Numerical study of wave energy converters with integrated tethered docks for UUV docking and charging.

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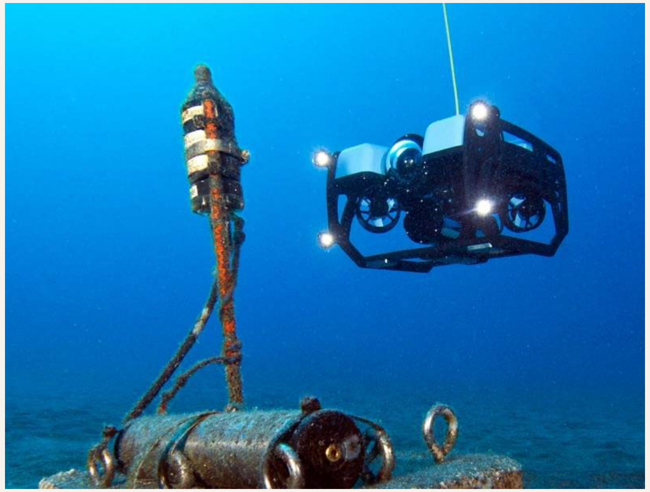
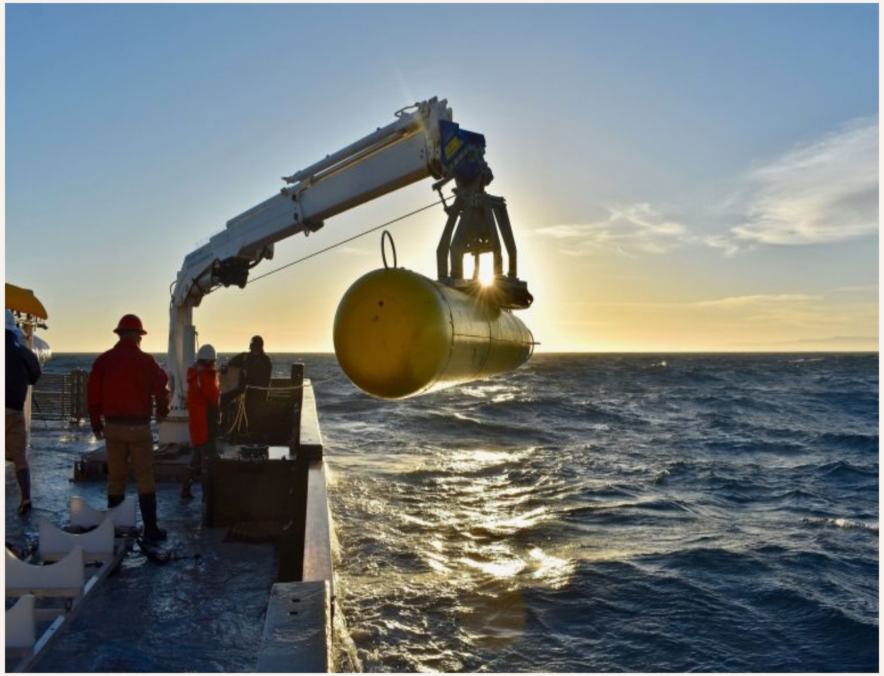
Introduction

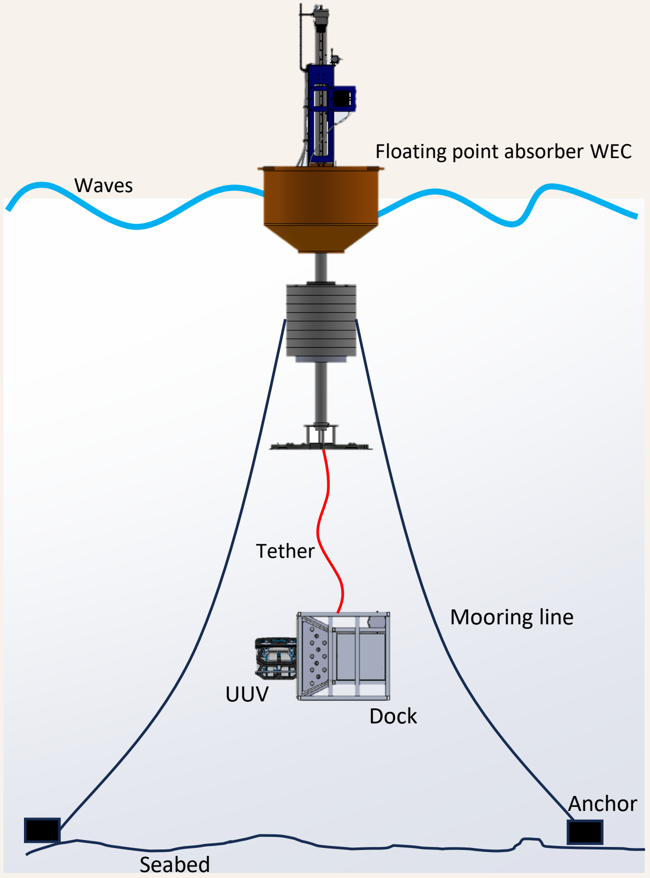
- Application of unmanned underwater vehicle (UUV)
  - Ocean data collection, ocean monitoring, military applications, Subsea inspection and maintenance, etc.
- UUVs are limited by onboard energy and data storage capacity, limiting endurance.
- UUVs are currently retrieved by specialized crew ships for recharge and data transfer:
  - Increase in operational cost
  - Recovery is time intensive.
  - Weather dependent.
  - Pose safety risks to both personnel and equipment.
  - Carbon emission from the ships.





