & Sterl (2003), Janssen et al. (2006), Muraleedharan et al. (2006), Portabella & Stoffelen (2009), …

- 3 Measurements, 3 Errors and Ability to Calibrate the SWAN Output
- X, Y, Z are three differing measurements, α_x is the y-intercept or bias, β_x the calibration constant and e_x the residual error component.

- Assumptions:
    - Linear dependence between truth and measurement
    - Independent, uncorrelated errors
    - Normally distributed errors.

- Previous works have removed the y-intercept; we have kept it in and will discuss further in later slides.

$$X = \alpha_x + \beta_x T + e_x$$
$$Y = \alpha_y + \beta_y T + e_y$$
$$Z = \alpha_z + \beta_z T + e_z$$

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Application Regime #1 and # 2

Application Regime #1: Single Value Calibration

- Caires and Sterl (2003):
  - Annual Variation, Latitude Dependence.
- Port Renfrew over 3 month = single set of coefficients and errors.

	Test	Bias (m)	Beta	Variance (m^2)	Normalized SD (%)
AWAC	AWAC	0	1	3.46e-04	1.45
	SWAN	0.032	0.99	5.41e-02	18.0
	Buoy	0.002	1.00	2.60e-04	1.26
SWAN	AWAC	-0.032	1.01	3.42e-04	1.45
	SWAN	0	1	5.37e-02	17.9
	Buoy	-0.031	1.01	2.60e-04	1.26
Buoy	AWAC	-0.150	0.99	3.47e-04	1.46
	SWAN	0.030	0.99	5.42e-02	18.0
	Buoy	0	1	2.60e-04	1.26

Month	Test	Bias (m)	Beta	Variance (m^2)
October	AWAC	0	1	1.60e-04
	SWAN	4.01e-02	0.982	5.91e-02
	Buoy	8.81e-04	1.00	3.13e-04
November	AWAC	0	1	5.02e-04
	SWAN	-1.63e-03	0.983	4.66e-02
	Buoy	6.62e-03	1.00	1.94e-04
December	AWAC	0	1	4.52e-04
	SWAN	2.20e-02	1.00	5.50e-02
	Buoy	1.90e-03	1.00	1.96e-04

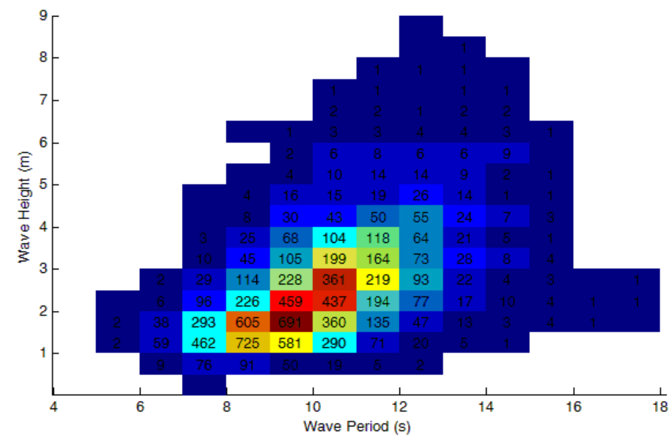
Application Regime #2: Monthly Calibration

- Janssen, Abdalla, Hersbach & Bidlot (2003):
  - Monthly dependence.
- Port Renfrew over 3 month = 3 set of coefficients and errors.
- AWAC defined as reference dataset.

Application Regime #3: Bivariate Calibration

<u>Application Regime #3: Bivariate Calibration</u>

- International Electro-technical Commission (IEC) is establishing standards around the assessment for wave resources for energy generation – bivariate histogram.
- Significant wave height and energy period dependent coefficients and error variances.

