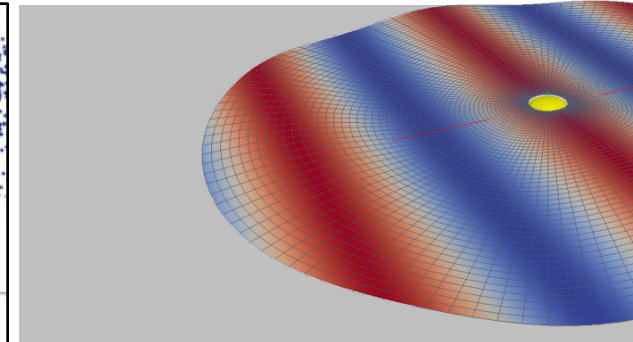
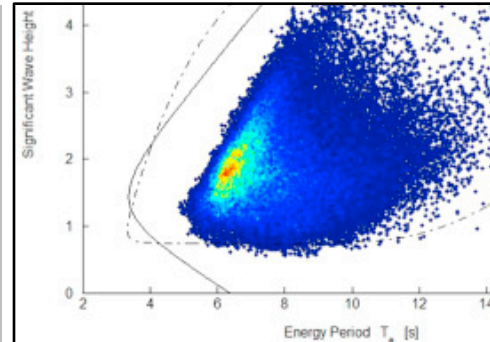
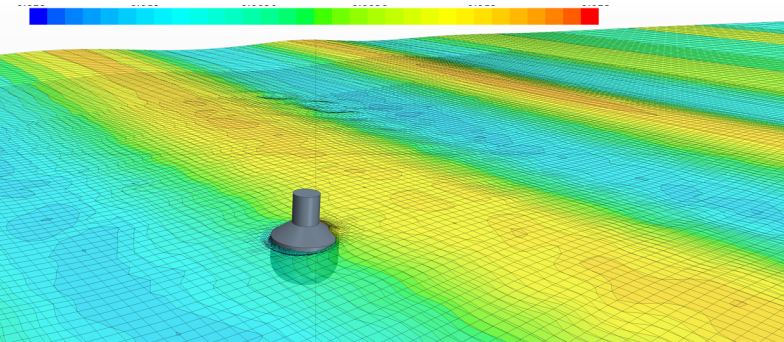


Exceptional service in the national interest



Design response modeling for wave energy converters

Ryan Coe

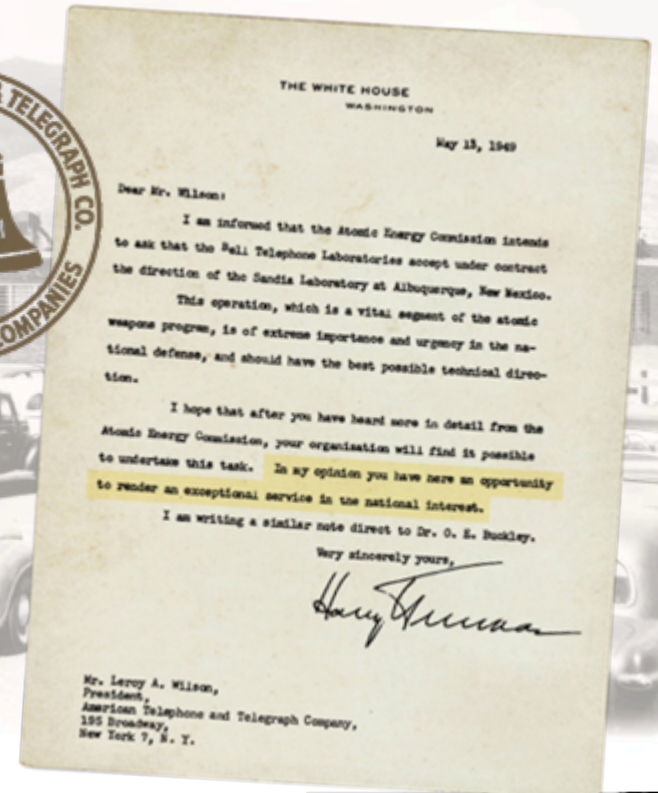
ryan.coe@sandia.gov

Sandia's History

Exceptional service in the national interest

- July 1945: Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949: Sandia Laboratory established

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.



Governance of Sandia Laboratories

Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–present
- Existing contract expires: April 30, 2017
- Government owned, contractor operated

Federally funded
research and development center



Albuquerque, NM



Sandia Sites

Albuquerque, New Mexico



Livermore, California



Kauai, Hawaii



*Waste Isolation Pilot Plant,
Carlsbad, New Mexico*

*Pantex Plant,
Amarillo, Texas*



*Tonopah,
Nevada*

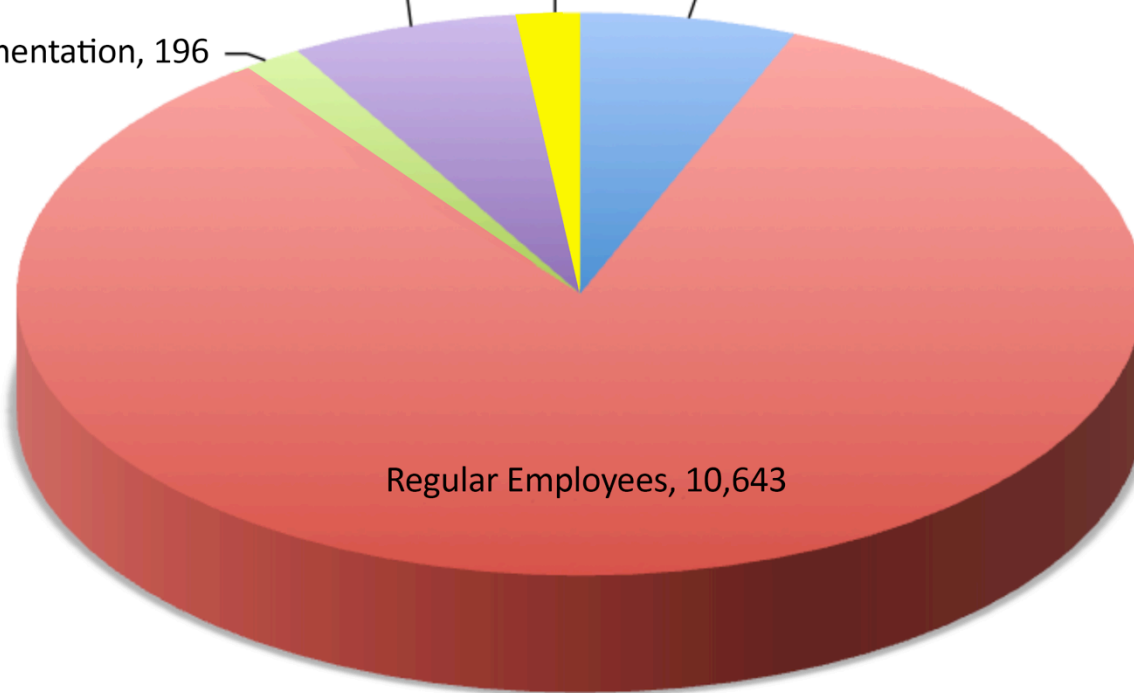
Our Workforce

- Total Sandia workforce: 12,611
- Regular employees: 10,643
- Advanced degrees: 5,898 (55%)

Data as of December 14, 2015

Temporary/Recurrent, 983 Other,* 133 PO Contractor, 656

Staff Augmentation, 196



- PO Contractor
- Regular Employees
- Staff Augmentation
- Temporary/Recurrent
- Other*

* Other badged personnel

History of Sandia Energy Programs

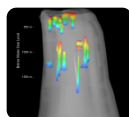


Sandia was born as a nuclear weapons engineering laboratory with deep science and engineering competencies



Energy crisis of the 1970s spawned the beginning of significant energy work

Strategic Petroleum Reserve -geologically characterizing salt domes to host oil storage caverns



DOE's Tech Transfer Initiative was established by Congress in 1991



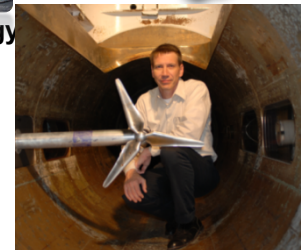
Advent Solar

Energy Policy Act of 2005

CRF & Cummins partner on their newest diesel engine



Joint BioEnergy Institute



Water Power Program

1950

1960

1970

1980

1990

2000

2007

2009

2010

Our core NW competencies enabled us to take on additional large national security challenges



Vertical-axis Wind Turbine

NRC cask certification studies & core melt studies



Solar Tower opens



Combustion Research Facility (CRF) opens to researchers



Power grid reliability study



SunCatcher™ partnership with Stirling Energy Systems

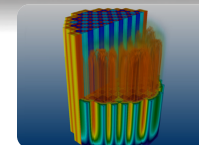


Distributed Energy Technology Laboratory (DETL) to integrate emerging energy technologies into new and existing electricity infrastructures



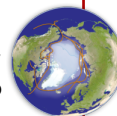
Sunshine to Petrol Pilot Test

Large-scale pool fire tests of liquefied natural gas (LNG) on water



Consortium for Advanced Simulation of Light Water Reactors (CASL)

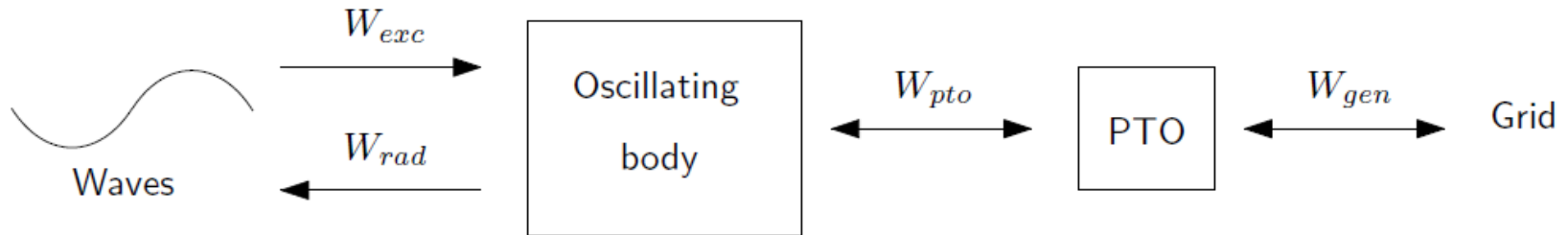
Climate study uncertainties to economies



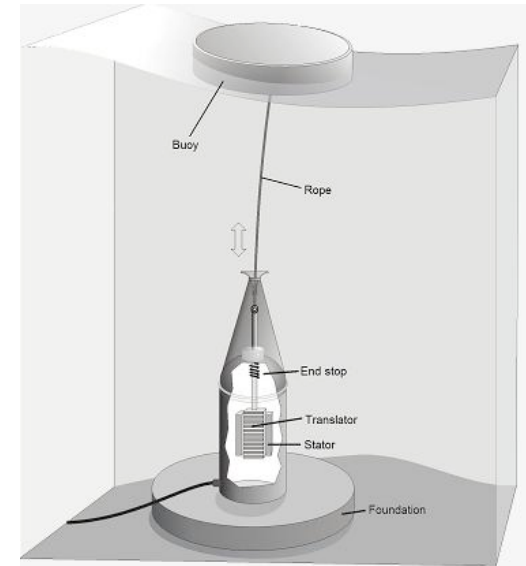
Combustion Research Computation and Visualization (CRCV) opens

WHAT IS A WAVE ENERGY CONVERTER?

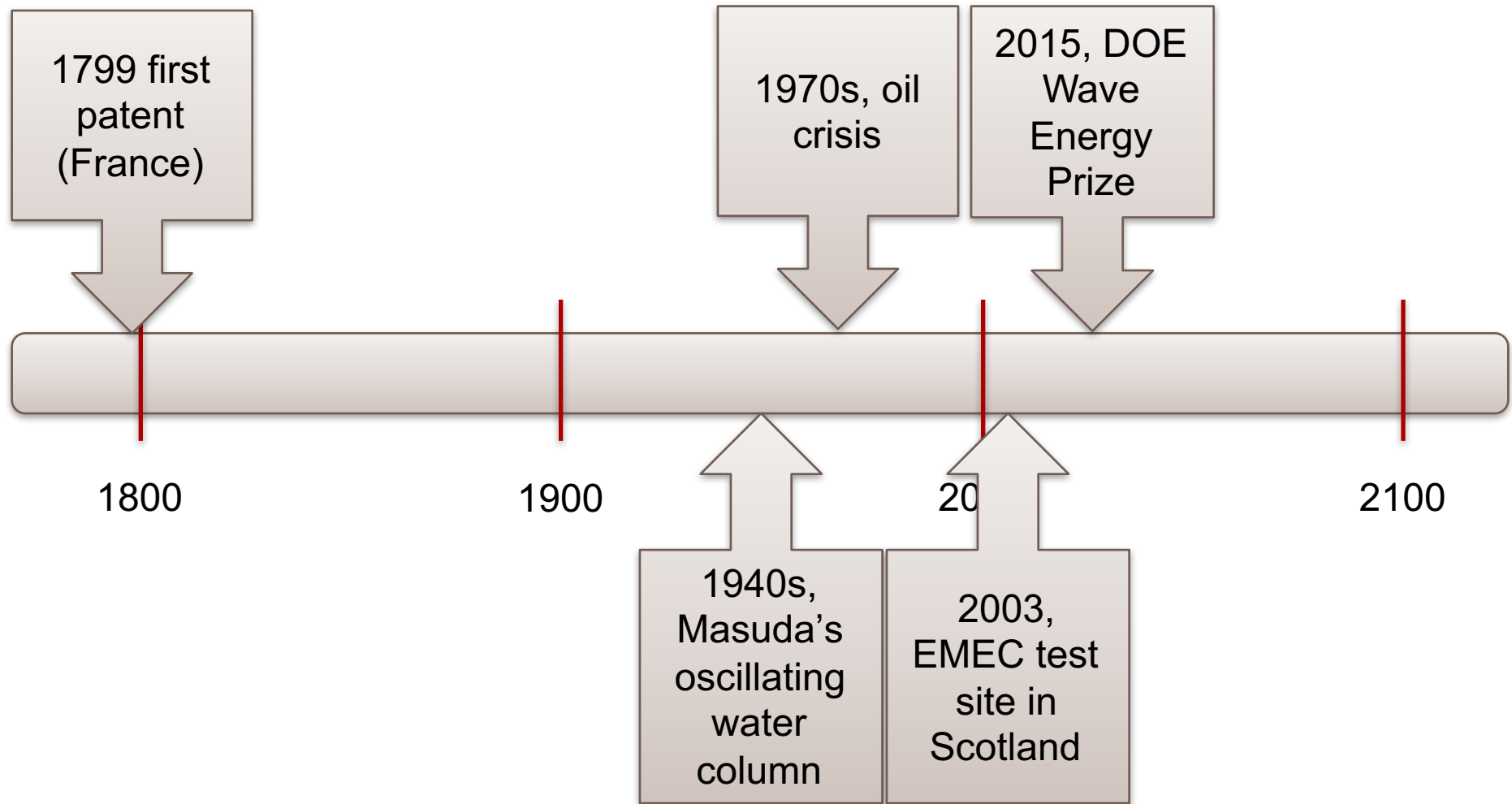
What is a Wave Energy Converter?