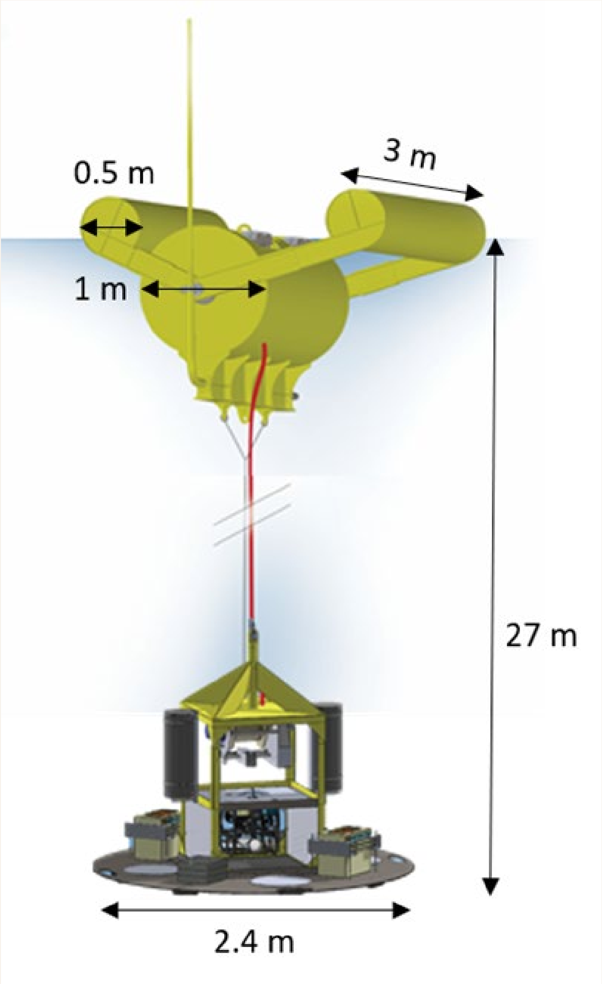
Background

- Underwater docking and charging (UDC) technology offers a solution to extend UUV endurance. (A review is found in *Liu et al. (2024)*).
  - Challenges in power source still exist.
  - Challenges in stable docking platform still exist.
- Wave energy converters (WECs) can act as power source and a UUV docking platform (WEC-UUV).
- WECs have been extensively studied for energy harvesting their integration with UUV remains underexplored.



Objectives

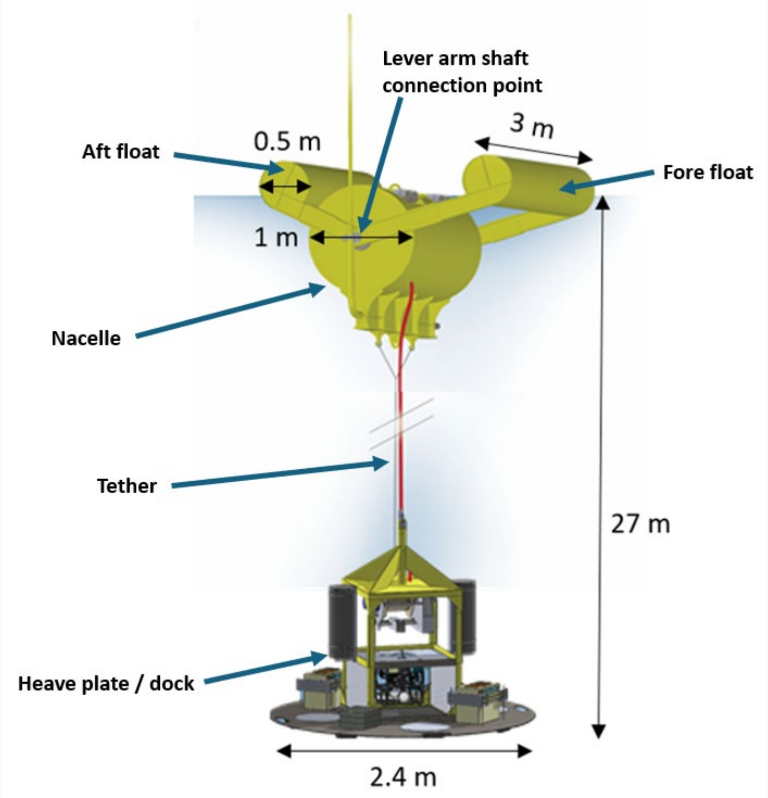
- Model and validate a real-world field-deployed WEC-UUV system, TigerRAY.
- Develop framework for assessing WEC-UUV functionality in:
  - Power performance
  - Docking feasibility
- Assess TigerRAY functionality in low energy seas along the US coast.