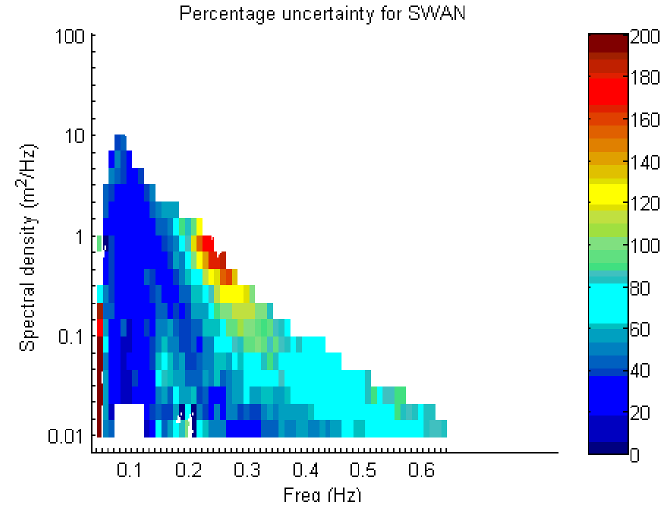


Energy Period - Te (s)

Hs (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0-0.5	0	0	0	0	8	8	8	20	30	10	0	0	0	0	0	0
0.5-1	0	0	0	1	86	91	85	192	142	48	10	2	0	0	0	0
1-1.5	0	0	0	0	39	39	45	79	225	209	80	40	4	2	0	0
1.5-2	0	0	0	0	0	1	8	33	111	119	101	62	29	10	4	0
2-2.5	0	0	0	0	0	0	3	14	28	51	40	27	9	5	1	0
2.5-3	0	0	0	0	0	0	0	3	5	8	4	0	6	2	1	0
3-3.5	0	0	0	0	0	0	0	1	1	4	2	2	2	3	0	0
3.5-4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

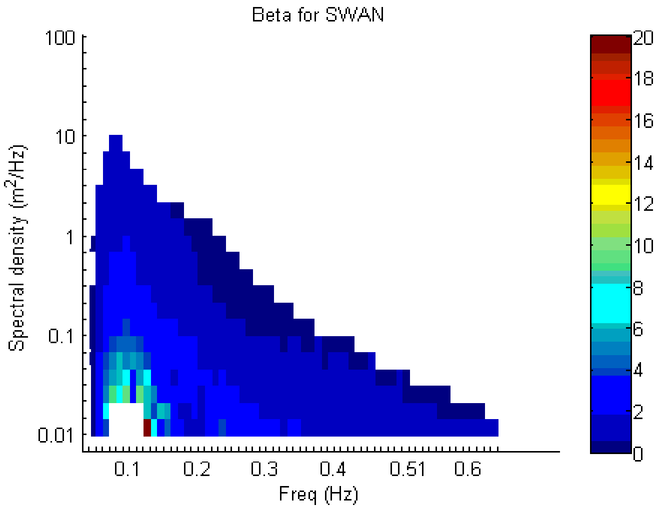
Hs % Uncertainty		Energy Period (s)								
		5	6	7	8	9	10	11	12	13
Hs (m)	0-0.5									
	0.5-1			19.48	15.28	14.72				
	1-1.5				16.38	11.84	13.82			
	1.5-2					15.01	18.76	13.04	10.17	
	2-2.5						16.75			
	2.5-3									

SWAN Bias		Energy Period (s)							
		6	7	8	9	10	11	12	13
Hs (m)	0-0.5								
	0.5-1		0.0083	0.0089	0.0121				
	1-1.5			0.0060	0.0058	0.0079			
	1.5-2				0.0015	0.0023	0.0039	0.0021	
	2-2.5					0.0011			
	2.5-3								



Application Regime #4: Spectral Calibration

- Lack of data dominates ability to do anything !
- Attempt to calibrate the variance density within each frequency band of the frequency domain wave spectrum…
- Error was greatly magnified
- Created significantly computational effort (compared to other methods)



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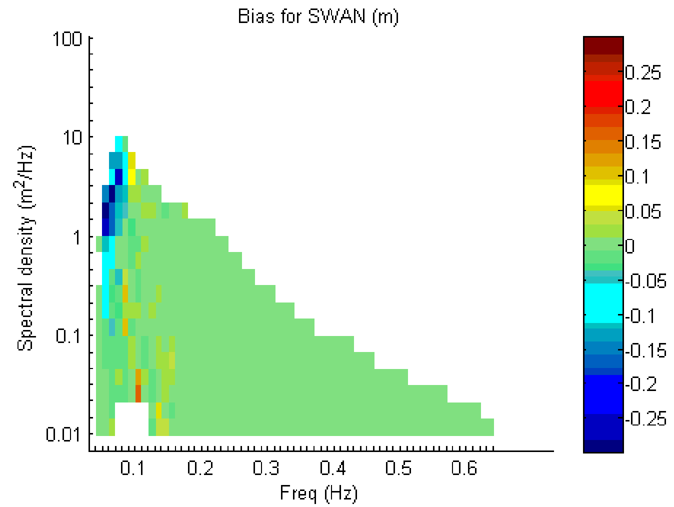
$$Y = \alpha_y + \beta_y T + e_y$$
$$Z = \alpha_z + \beta_z T + e_z$$