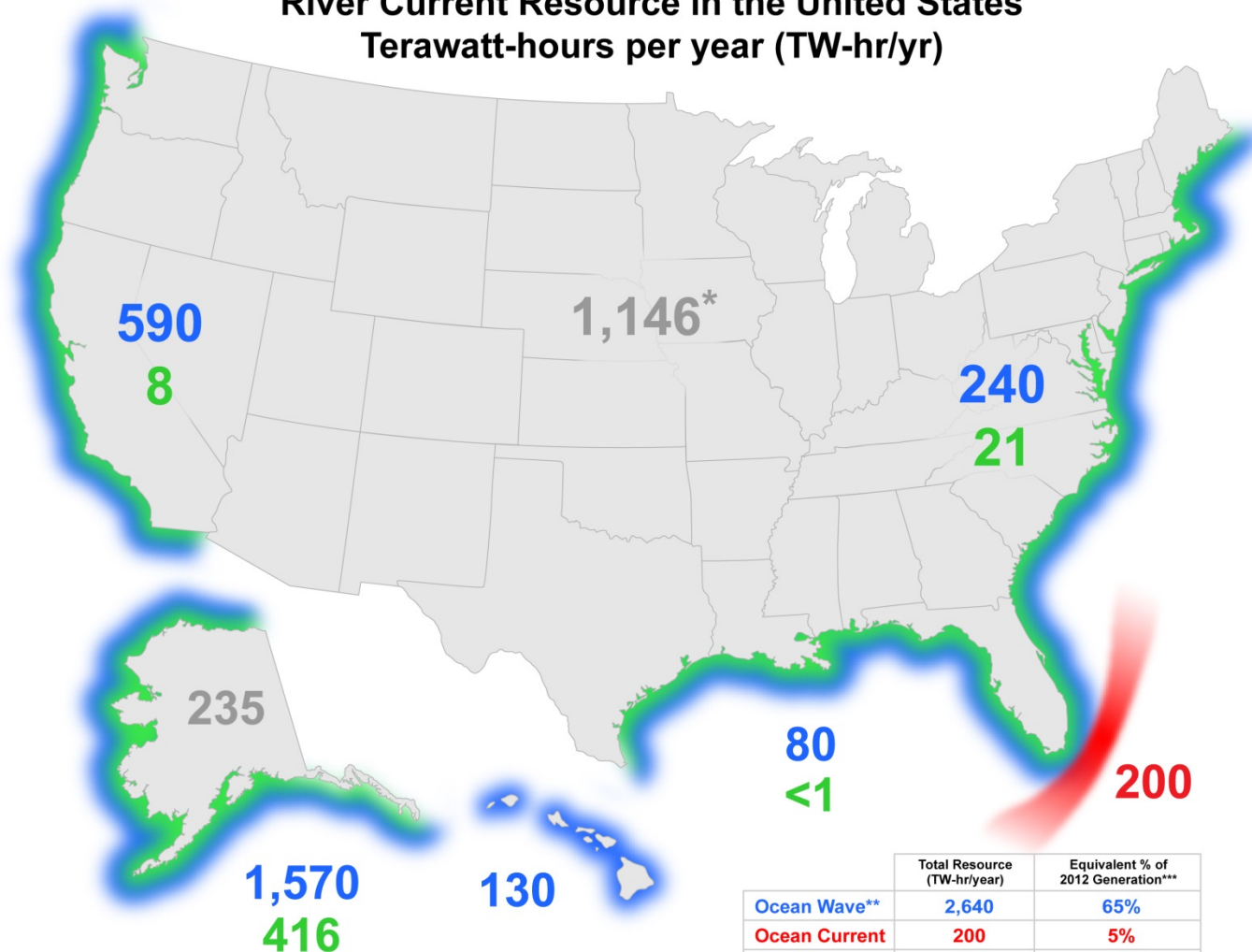
Energy transfer through an oscillating body wave energy converter



A (brief) history of wave energy



The Ocean Wave, Ocean Current, Tidal Current, and River Current Resource in the United States Terawatt-hours per year (TW-hr/yr)



	Total Resource (TW-hr/year)	Equivalent % of 2012 Generation***
Ocean Wave**	2,640	65%
Ocean Current	200	5%
Tidal Current	445	11%
River Current	1,381	34%

Ocean Wave: P. Jacobson, G. Hagerman, and G. Scott, "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011.

Ocean Current: K. Haas, H. Fritz, S. French, and V. Neary, "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013.

Tidal Current: K. Haas, H. Fritz, S. French, B. Smith, and V. Neary, "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011.

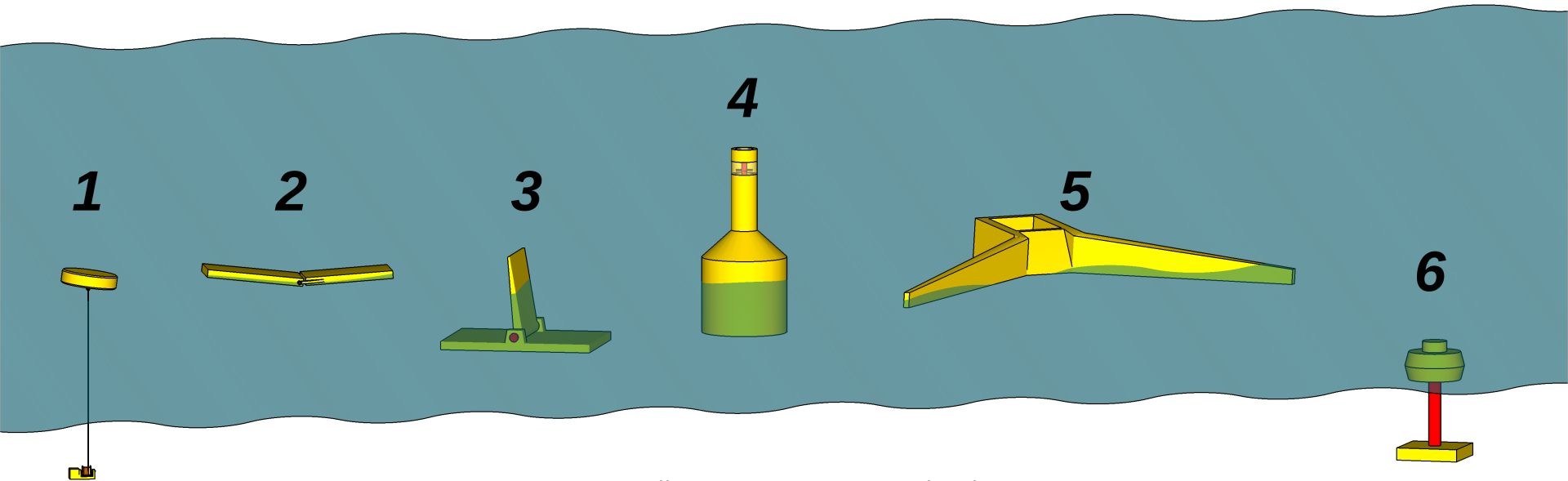
River Current: T. Ravens, K. Cunningham, and G. Scott, "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012.

*Resource distributed throughout the river systems in the United States.

**Resource data for the 200-m depth contour.

***The size of the resource with respect to total U.S. electricity generation in 2012, which was 4,054 TW-hr (U.S. Energy Information Administration, "Electric Power Monthly," May 2013).

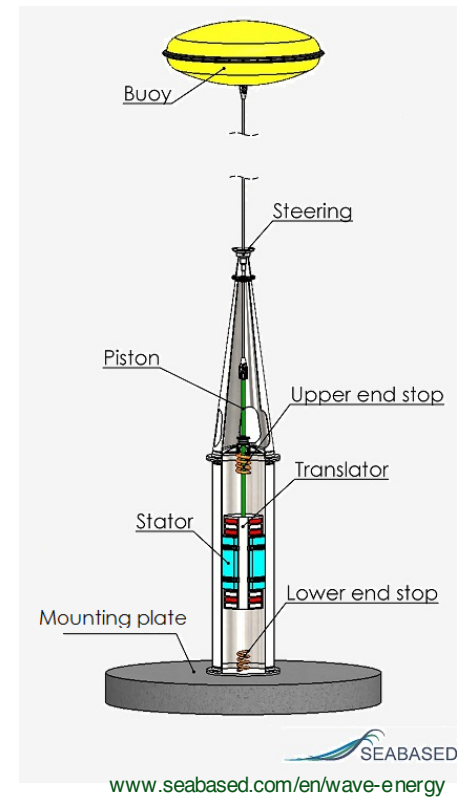
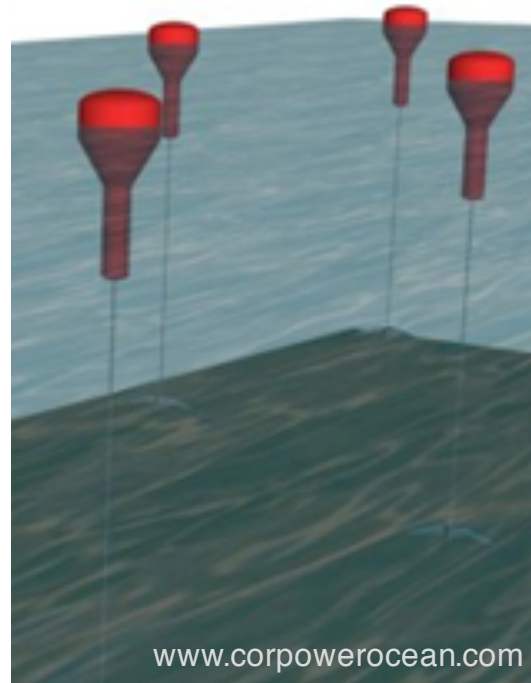
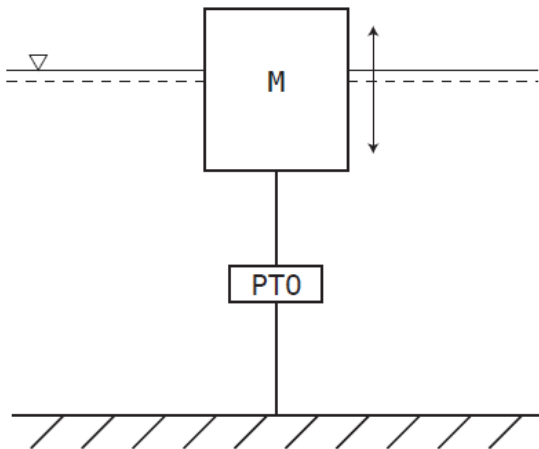
Concepts



https://commons.wikimedia.org/wiki/File:Wave_energy_concepts_overview_numbered.png

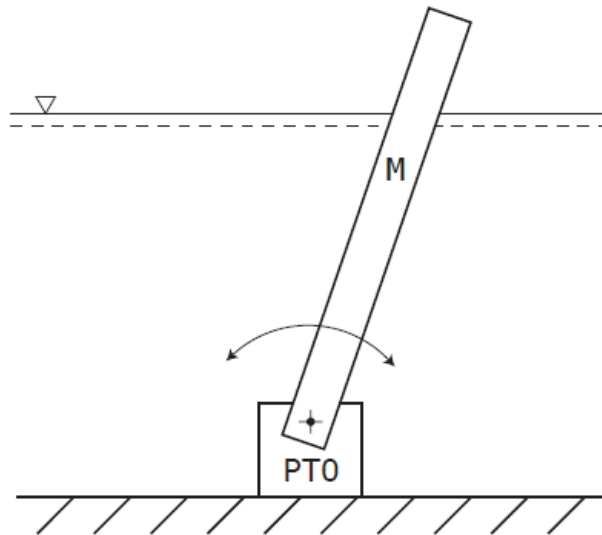
Concepts

Seabed referenced heaving wave energy converter



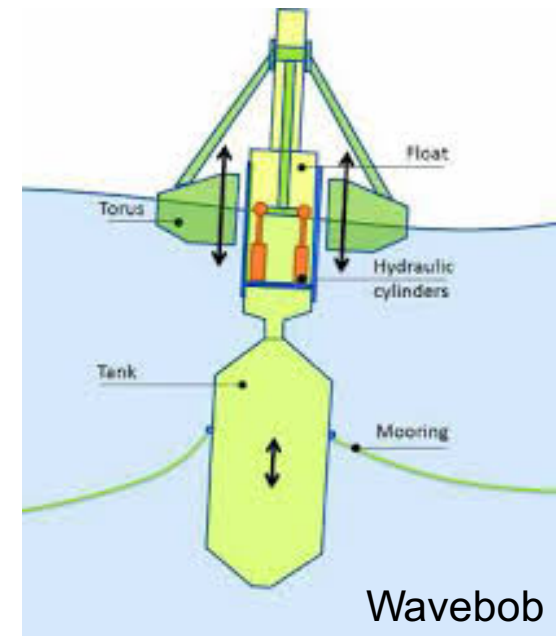
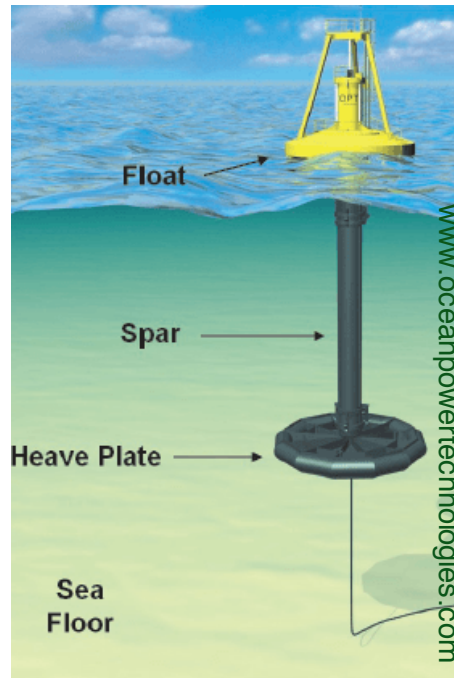
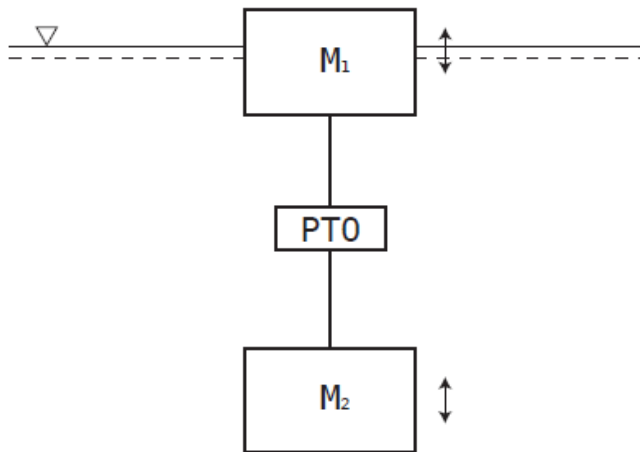
Concepts