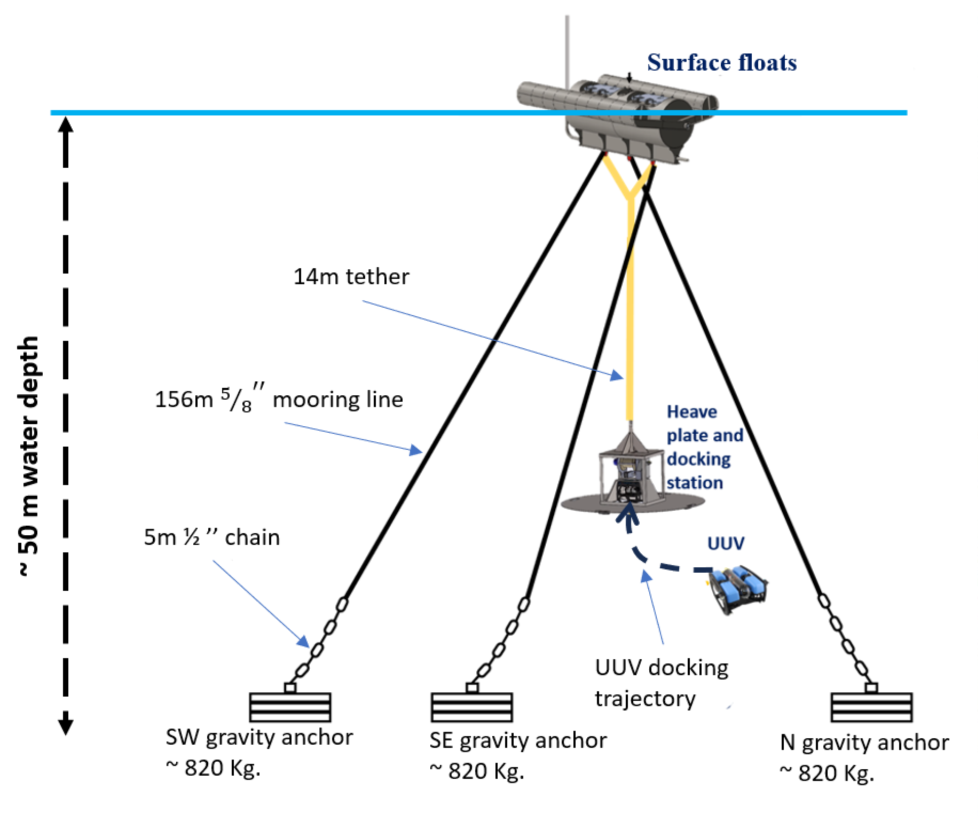
TigerRAY WEC-UUV

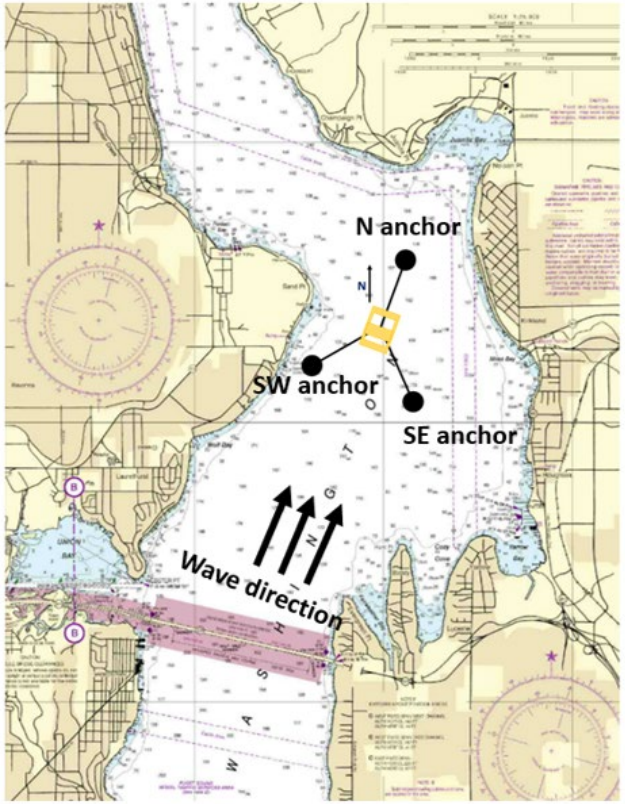
TigerRAY case study WEC-UUV

Schematic of TigerRAY WEC-AUV system



Mooring configuration for winter 2024 moored deployment field testing





TigerRAY numerical modeling

Partially nonlinear potential flow hydrodynamic time-domain model for dynamic response:

$$\boldsymbol{m}\ddot{x}(t) = \boldsymbol{F}_{FK}(t) + \boldsymbol{F}_{rad}(t) + \boldsymbol{F}_{PTO}(t) + \boldsymbol{F}_{m}(t) + \boldsymbol{F}_{v}(t)$$

$\boldsymbol{m}$: mass matrix

$\ddot{x}(t)$: acceleration vector of the device

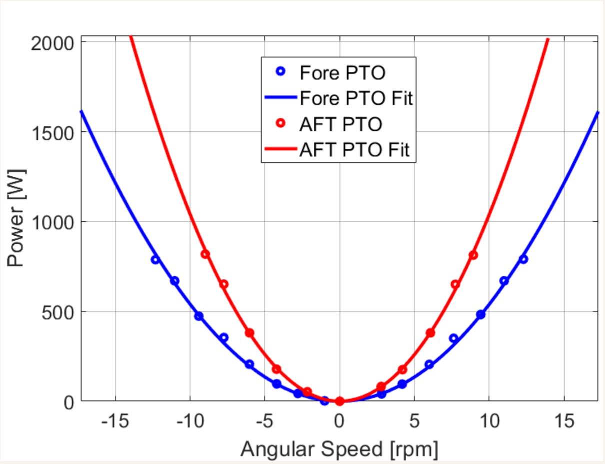
$\boldsymbol{F}_{FK}(t)$: Froud-Krylov hydrostatic and dynamic wave excitation force (**nonlinear**)