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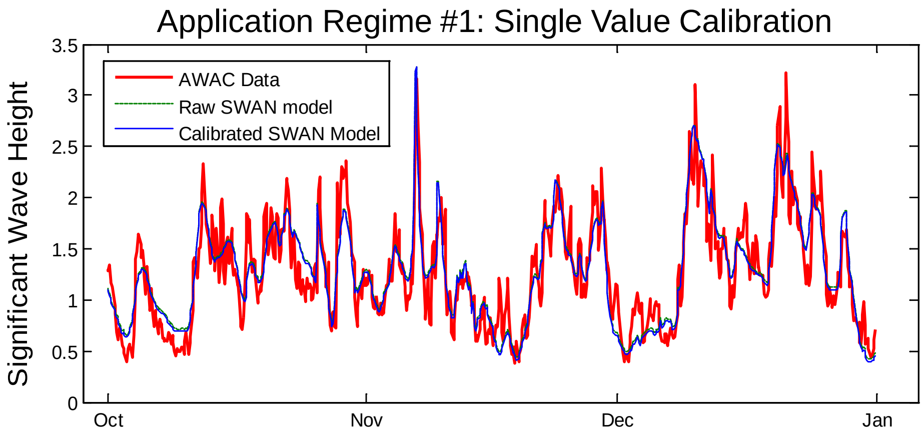
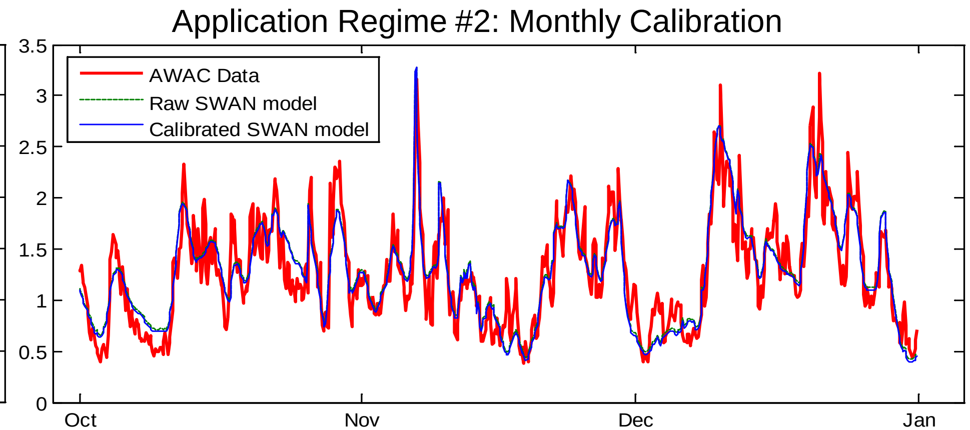
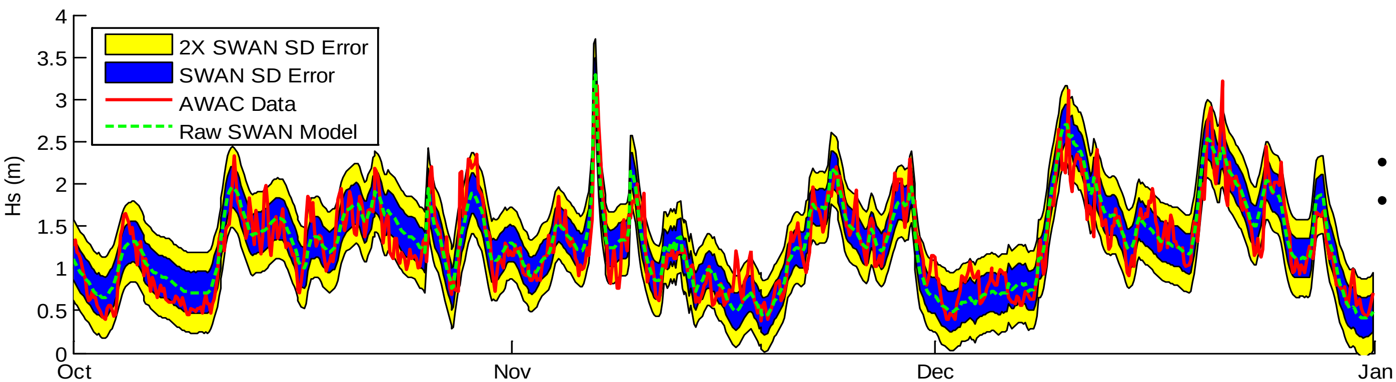
Regime #1 & #2: Calibration Results.