Seabed referenced pitching-surfing wave energy converter



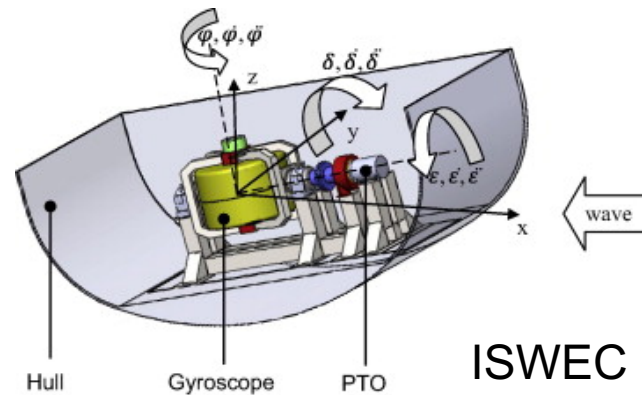
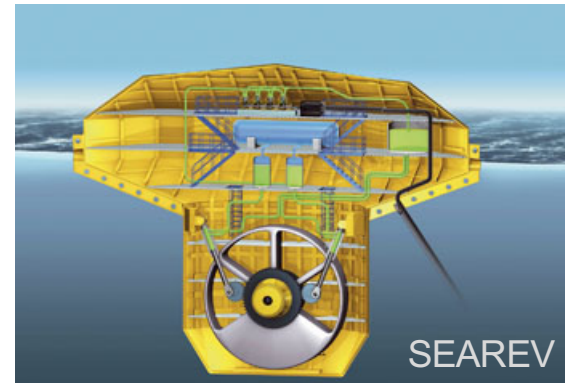
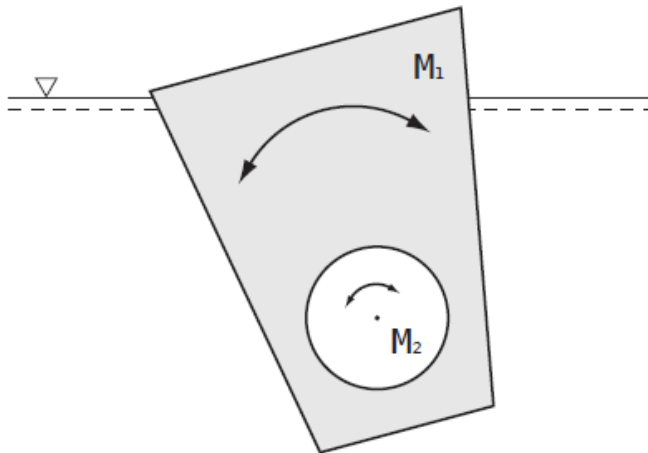
Concepts

Self-reacting wave energy converter



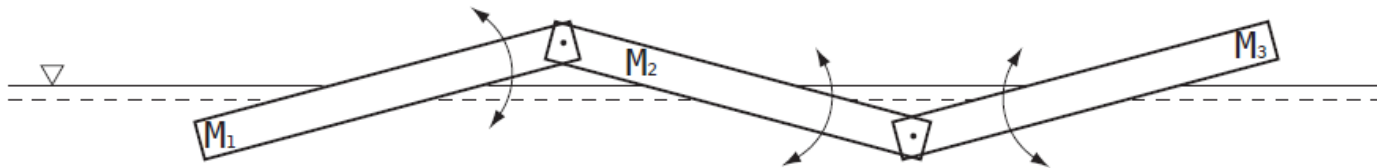
Concepts

Self-reacting wave energy converter with internal mass



Concepts

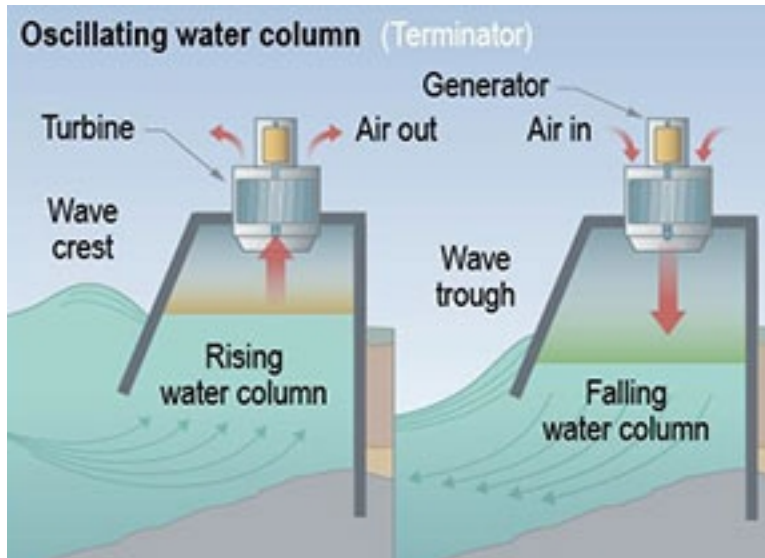
Self-reacting pitching wave energy converter (a.k.a. attenuators)



Pelamis wave energy

Concepts

Oscillating water column (OWC)



ENERGY TRANSPORTED BY WAVES

Wave Energy Transport

Most of the energy within a wave is contained near the surface.



wave energy devices are designed to stay near the water surface to maximize the energy available for capture

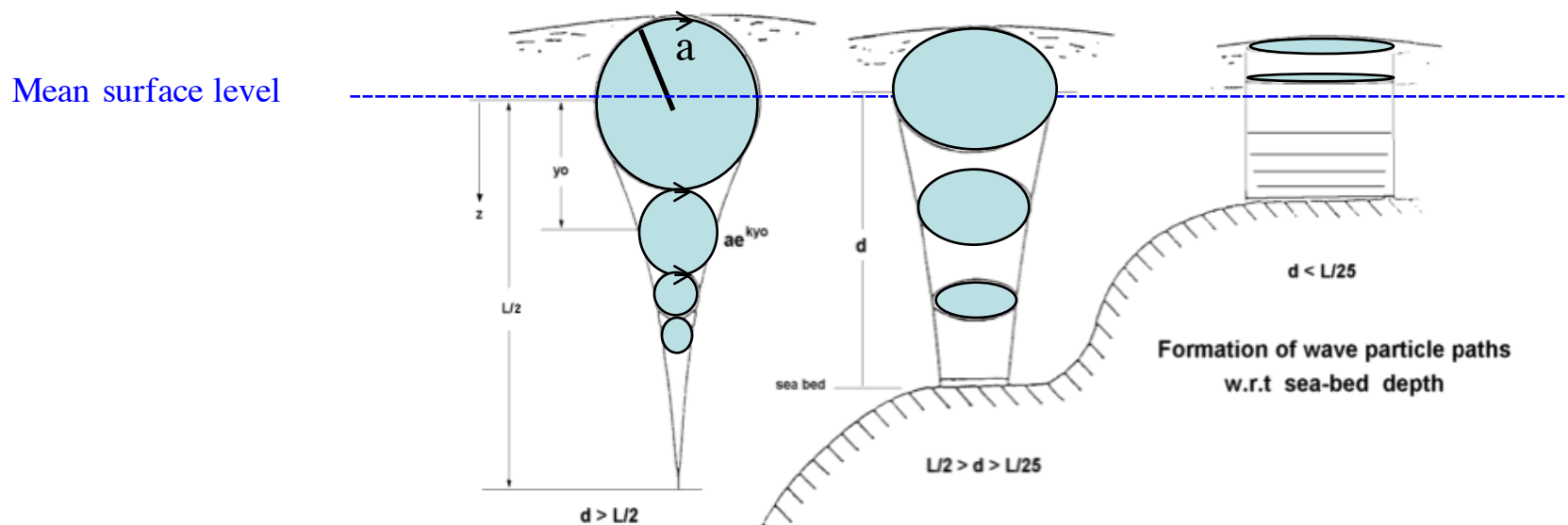


Fig. orbital motion of the water particles

Wave Energy Transport

Plane wave

$$J \approx \frac{\rho g |A|^2}{2} \cdot \frac{g}{2\omega} = \frac{\rho g^2 H^2}{16\omega} = \frac{\rho g^2 T H^2}{32\pi} \left[\frac{W}{m} \right]$$

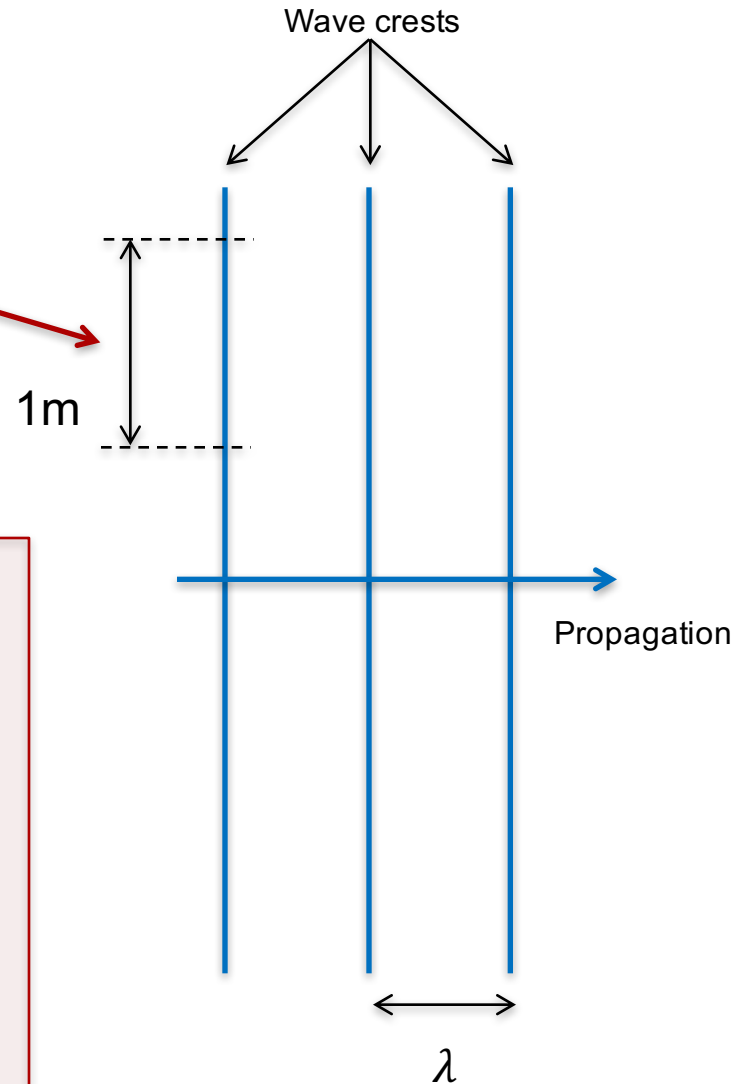
J = wave energy flux

Water waves are dispersive

$$\omega^2 = g k \tanh(k h)$$

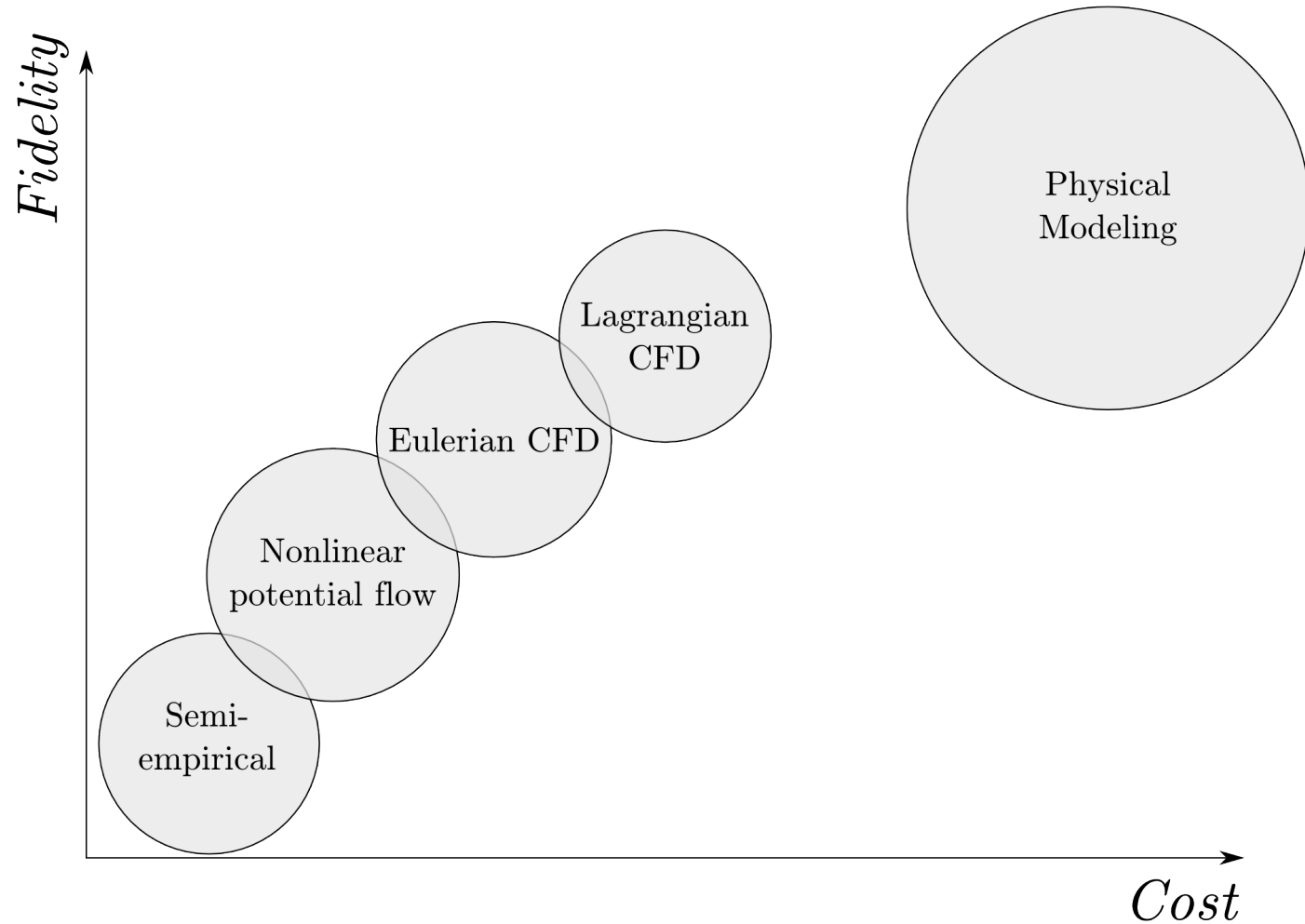
$$k = \frac{2\pi}{\lambda}$$

$$\omega = \frac{2\pi}{T}$$



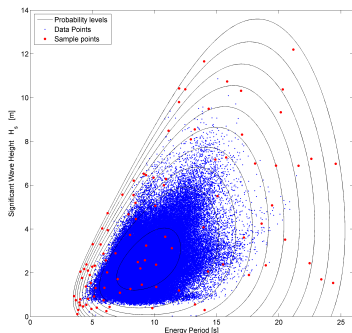
WEC DESIGN RESPONSE MODELING

Multi-fidelity analysis

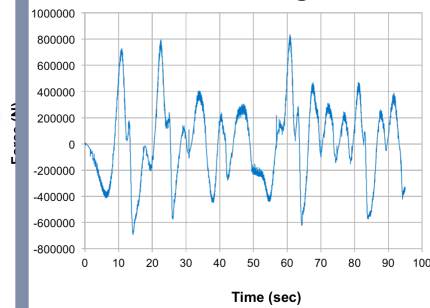


Multi-fidelity analysis

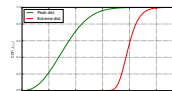
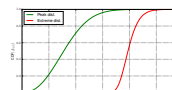
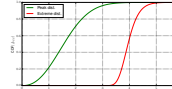
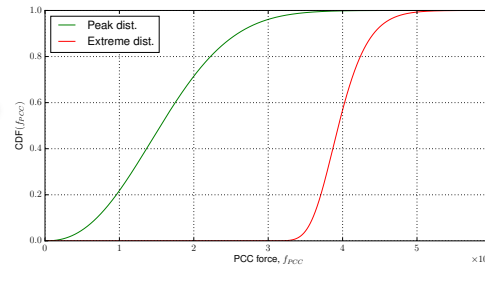
Environmental characterization