$\boldsymbol{F}_{rad}(t)$: wave radiation force (**linear computed with WAMIT**)

$\boldsymbol{F}_{PTO}(t)$: power-take-off (PTO) force

$\boldsymbol{F}_{m}(t)$: mooring and tether forces

$\boldsymbol{F}_{v}(t)$: quadratic viscous force



Notes:

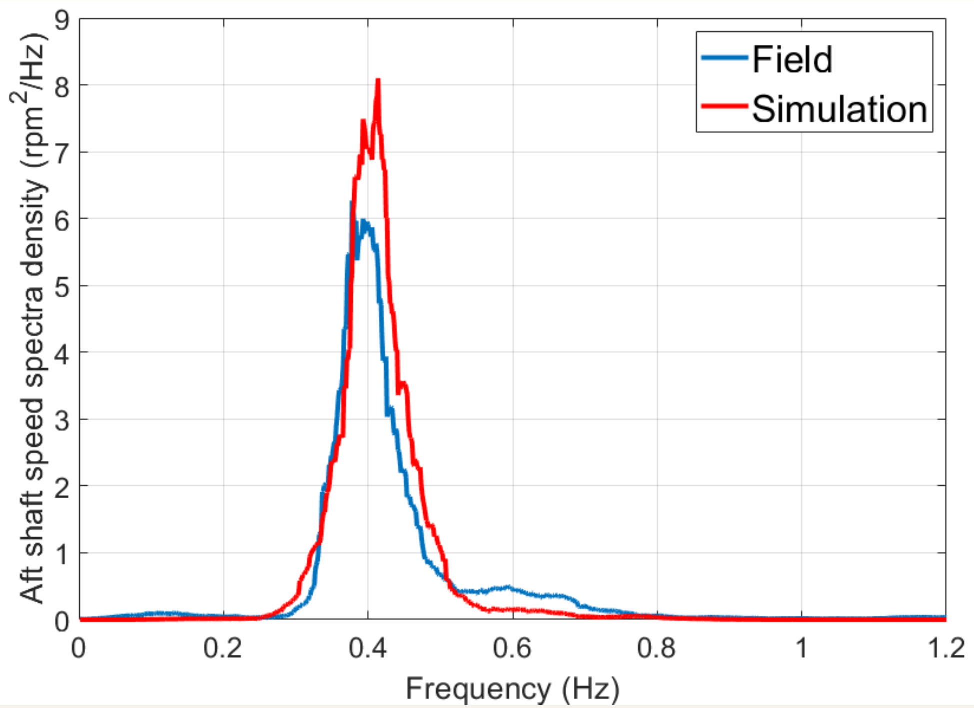
1. The time domain equation is simulated in ProteusDS marine dynamic analysis software

2. Model uses a parametric relationship to predict generator electrical power output from simulated PTO velocity

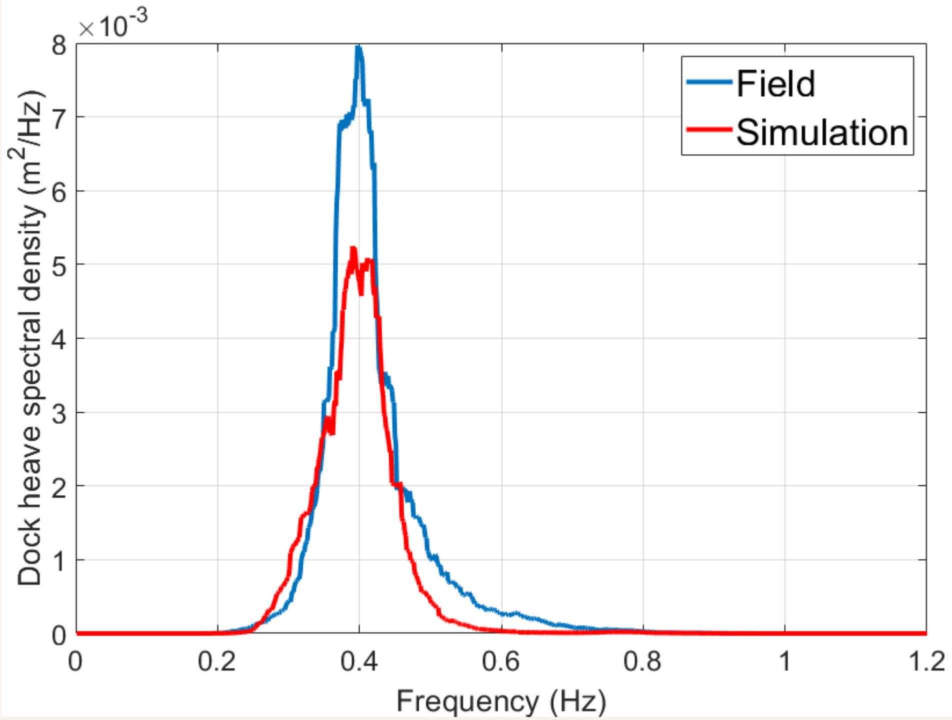
TigerRAY model validation

- Validation is performed based on the two key functional requirements of WEC-UUV systems; (**power performance & docking feasibility**).