Result: Constant r and RMSE (0.90, 0.23m) = ….. Nothing



<u>Normal Distribution:</u>

- 67 % SWAN (1 SD) = 71% AWAC
- 95 % SWAN (2 SD) = 94% AWAC

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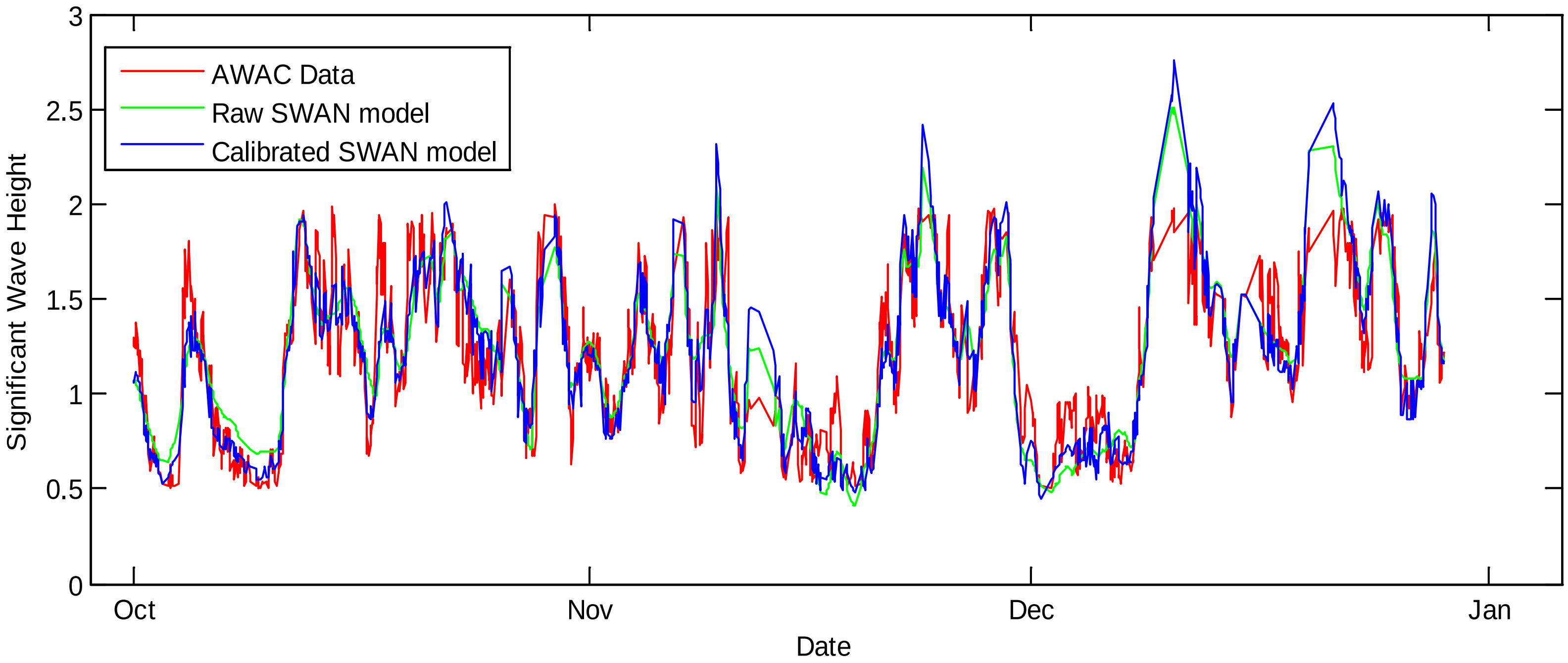
Application Regime #3: Bivariate Calibration