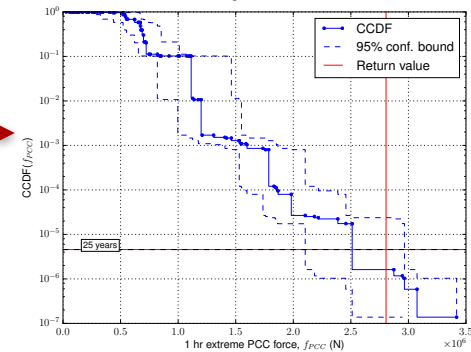
Mid-fidelity modeling



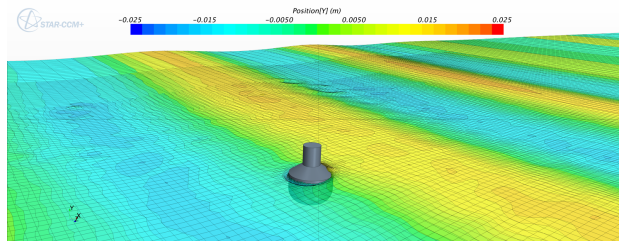
Short-term response



Long-term response



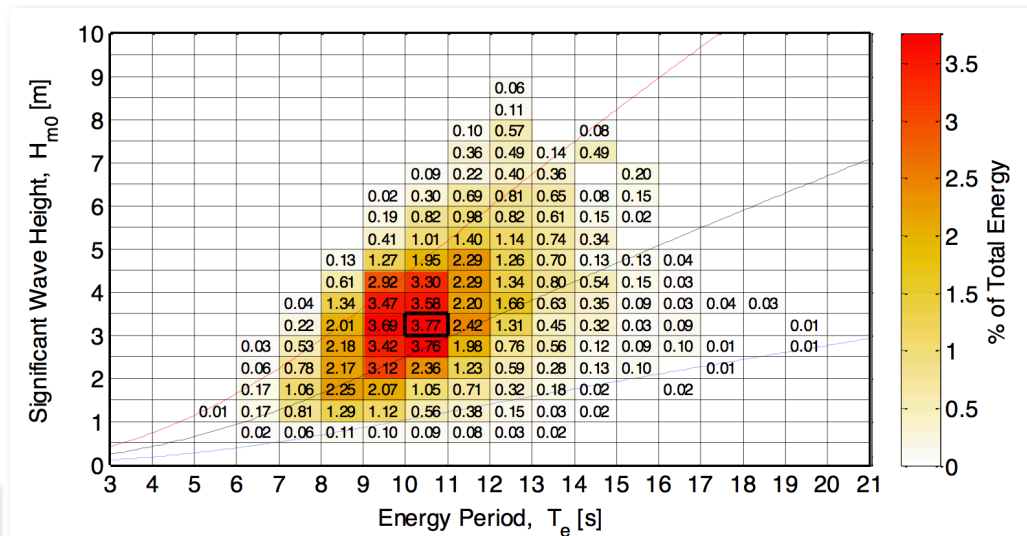
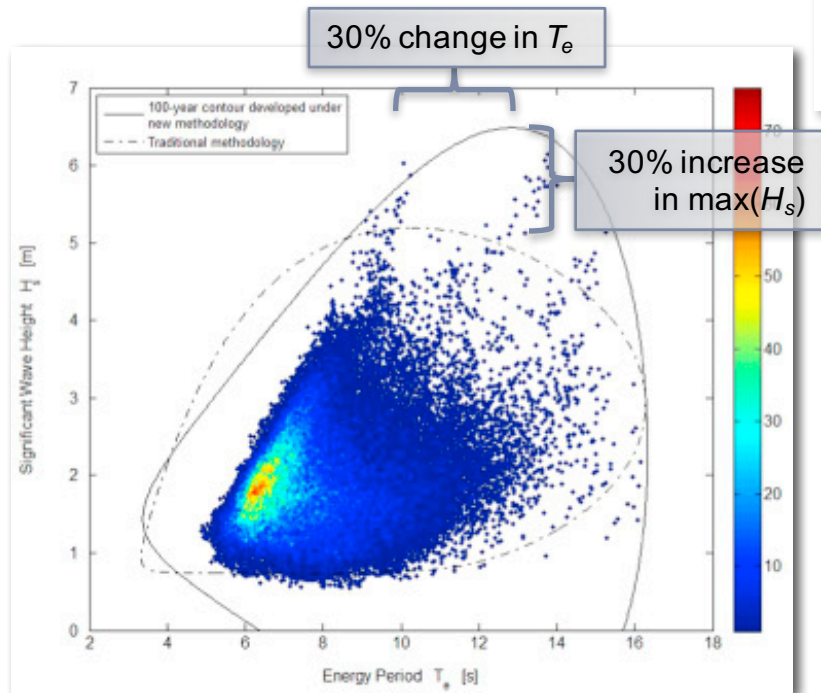
High-fidelity modeling



Design load
conditions

Environmental characterization

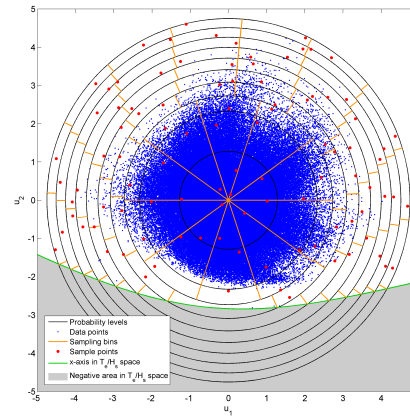
US WEC test site met-ocean catalogue



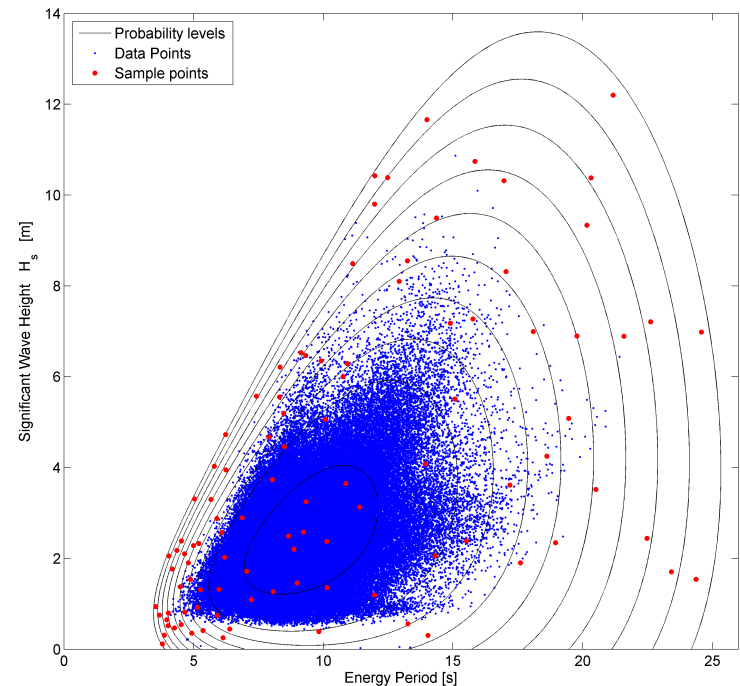
Improved inverse first-order reliability method (iFORM) better approximates extreme contours

Environmental Conditions

- Inverse first-order reliability method (I-FORM)
- Sampling technique

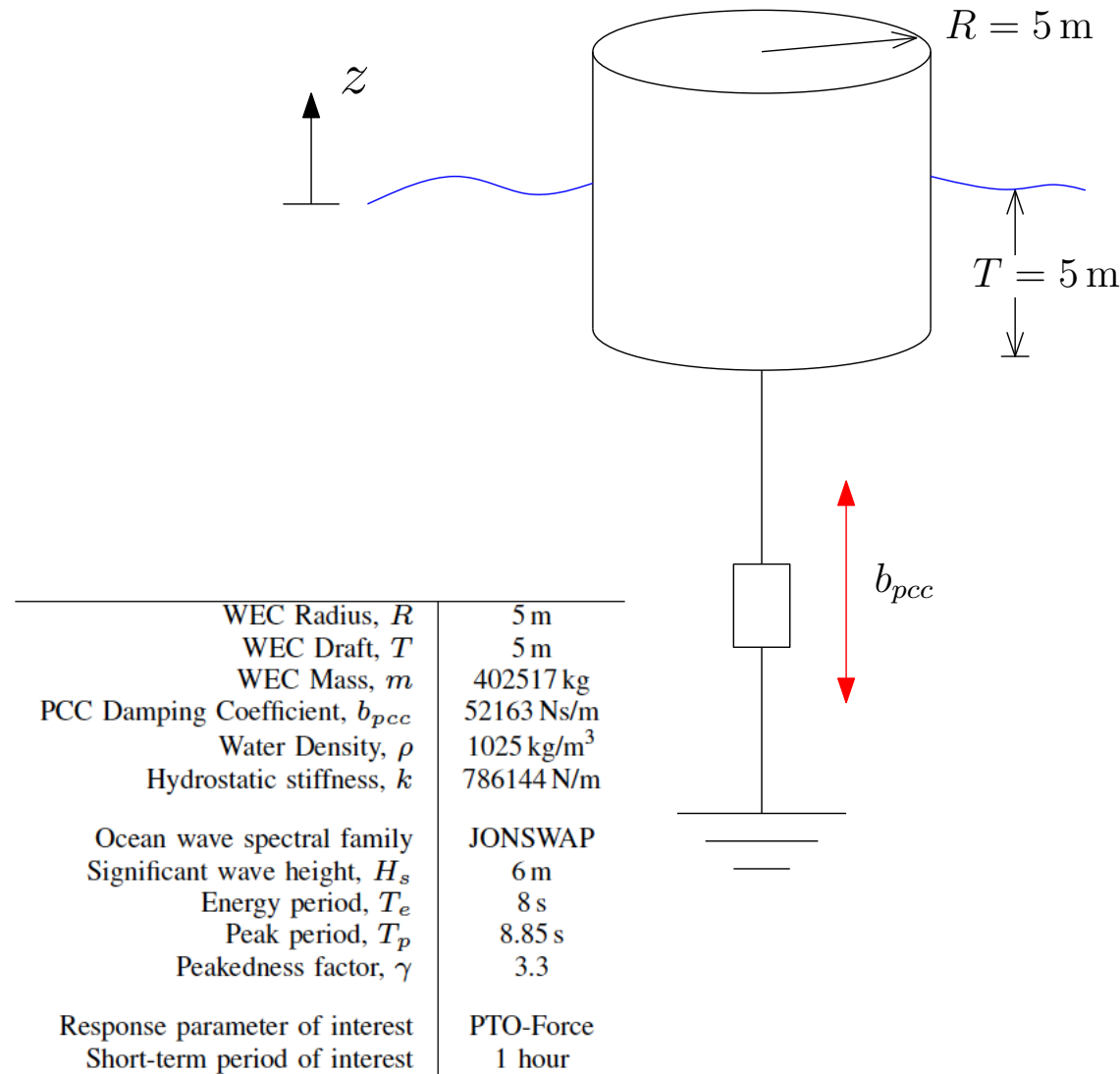


- Each ring represents an order of magnitude, log-uniform sampling to have same number of points within each ring in standard normal space
- Uniform sampling within each; limited to the positive input space
- Each point represents an area of the input space weighted by a probability of occurrence



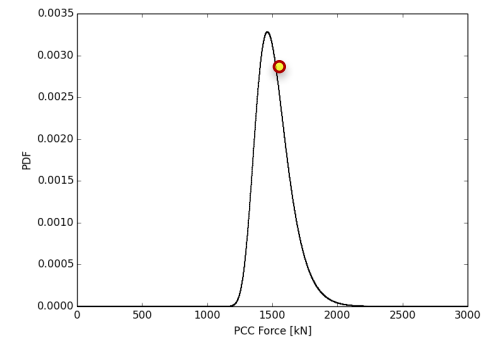
Case Study

- WEC Geometry
 - Heaving Cylinder
 - Optimized linear damping coefficient
 - Nemoh BEM coefficients
- Wave Environment
 - Irregular
 - JONSWAP spectrum
- Extreme Condition
 - Expected 1-hour extreme PCC force
- Hydrodynamic Model
 - Frequency domain



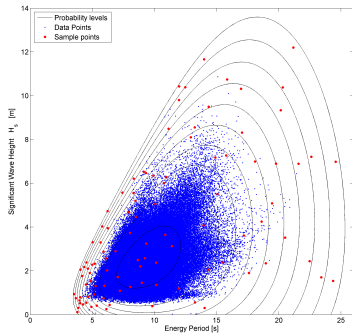
Extreme Event

- “If a device is in sea-state X for Y amount of time, what will be the largest Z observed”
 - X = environmental condition (JONSWAP, $H_s=6\text{m}$, $T_e=8\text{s}$)
 - Y = short-term period (1 hour)
 - Z = response parameter of interest (PCC force)
- Extreme event = probability distribution
- Characteristic extreme value = representative scalar
 - Expected value
 - r^{th} percentile
- Expected 1-hour extreme PCC force

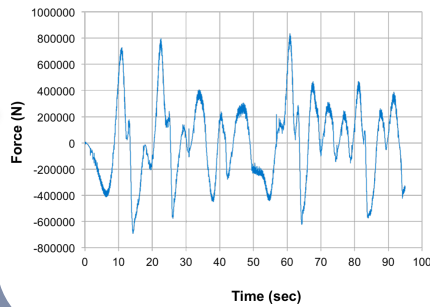


Multi-fidelity analysis

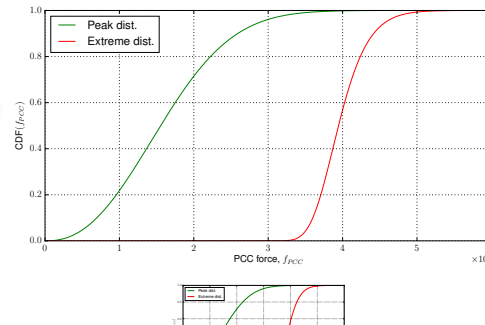
Environmental
characterization



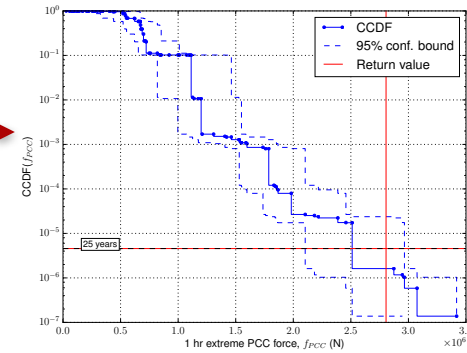
Mid-fidelity
modeling



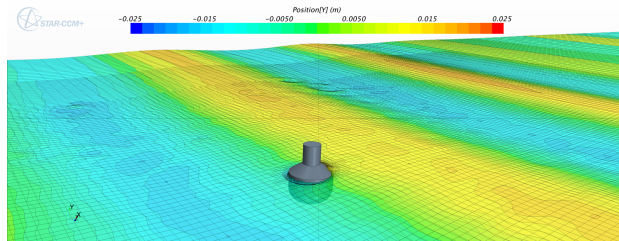
Short-term
response



Long-term
response



High-fidelity
modeling

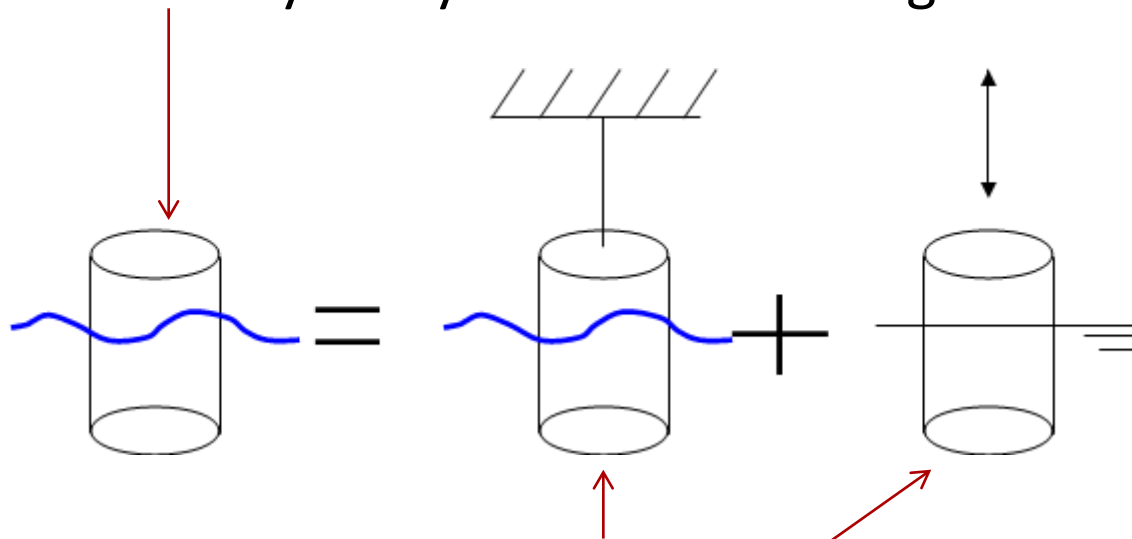


Design load
conditions

Mid-fidelity modeling

Assumption: Linear hydrodynamic interactions
between water and oscillating body

Total hydrodynamic force acting on the body:

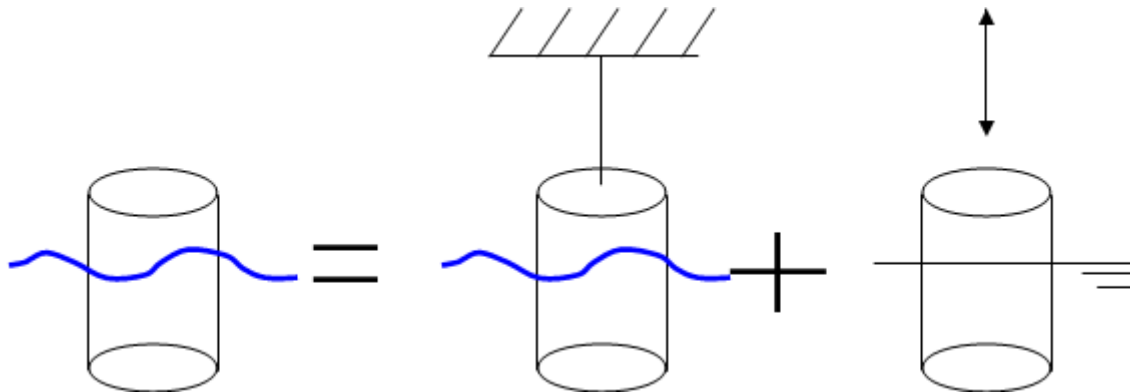


- Excitation (Incoming waves)
- Radiation (Body velocity) + hydrostatic (Body position)

Linearity $\rightarrow$ Superposition

Mid-fidelity modeling

Assumption: Linear hydrodynamic interactions
between water and oscillating body



$$F_{tot} = f(x, v, \eta) \approx Sx + Z_r v + H_e \eta$$

S : hydrostatic restoring coefficient

Z_r : radiation impedance

H_e : wave excitation coefficients

x : position

v : velocity

η : wave elevation

Mid-fidelity modeling

Particular type of oscillator

(frequency dependent damping, but linear)

From Newton's second law:

$$\sum F = Ma$$

$$\left(j\omega M + Z_r(\omega) + B - j\frac{S}{w} \right) \hat{v} = \hat{F}_e$$

$$\hat{F}_e = H_e \hat{\zeta}$$

$$\left(j\omega (M + M_a) + R(\omega) + B - j\frac{S}{w} \right) \hat{v} = \hat{F}_e$$

$$Z_r(\omega) = R(\omega) + j\omega M_a(\omega)$$

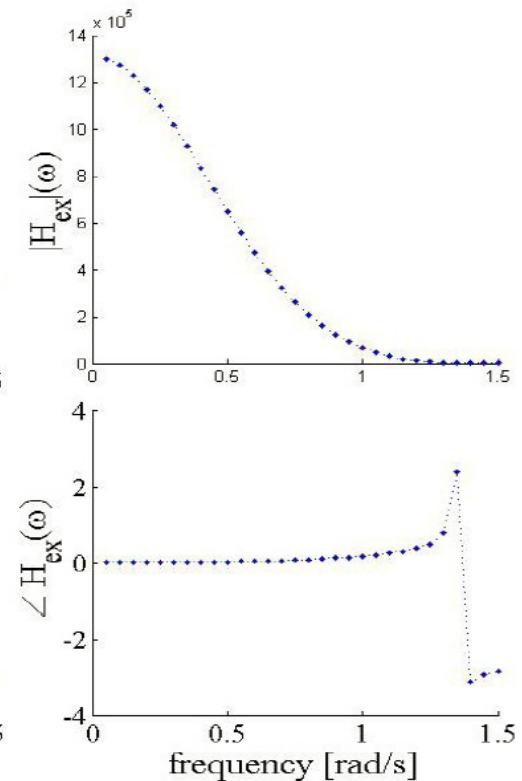
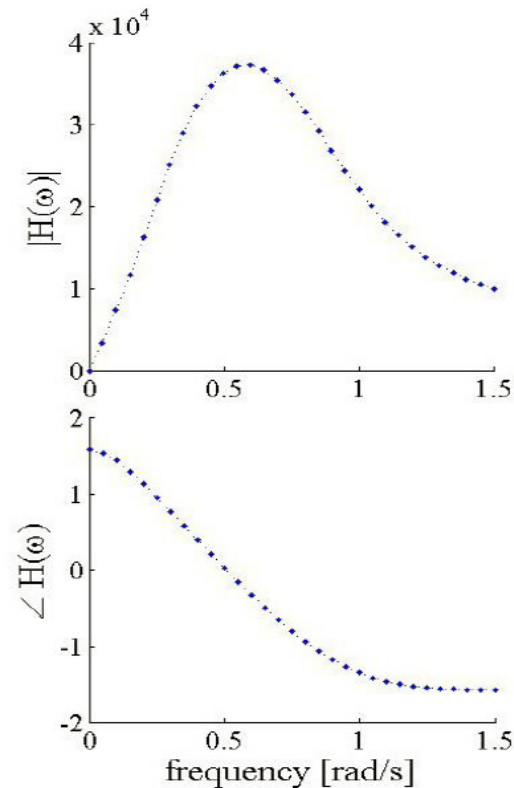
$R(\omega)$ = Radiation resistance

$M_a(\omega)$ = Added mass

Mid-fidelity modeling

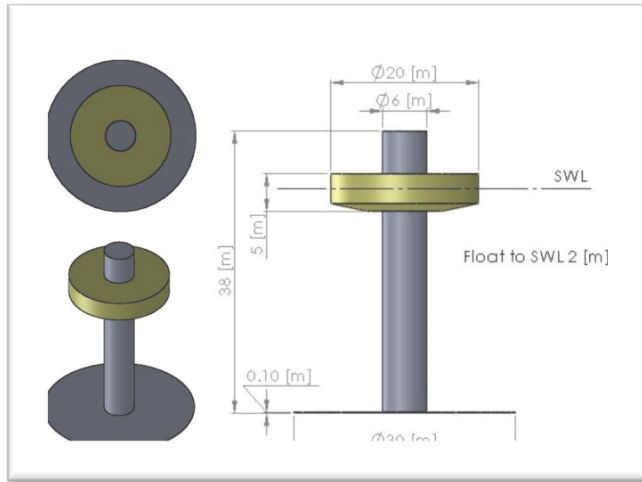
How do we get the hydrodynamic coefficients?

- Hydrodynamic software based on linear potential theory (WAMIT, NEMOH, AQUA...)
- Experiments

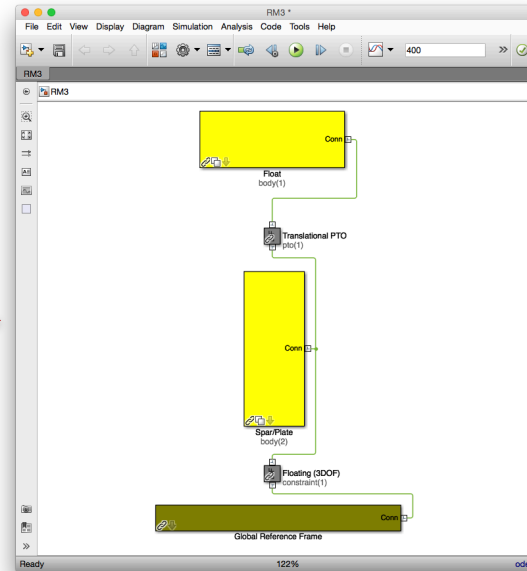


Mid-fidelity modeling

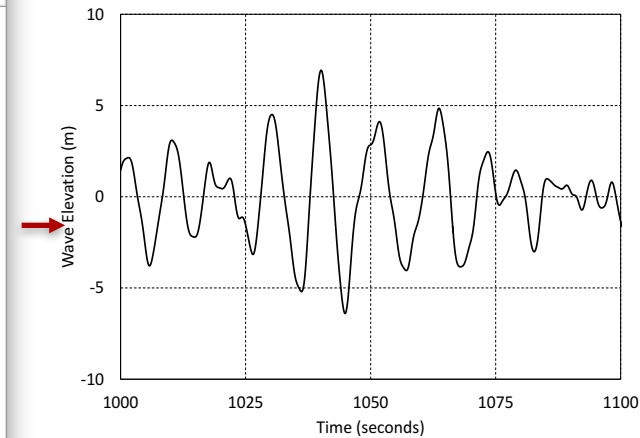
Schematic representation
of the Reference Model 3
(RM3) point absorber:



WEC-Sim block
diagram model of
RM3 device.



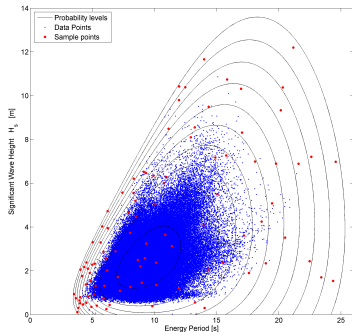
Time-domain
response



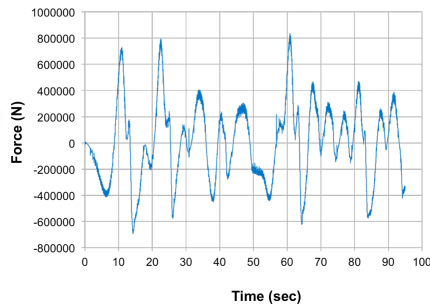
$$[\mathbf{M}_{RB} + \mathbf{A}_{\infty}] \ddot{\xi} + \int_0^t \mathbf{K}_r(t - \lambda) \dot{\xi}(\lambda) d\lambda + \mathbf{J}(\vartheta)^{-1} (\mathbf{G} + \mathbf{C}_m) \eta + \tau_v = \tau_e + \tau_u.$$

Multi-fidelity analysis

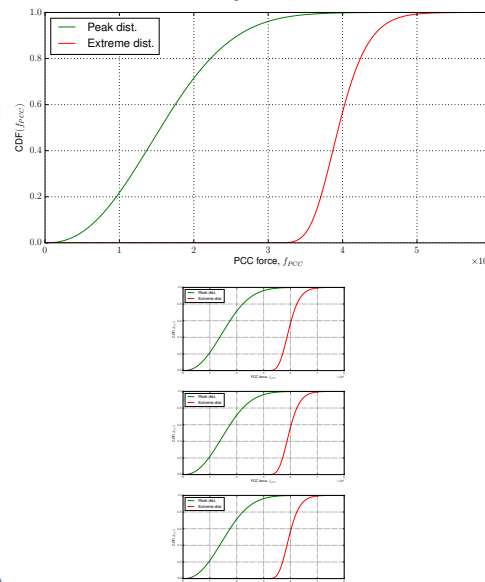
Environmental
characterization



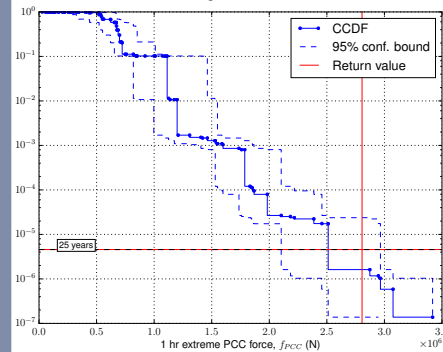
Mid-fidelity
modeling



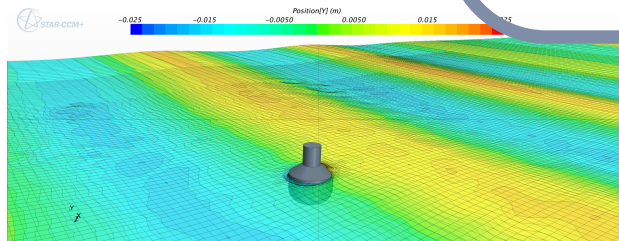
Short-term
response



Long-term
response



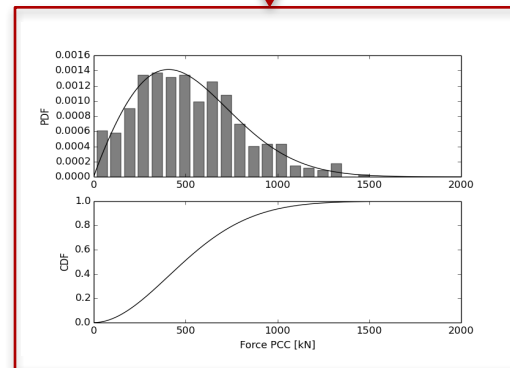
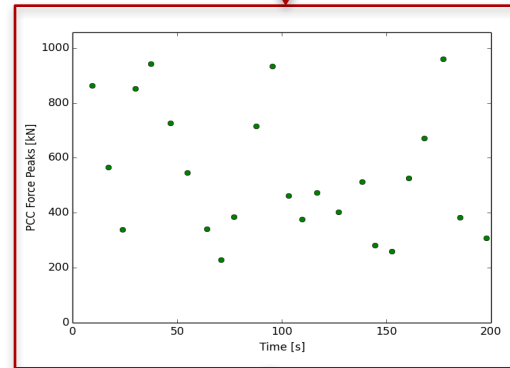
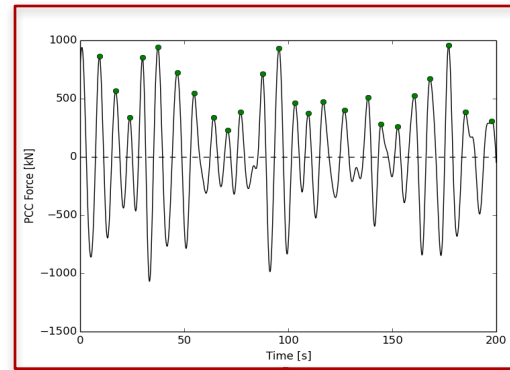
High-fidelity
modeling