➢Spectral comparison of PTO shaft speeds

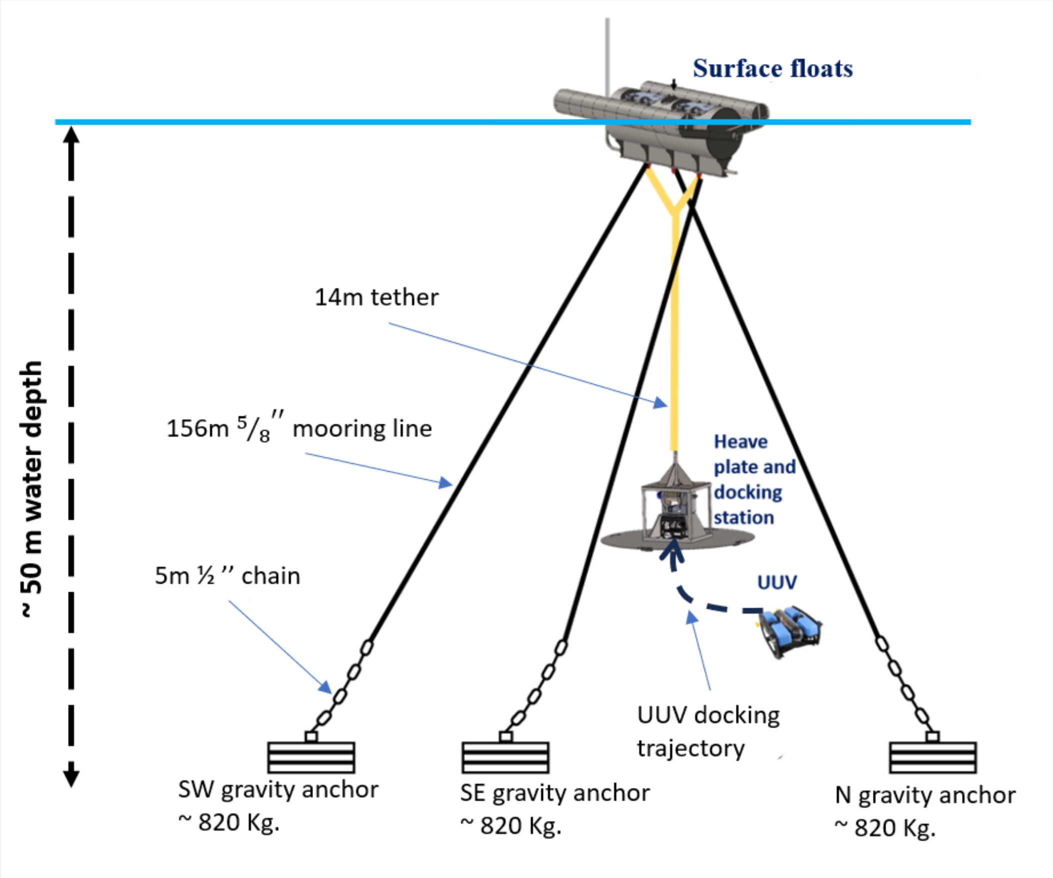


➢Spectral comparison of dock heave motion



Performance assessment of WEC-UUV systems

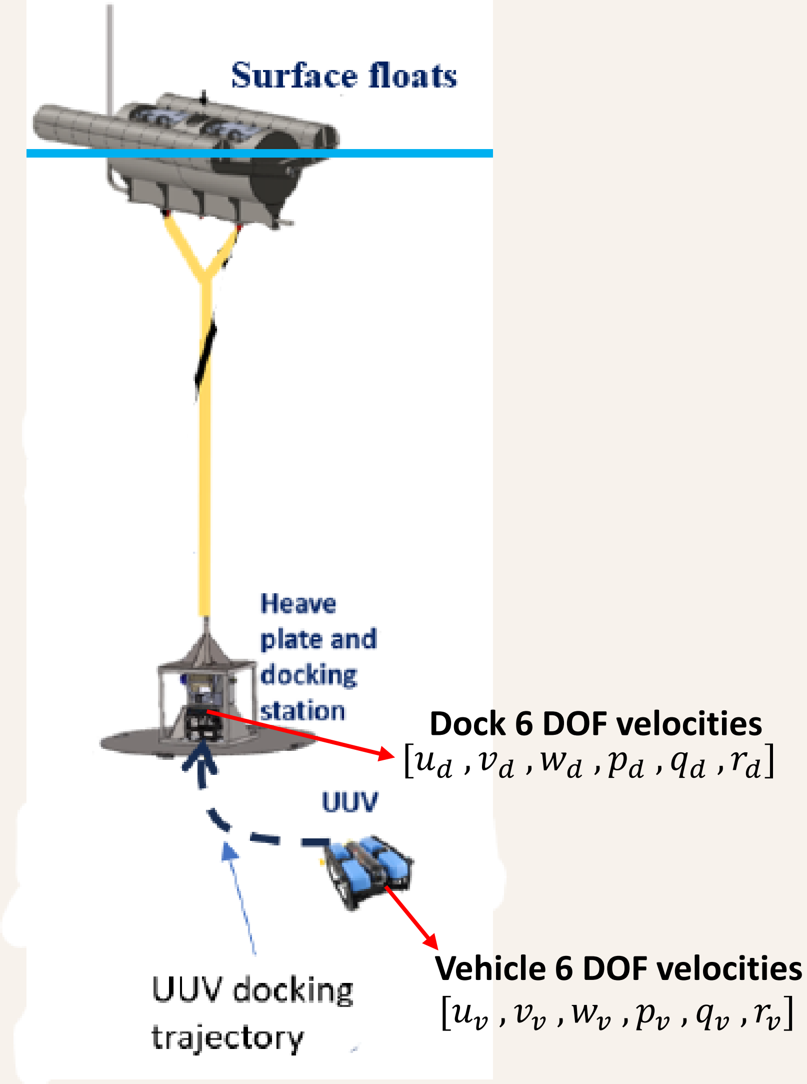
- **Performance metrics:**
    1. Docking feasibility
    2. Power and recharge frequency