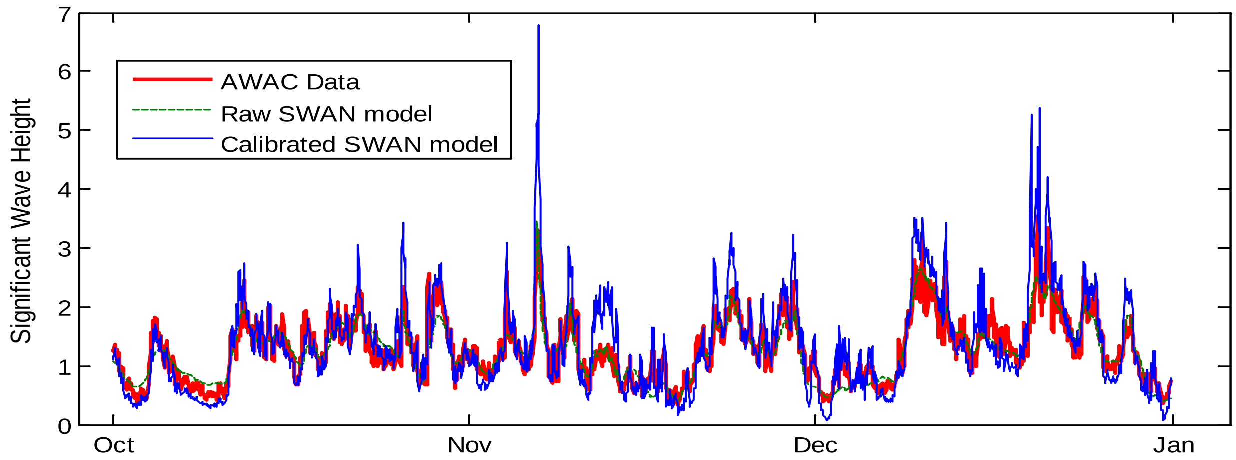


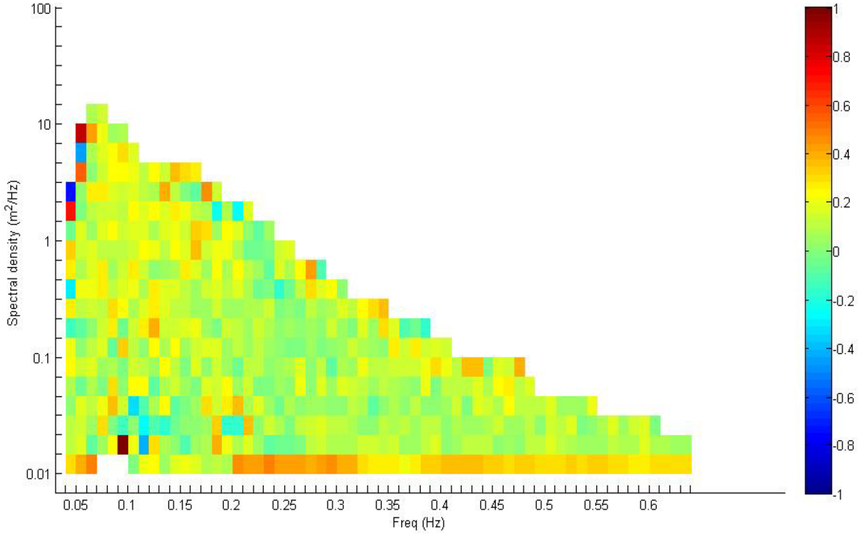
	SWAN_Raw Vs AWAC	SWAN_Calibrated Vs AWAC
	Significant Wave Height	
Mean	1.20	1.19
Bias	-0.010	0.00
RMSE	0.212	0.186
SI	0.176	0.156
r	0.856	0.900

Only using data with convergence (62% of dataset):