Design load
conditions

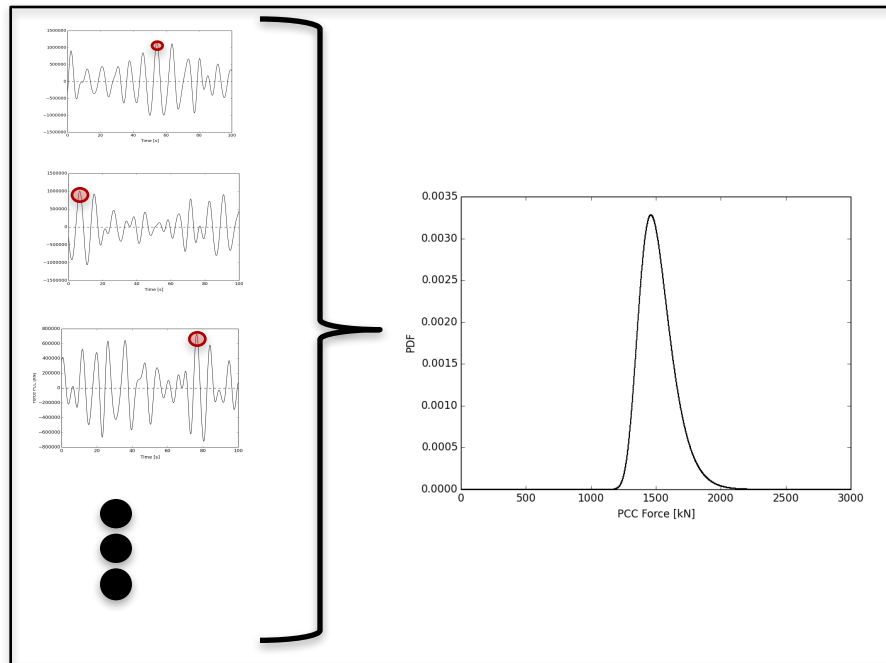
Methods

- Time-history
- Global Peaks
 - Independent random variable
- Methods
 - Block Maxima
 - All Peaks Weibull
 - Weibull Tail Fit
 - Peaks Over Threshold
- Data Relevance vs. Amount of Data



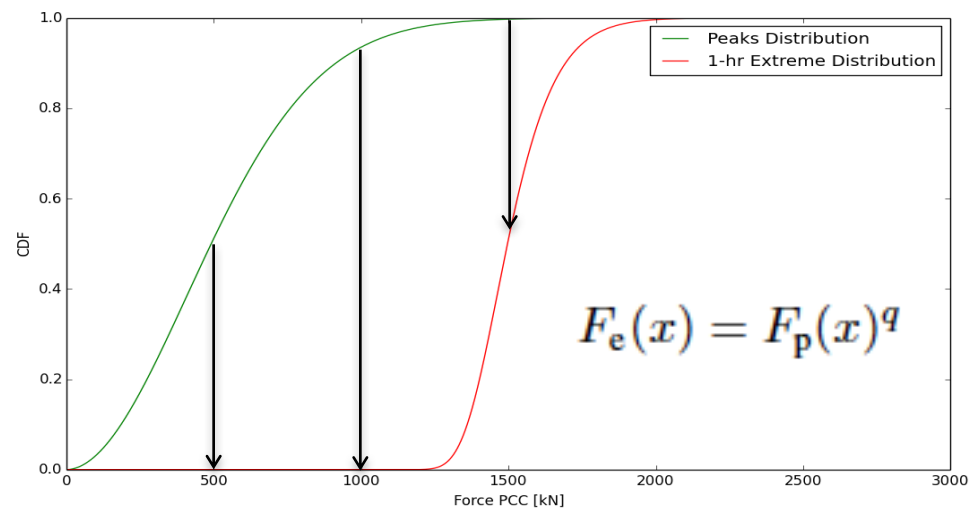
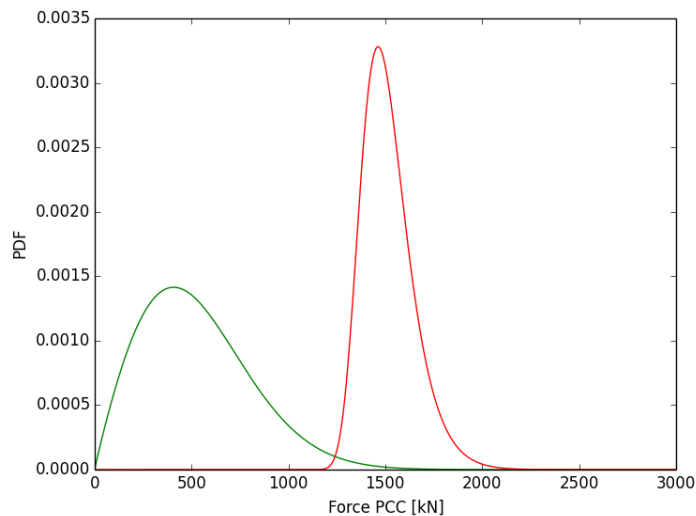
Block Maxima

- Max event in one observation of short-term period.
- Repeat N times
- Fit a GEV distribution
- Most robust way of obtaining the short-term extreme distribution
- Uses the least data, but the most significant



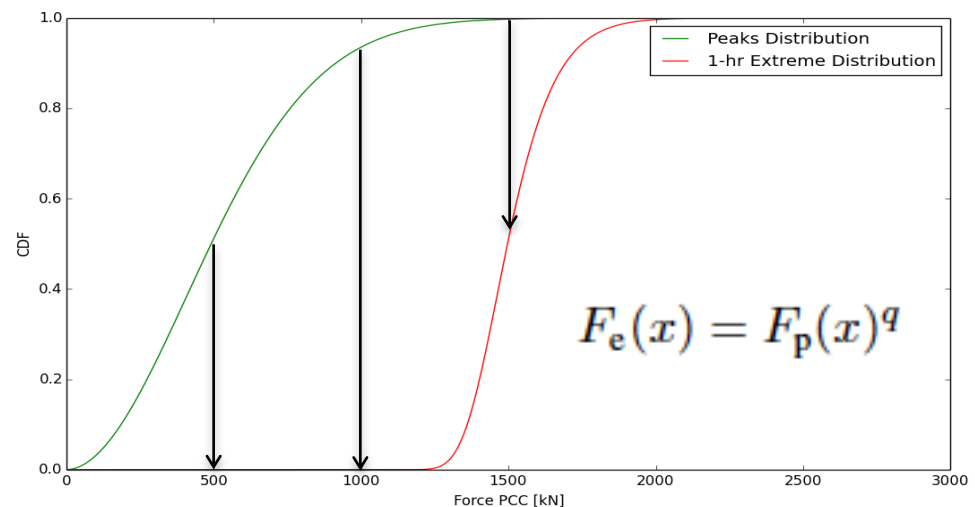
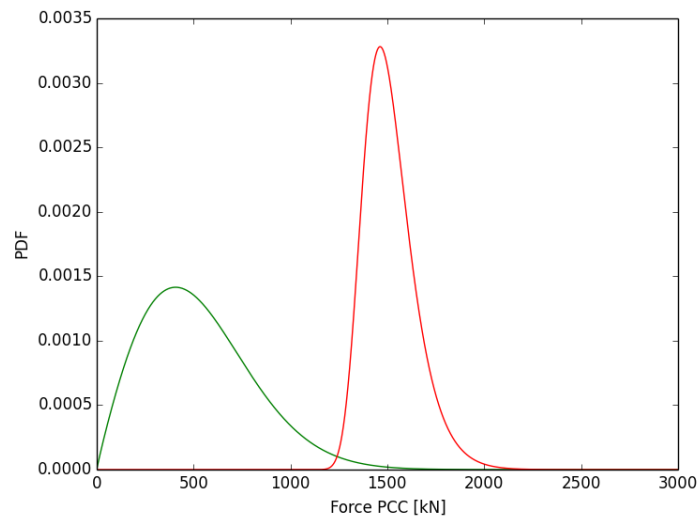
All Peaks Weibull

- A Weibull distribution is fit to all peaks.
- The short term extreme distribution is obtained as :
 - F_e = short-term extreme distributions
 - F_p = peaks distribution
 - q = number of peaks in short-term period
 - $F_e(x) = F_p(x)^q$
 - $= Pr\{X_1 \leq x\} * Pr\{X_2 \leq x\} * \dots * Pr\{X_q \leq x\}$
- Uses the most data, but most of it is insignificant to extreme



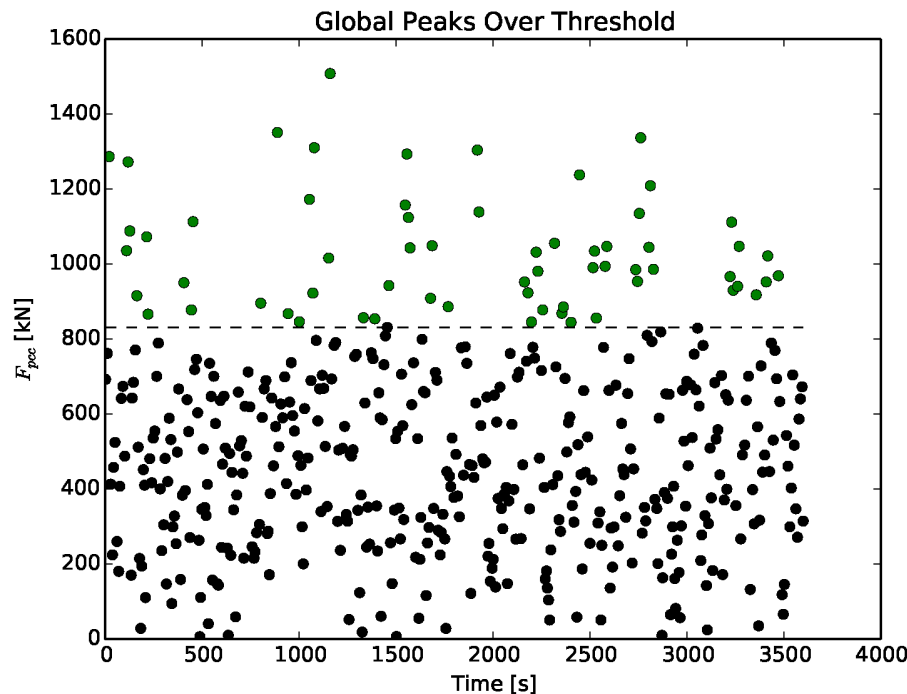
Weibull Tail Fit

- Fit 7 distinct Weibull distributions to the data with empirical $CDF > \{0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95\}$
- Use the average of the seven distributions as the peaks' distribution
- Emphasizes the tail of the distribution
- Uses an intermediate amount of data and weights based on relevance



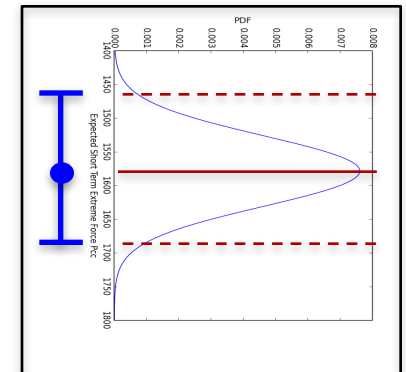
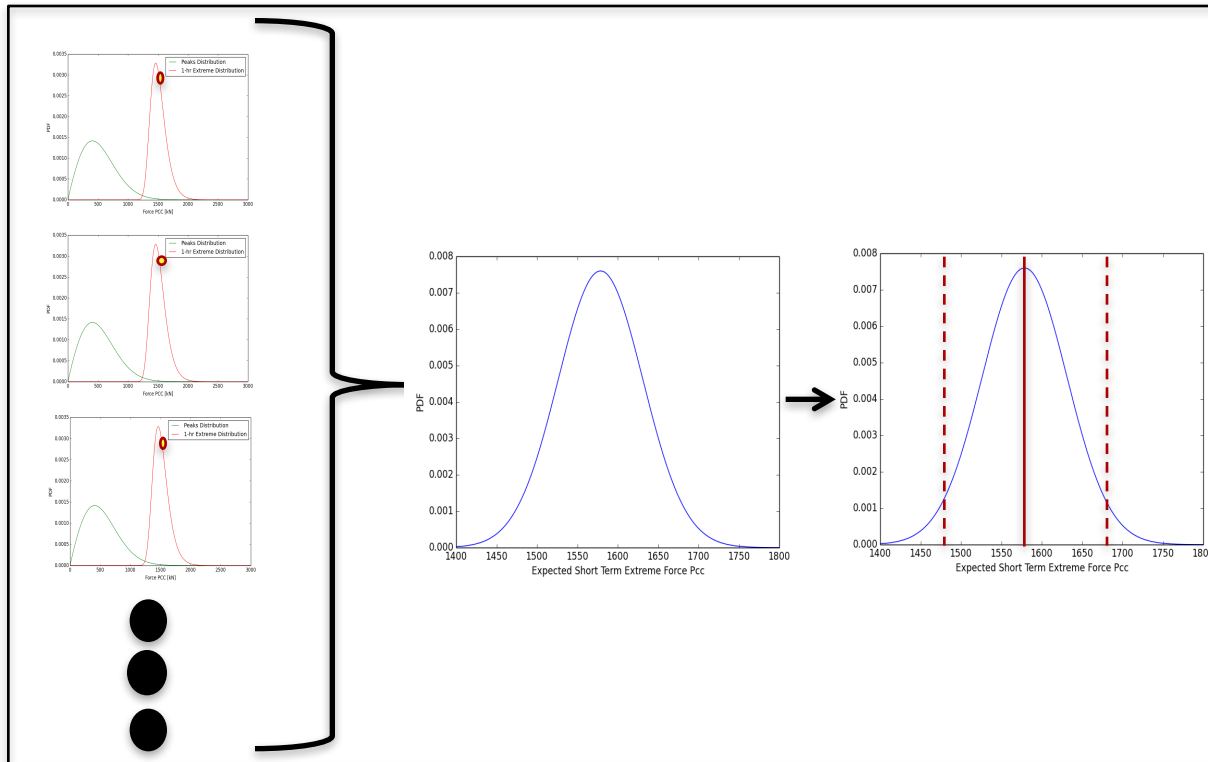
Peaks Over Threshold

- Fit a Generalized Pareto distribution to all peaks above a certain threshold.
- Threshold selected is 1.4 standard deviations above mean.
- Obtain peaks distribution as: $F(x)_p = 1 - (\zeta_u(1 - F(x - u)_{pot}))$
- Uses intermediate amount of data (most relevant).



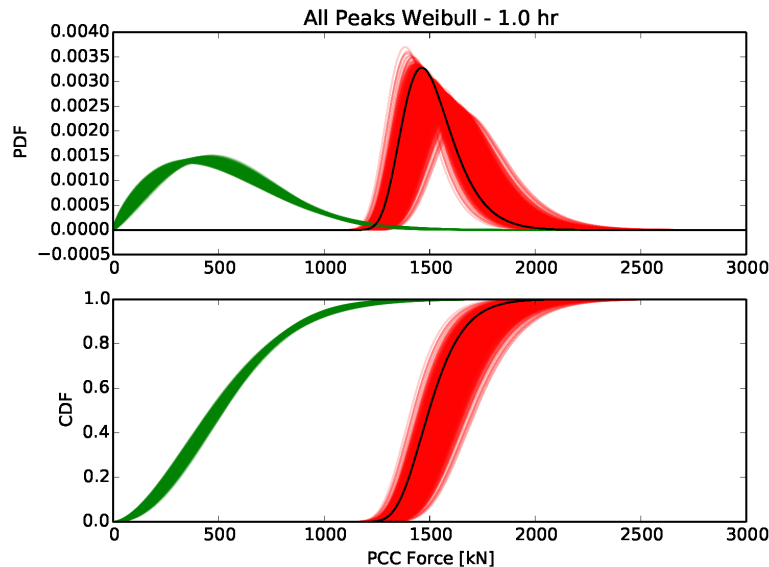
Method Comparison

- Each method provides an estimate of the characteristic extreme value.
- Each method is repeated n times, providing n estimates.
- A normal distribution is fit to these estimates to characterize the methods accuracy and spread.