UUV docking feasibility framework

Methodology:

- Neglect UUV control strategy, focus is on physical limits beyond which any control strategy is expected to fail.
- **Evaluate UUV motion limit** (analytically or experimentally)**.**
- **Check dock motion against UUV motion limit** (dock motion < UUV motion limits for feasible docking).



Power and recharge frequency

- Power generated by the WEC is stored in an onboard battery storage for UUV recharging.
- The net available in the battery storage is given by:

$$E_{net} = E_0 + E_{in} - E_{out}$$

The incoming energy from the WEC over a power transfer period T is modeled as:

$$E_{in} = \eta_{bat}\, T\, P_w;$$

- $\eta_{bat} = 0.8$ (battery charging efficiency Jenkins et al (2008))
- P_w is the simulated WEC average power output

The output energy consumed to charge UUVs is expressed as

$$E_{out} = \frac{E_{uuv}\ N_{uuv}\, N_{cyc}}{\eta_{uuv}}$$

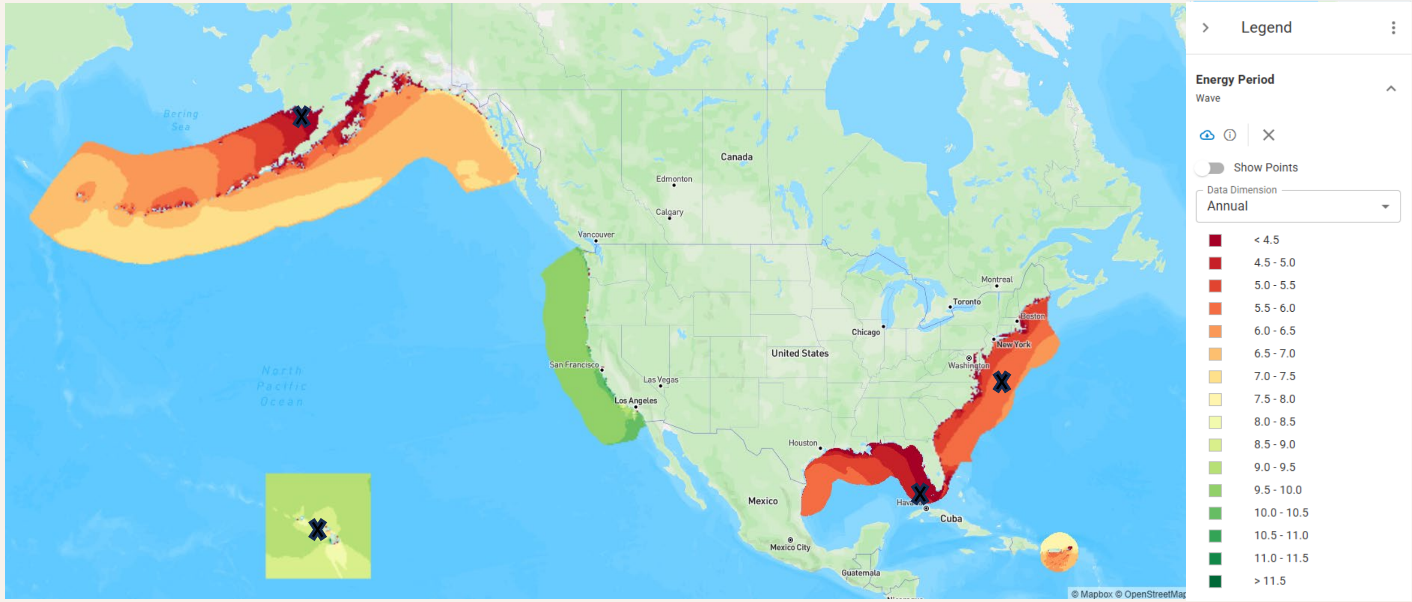
- E_{uuv} is the UUV battery capacity
- N_{uuv} is the number of UUV supported, N_{cyc} is the number recharging cycles
- $\eta_{uuv} = 0.5$ (UUV wireless charging efficiency Manalang et al (2022)