5.14% Improvement in correlation

Application Regime #4: Spectral Calibration





	SWAN_Un Vs AWAC	SWAN_Cal Vs AWAC
	Significant Wave Height	
Mean	1.26	1.36
Bias	0.0199	-0.0786
RMSE	0.246	0.373
SI	0.196	0.275
r	0.891	0.921

3.37% improvement in correlation

Impact of WEC Energy Production

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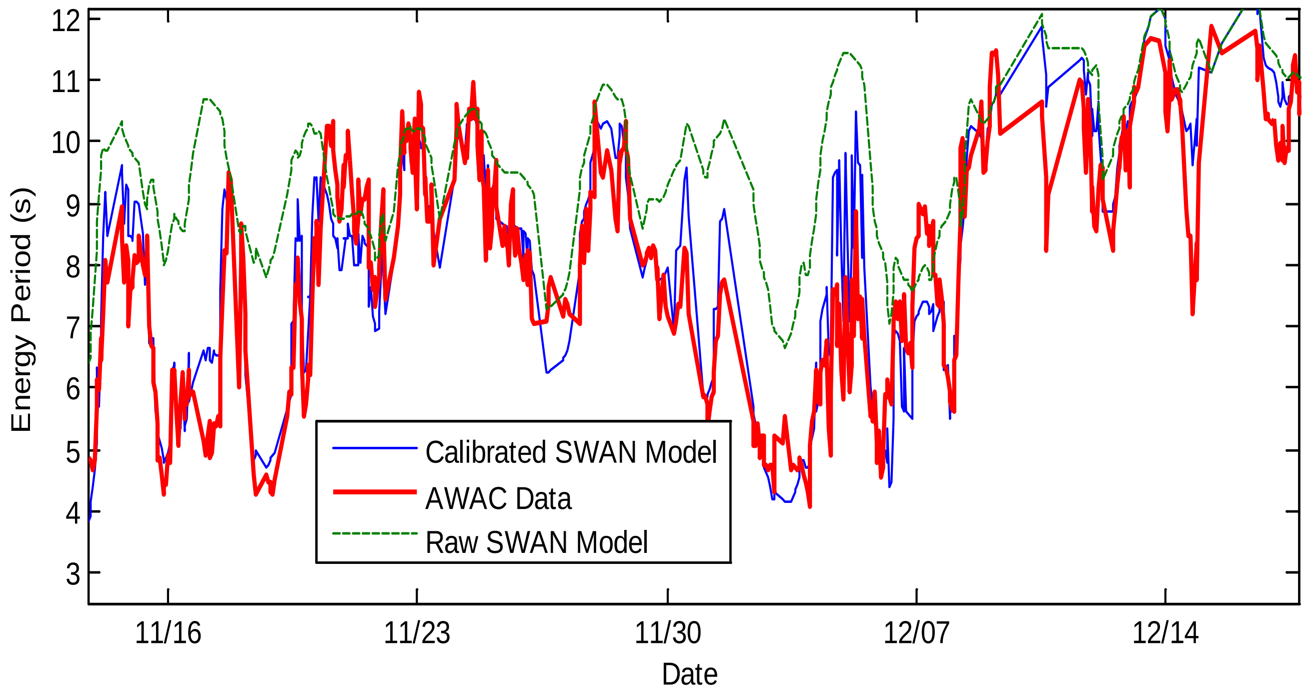
Energy Period Calibration



	SWAN_Raw Vs AWAC	SWAN_Calibrated Vs AWAC
	Energy Period	
Mean	9.50	8.48
Bias	-1.02	0.000
RMSE	1.57	0.673
SI	0.165	0.079
r	0.654	0.917

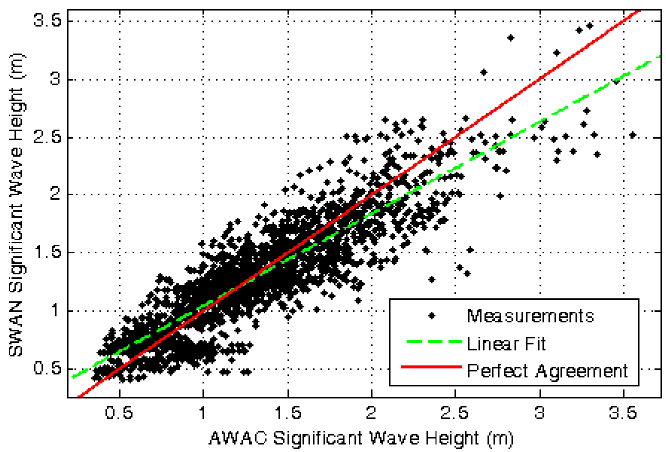
Only using data with convergence:

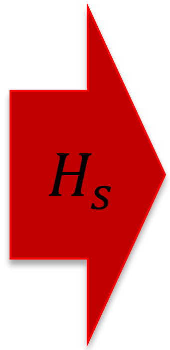
29.2% Improvement in correlation

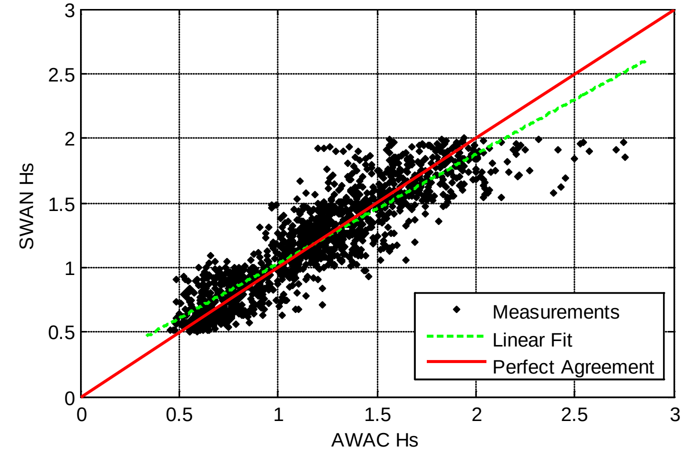
Note: Model and device frequency binning effects

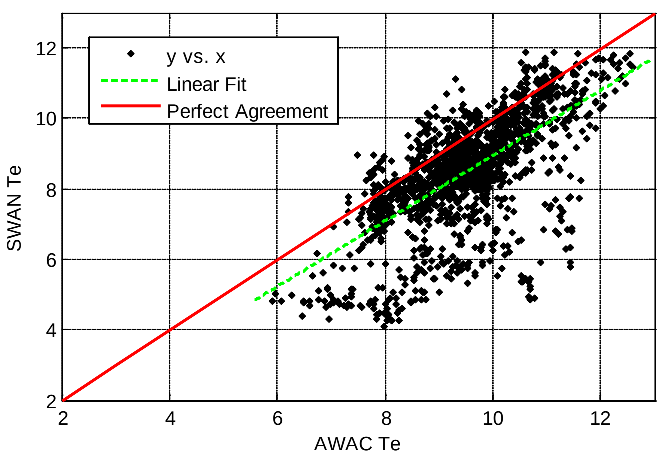
Improvements through Calibration

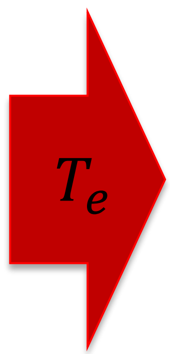
Motivation | Measurements &Theory | Application Regime | **Calibration Results** | Wave Energy Application