Method Comparison (continued)

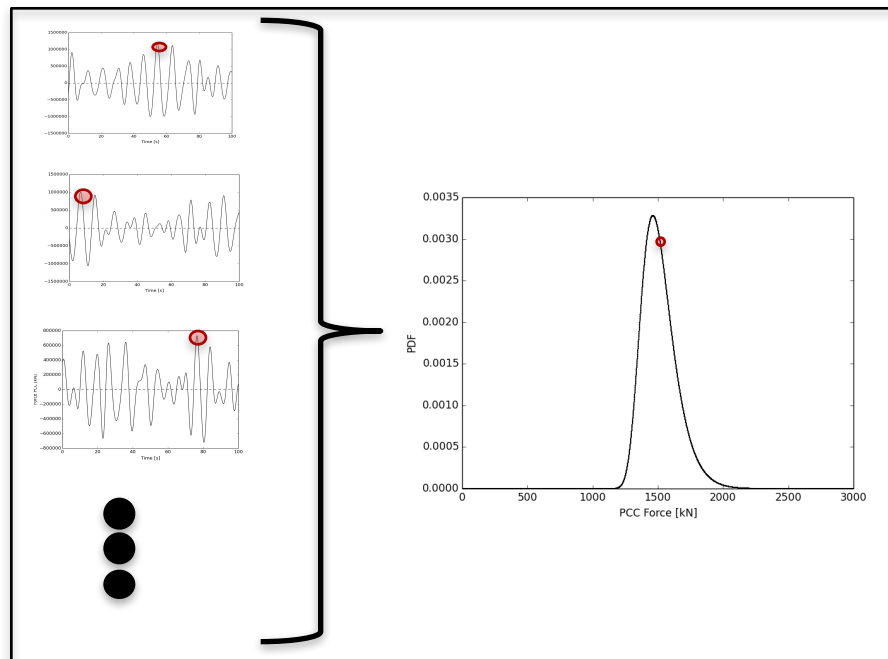
- 1000 hours of simulation = n_i realizations of i^{th} method.



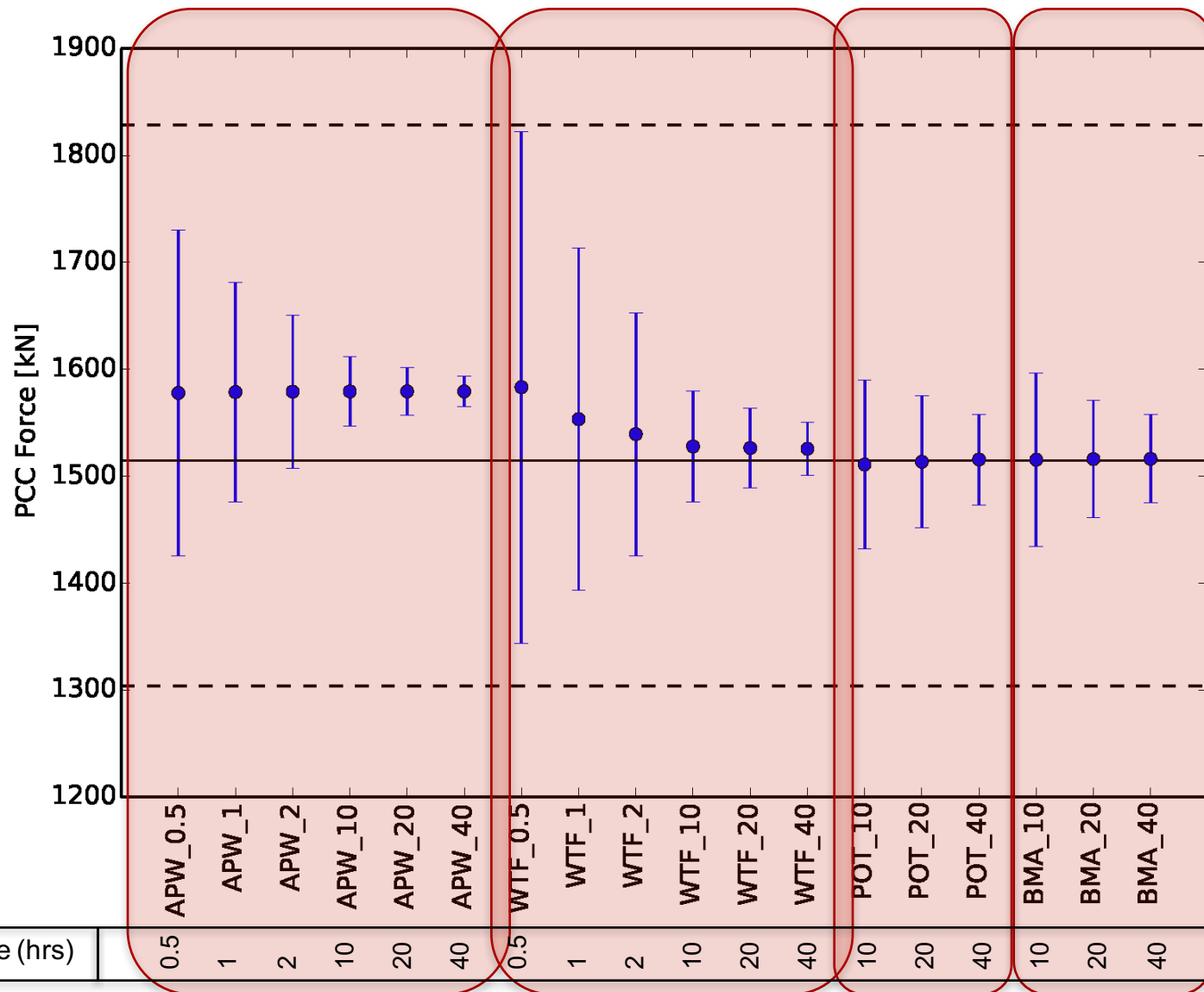
Case name	Method	Simulation duration (hr)	Number of realizations
APW_0.5	all-peaks Weibull	0.5	2000
APW_1	all-peaks Weibull	1	1000
APW_2	all-peaks Weibull	2	500
APW_10	all-peaks Weibull	10	100
APW_20	all-peaks Weibull	20	50
APW_40	all-peaks Weibull	40	25
WTF_0.5	Weibull Tail-Fit	0.5	2000
WTF_1	Weibull Tail-Fit	1	1000
WTF_2	Weibull Tail-Fit	2	500
WTF_10	Weibull Tail-Fit	10	100
WTF_20	Weibull Tail-Fit	20	50
WTF_40	Weibull Tail-Fit	40	25
BMA_10	Block Maxima	10 × 1	100
BMA_20	Block Maxima	20 × 1	50
BMA_40	Block Maxima	40 × 1	25
POT_10	Peaks Over Threshold	10 × 1	100
POT_20	Peaks Over Threshold	20 × 1	50
POT_40	Peaks Over Threshold	40 × 1	25
EMP	Block Maxima	1	1000

Empirical “truth”

- Block maxima method using all 1000 hours of simulation.
- Taken as true 1-hour extreme distribution
- Expected value and 90% interval bounds plotted in comparison plot

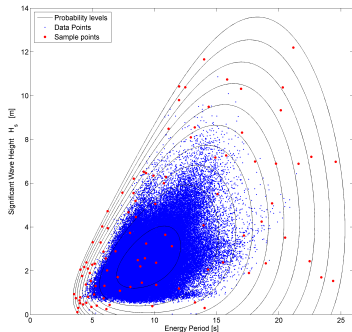


Results

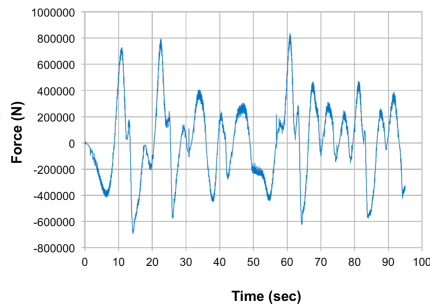


Multi-fidelity analysis

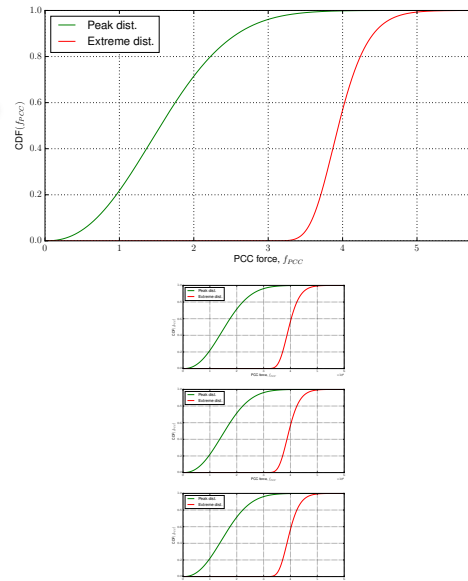
*Environmental
characterization*



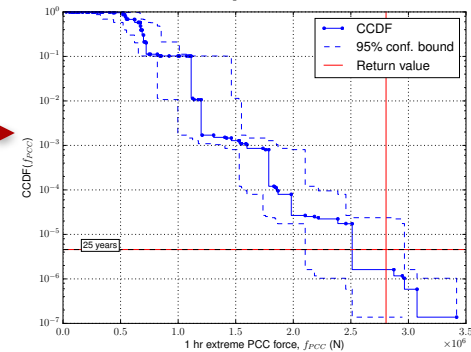
*Mid-fidelity
modeling*



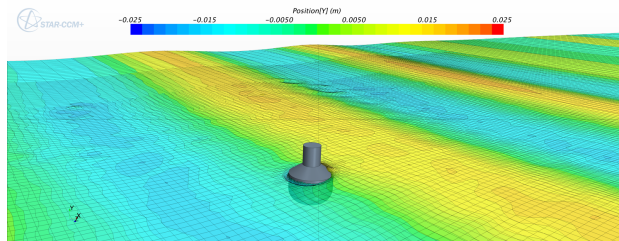
*Short-term
response*



*Long-term
response*



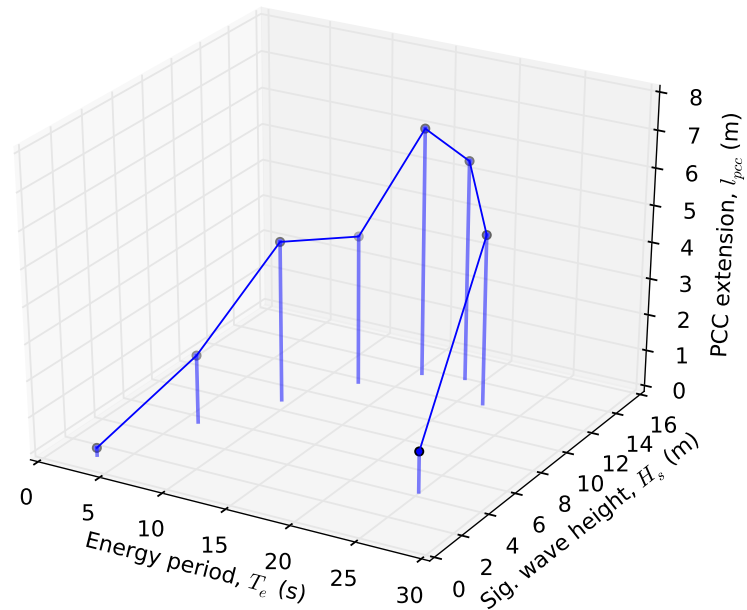
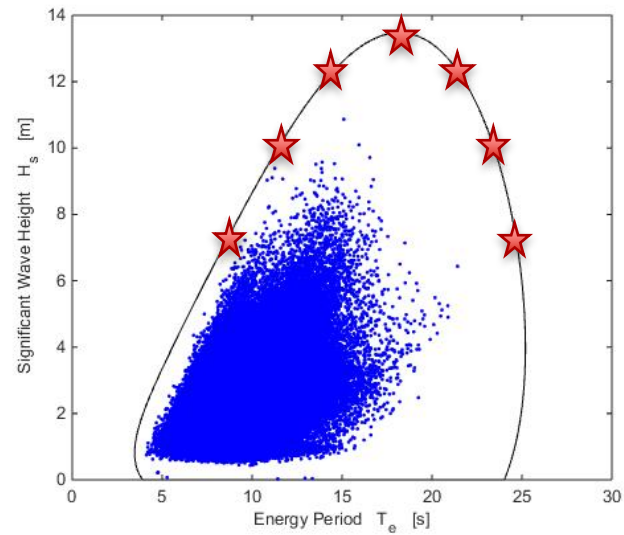
*High-fidelity
modeling*



*Design load
conditions*

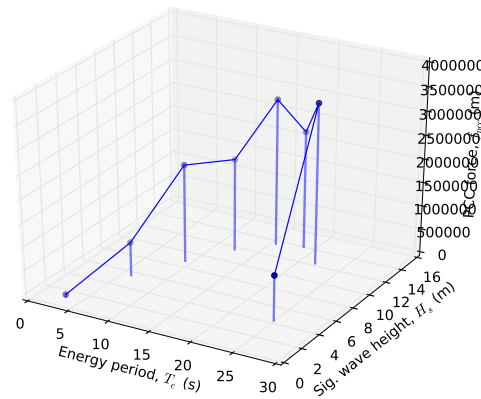
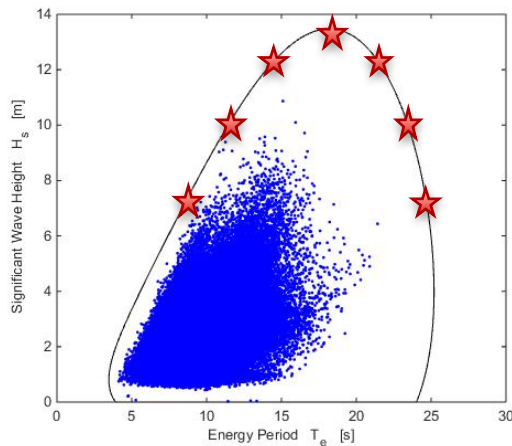
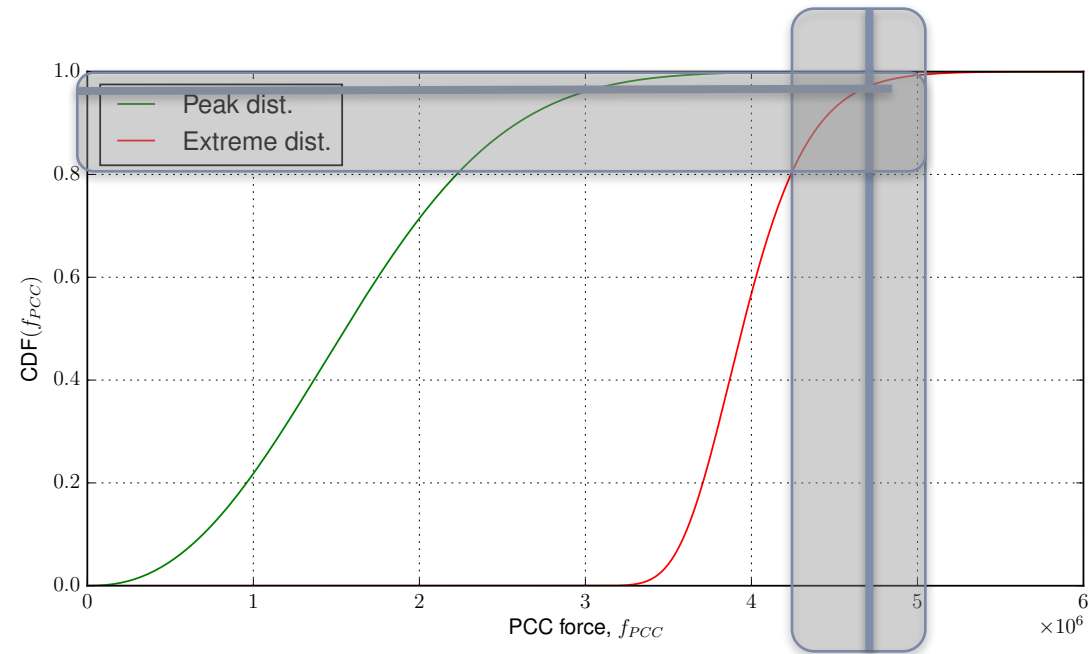
Contour approach