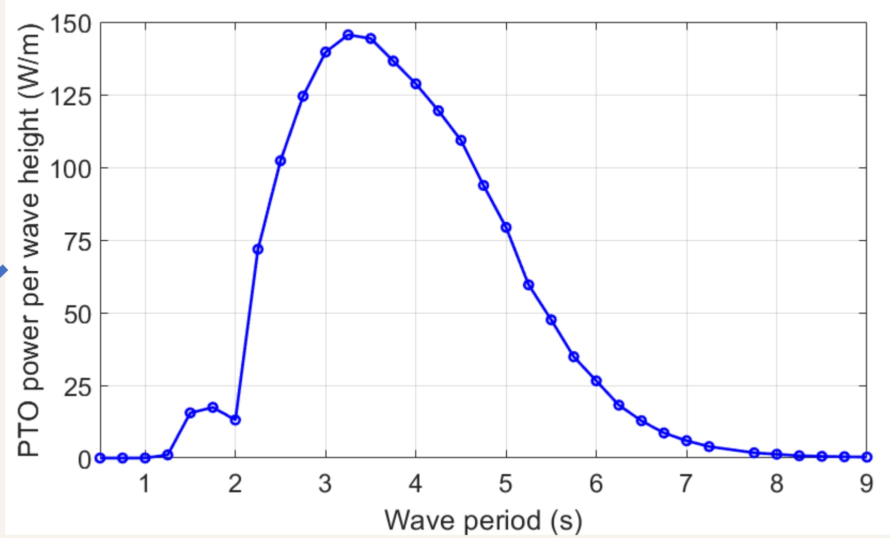
- The recharge frequency for a given sea states is the time it takes to store enough energy to fully recharge UUV:

$$T = \frac{1}{\eta_{bat}\ P_w}\left(\frac{E_{uuv}\ N_{uuv}\, N_{cyc}}{\eta_{uuv}} - E_0\right)$$

Performance assessment of TigerRAY WEC-UUV system

- Annual average energy period across US coastline [NREL Marine Energy Atlas]





- Power outputs in representative US coastal site

Location	Latitude	Longitude	H_s (m)	T_e (s)	WEC Mech. Power (W)	Electrical Power out of PTO Generator (W)	Electrical Power out of Power Electronics (W)
Alaska	58.37337	-158.0060	0.82	3.57	221.47	91.36	82.22
Atlantic – East Coast	43.28570	-70.1410	1.18	5.25	264.80	94.40	84.96
Atlantic – South Coast	24.74330	-80.4880	0.67	3.22	180.35	73.87	66.48
Hawaii	20.98887	-156.9027	1.20	6.04	160.38	58.72	52.85

TigerRAY Docking feasibility for BlueROV2 heavy configuration

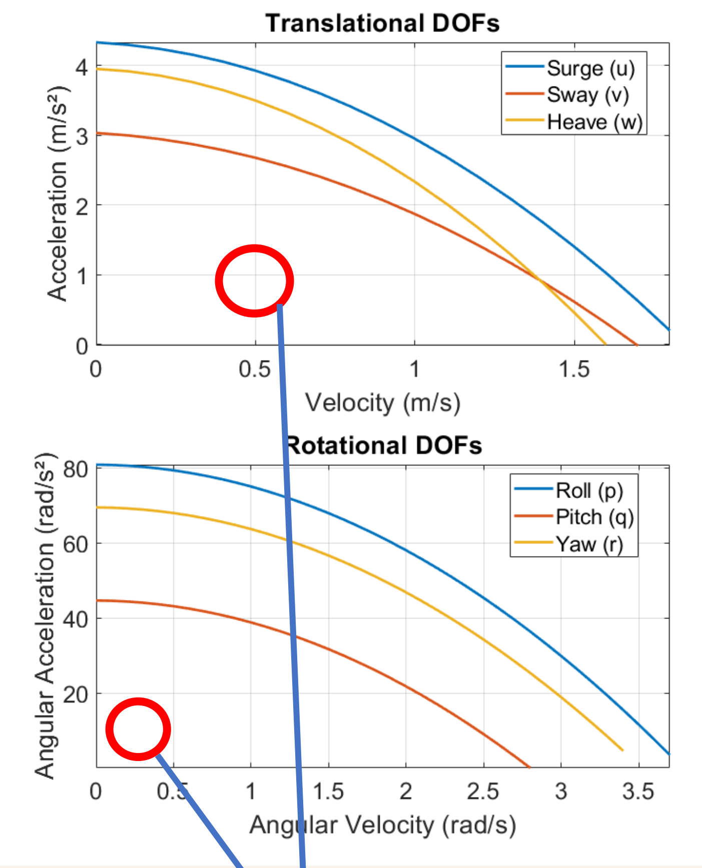
Simulated maximum dock motion amplitudes at representative sites

Location	Heave			Pitch			Roll		
	Disp. (m)	Vel. (m/s)	Accel. (m/s^2)	Disp. (deg)	Vel. (rad/s)	Accel. (rad/s^2)	Disp. (deg)	Vel. (rad/s)	Accel. (rad/s^2)
Alaska	0.40	0.51	1.18	1.95	0.51	0.34	4.01	0.17	0.55
Atlantic – East Coast	0.53	0.58	1.25	2.01	0.58	0.43	4.33	0.16	0.68
Atlantic – South Coast	0.31	0.44	1.00	1.74	0.44	0.30	3.29	0.17	0.53
Hawaii	0.60	0.62	1.15	2.39	0.62	0.41	4.07	0.15	0.63