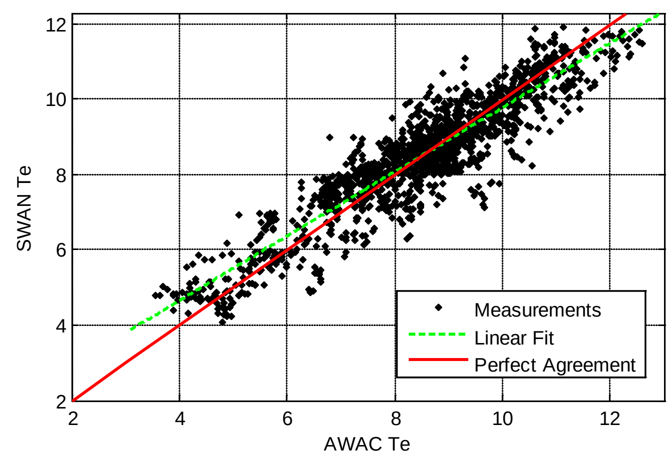








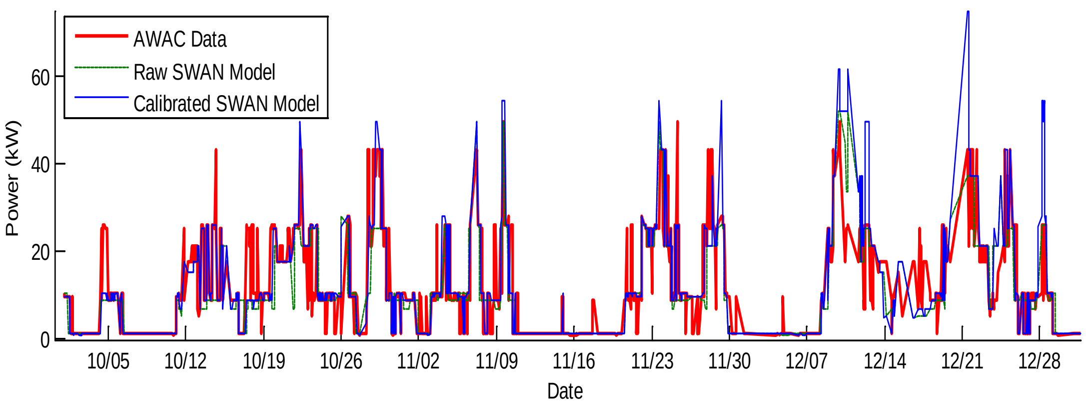




Application to WEC Power & Energy

Motivation | Measurements &Theory | Application Regime | Calibration Results | **Wave Energy Application**

Power (kW)	Te (s)																		
Hs (m)	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	19.5	20.5	21.5	22.5
0.25	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.75	4	7	7	12	8	8	6	3	3	3	3	2	2	2	2	1	1	1	1
1.25	9	11	19	32	22	23	14	24	7	5	9	5	11	4	6	3	3	2	3
1.75	21	31	45	40	34	29	47	22	25	23	18	11	16	7	7	5	6	4	3
2.25			93	99	110	104	39	63	30	41	20	22	25	15	26	15	11	3	7
2.75			99	111	132	95	105	28	39	36	46	25	21	32	22	9	18	18	8
3.25			95	111	195	107	79	129	87	47	63	67	41	50	46	33	28	16	20
3.75			207	175	138	128	192	124	108	144	79	86	56	36	25	18	25	28	22
4.25				225	189	310	106	200	86	200	81	80	48	86	64	43	46	31	23
4.75					223	218	177	130	172	127	195	81	120	84	54	39	71	27	34
5.25						344	323	253	282	192	195	109	137	73	45	69	45	61	38
5.75							379	251	234	162	107	146	79	109	71	84	72	53	46
6.25							317	267	151	236	321	217	121	80	68	132	45	69	47
6.75							372	337	433	215	155	159	117	167	139	116	105	112	54
7.25							479	375	237	224	307	168	180	110	147	127	74	58	79
7.75							394	426	447	127	255	255	252	116	84	103	68	79	73



	SWAN_Raw Vs AWAC	SWAN_Calibrated Vs AWAC
	Wave Power	
Energy	34.992 MWhr	36.583 MWhr
STD	12.572 kW	16.356 kW
Mean	22.991 kW	24.037 kW
Bias	0.519 kW	-0.526 kW
RMSE	9.893 kW	9.467 kW
SI	0.430	0.394
r	0.711	0.816

Results:

- 4.54 % Increase in 3-month energy production
- 30.1 % increase in the standard deviation - more power variability
- 14.8 % increase in correlation

Conclusions

- “An Effort to Apply Powerful Techniques to Small Datasets” - Collect more data
- Application under single value or monthly regime confirmed the normal distribution of uncertainty but provided little additional improvement in calibrated SWAN predictions.
- Application of the triple collocation technique on a bivariate regime captures more of the uncertainty and may be applicable to other years or time periods.
- Bivariate calibration of Hs and Te resulted increased correlation to AWAC signal (14.8%), increased WEC energy production (4.57%), yet increased the variability in WEC power production (30.1%).
- Triple collocation technique is extremely powerful and just scratching the surface…

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