Check dock motion against UUV motion limits

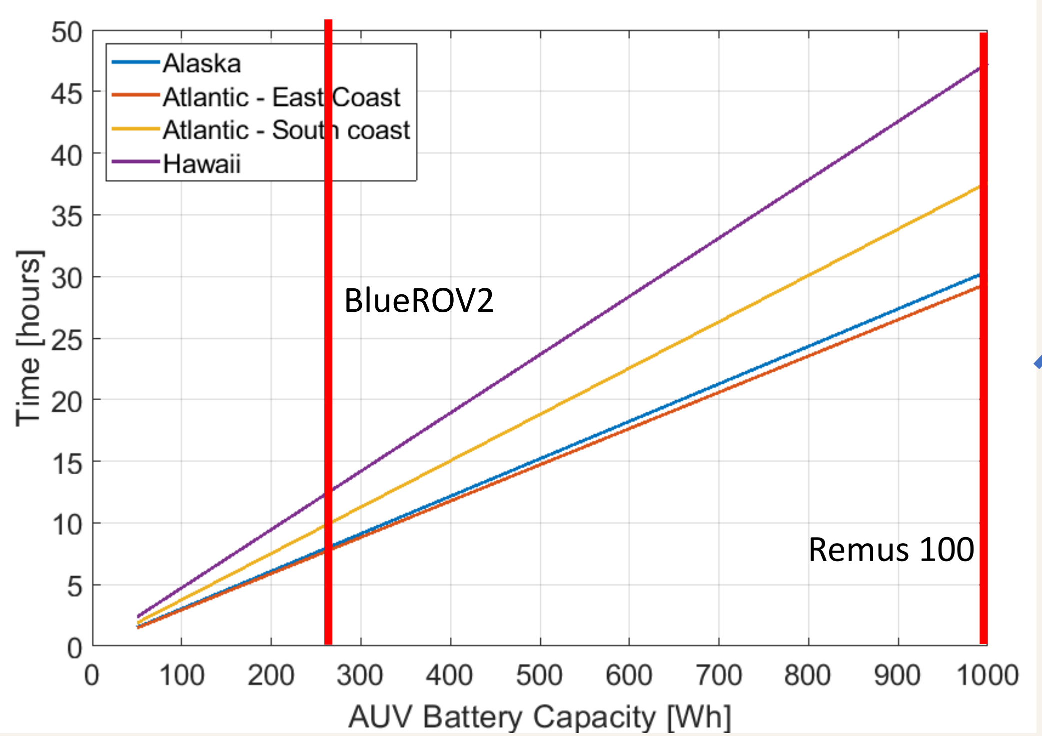
BlueROV2 heavy configuration

Analytical motion limits for BlueROV2



All dock motion is within feasible limit for docking BlueROV2 UUV

UUV recharging frequency at representative site



	BlueROV2 (266 Wh)	Remus 100 (1000 Wh)
Alaska	8.09 hours	30.40 hours
Atlantic – East Coast	7.83 hours	29.43 hours
Atlantic – South Coast	10 hours	37.60 hours
Hawaii	12.58 hours	47.30 hours

** Required time in hours it takes for TigerRAY to produce required energy to fully charge one AUV for one mission.

Summary

- Modeled and validated a field developed WEC-UUV system, TigerRAY.
- Developed frameworks for preliminary assessment of WEC-AUV system viability and feasibility.
- Demonstrated opportunity for TigerRAY utility in multiple low energy seas along the US coast.
- The recharging cycle assumes constant sea state; future work will account for overall sea state variability.
- TigerRAY dock could be adapted to enable autonomous UUV docking as a future work.
- Overall, the results are expected to serves as a stimulant for increased research in WEC-UUV technologies.

Acknowledgement

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Thank you!

Questions??

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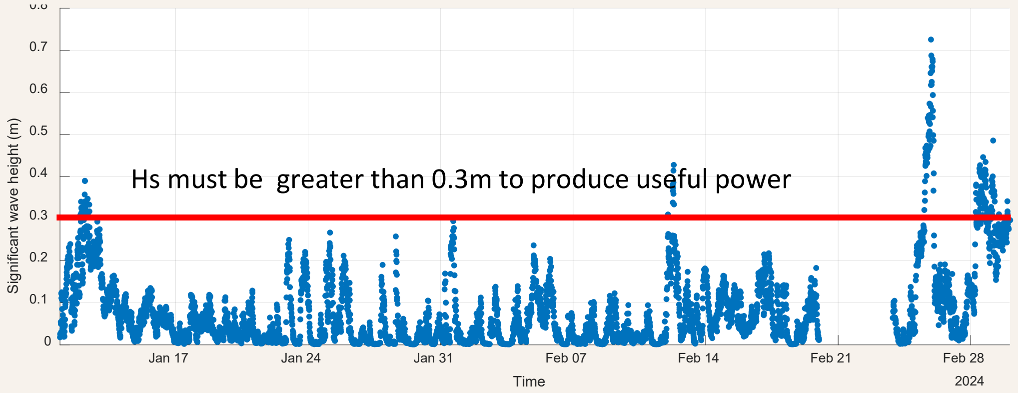
TigerRAY Field testing and demonstration

- **TigerRAY WEC-UUV system deployed and tested in Lake Washington in 2024 winter.**

- **Measurement of significant wave height in Lake Washington**



- **Power output statistics from overall field deployment**

Date	Time on	Avg power	Wave height
Jan 12	1:45	16 W	0.39 m
Jan 13	0:30	0 W	0.26 m
Jan 31	2:00	8 W	0.34 m
Feb 12	2:00	28 W	0.44 m
Feb 25	10:00	55 W	0.55 m (up to 0.7m)
Feb 28	6:00	24 W	0.5 m
Feb 29	1:00	3 W	0.31 m
Mar 2	2:00	22 W	0.43 m
Mar 3	6:00	10 W	0.36 m