1. Select cases along the desired return contour
2. Find case with largest response
3. Use *insight* to select proper percentile response



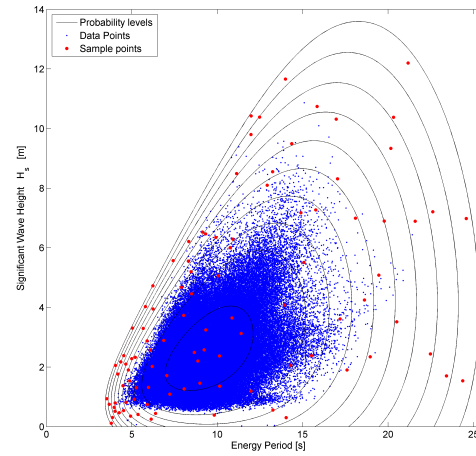
Contour approach

1. Select cases along the desired return contour
2. Find case with largest response
3. Use *insight* to select proper percentile response

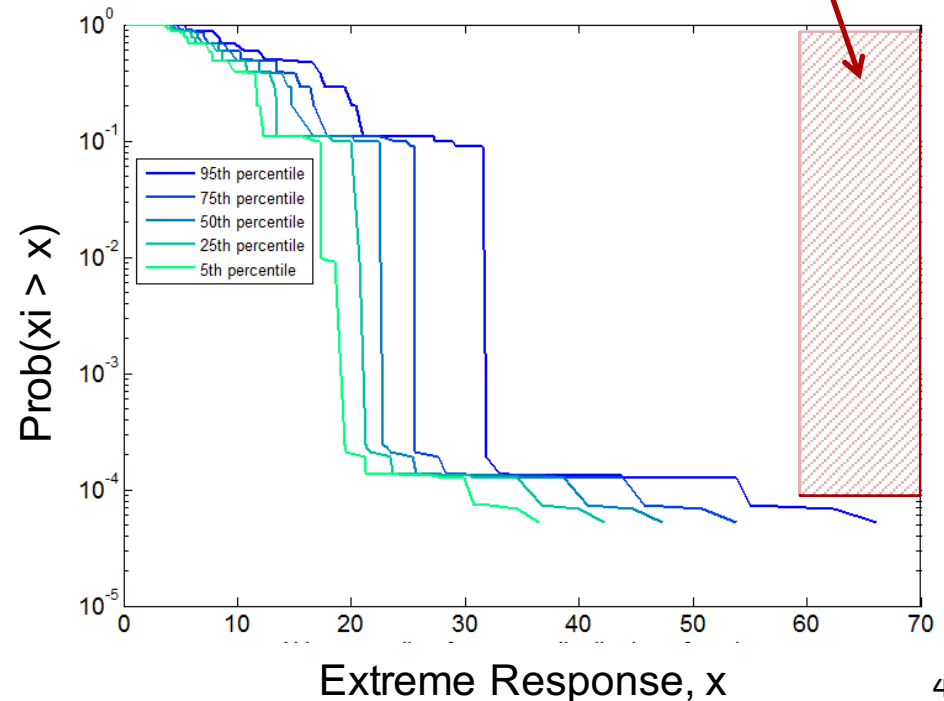


Full Long Term

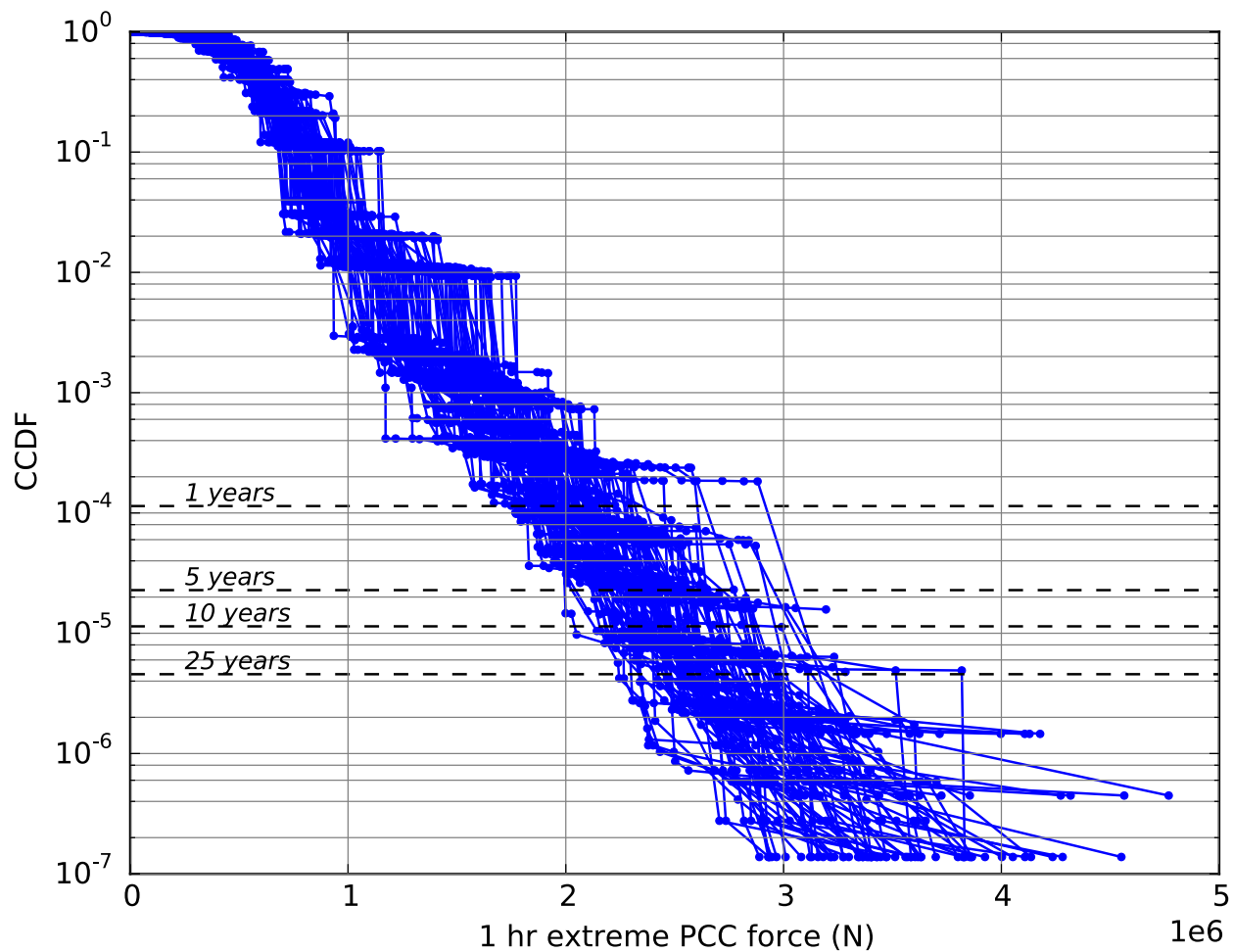
1. Run cases that encompass full space within environmental envelop
2. Synthesize short-term extreme device response w/ sea state likelihoods



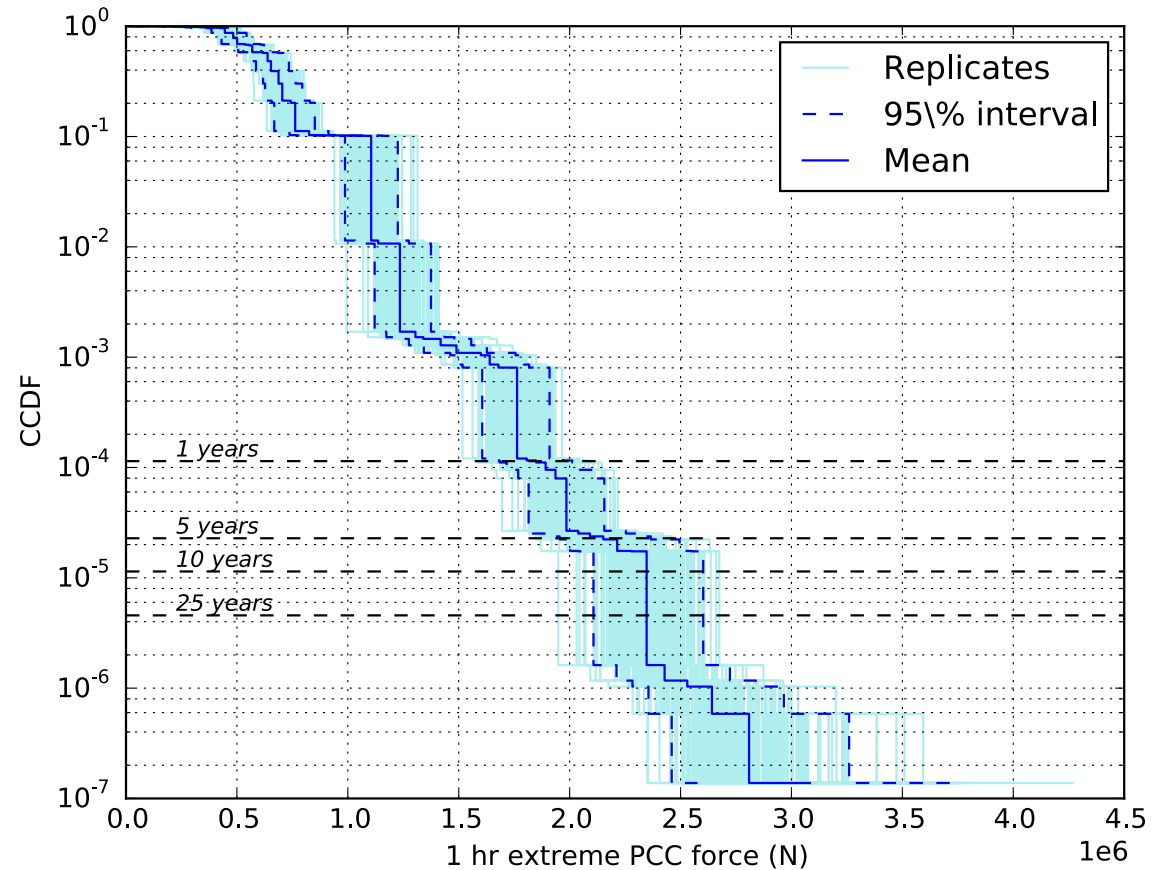
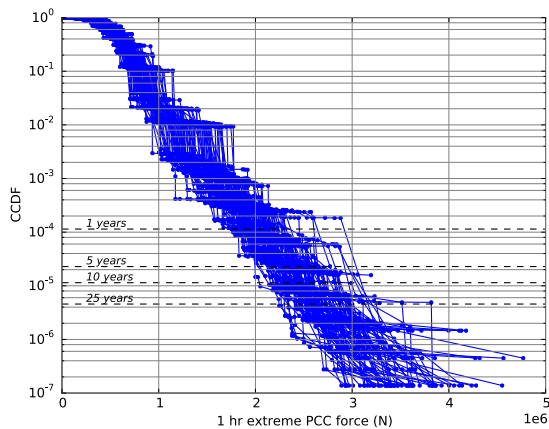
Example of risk limit
beyond which risk is
unacceptable



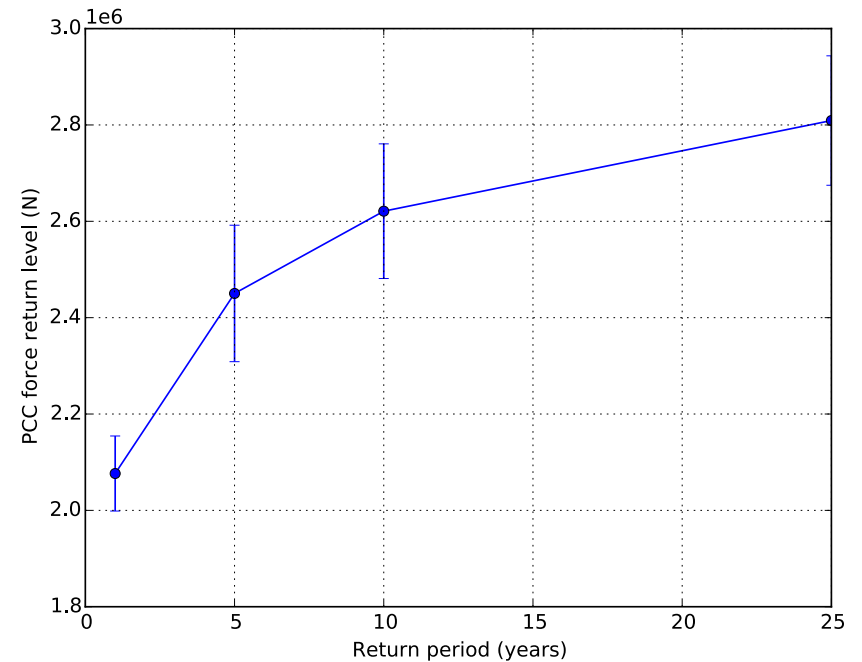
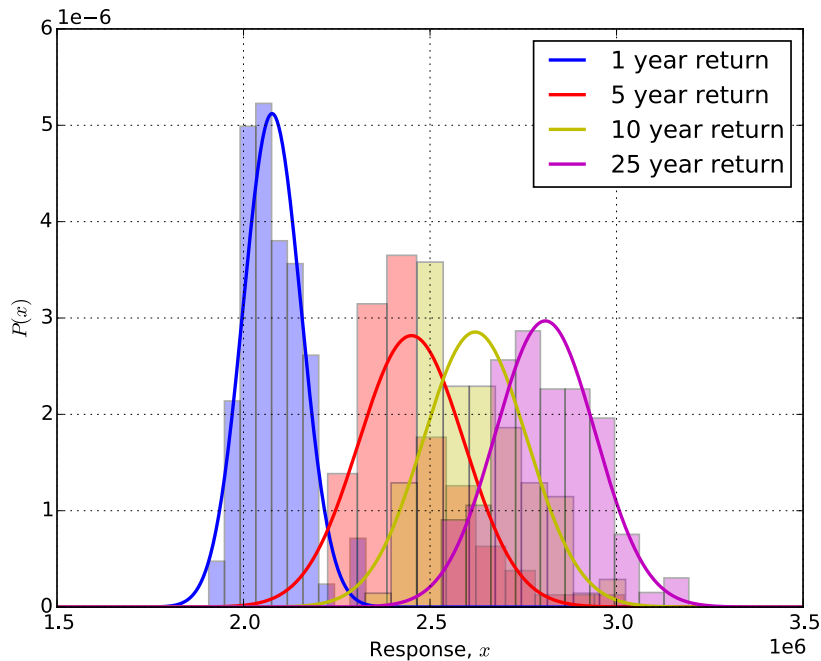
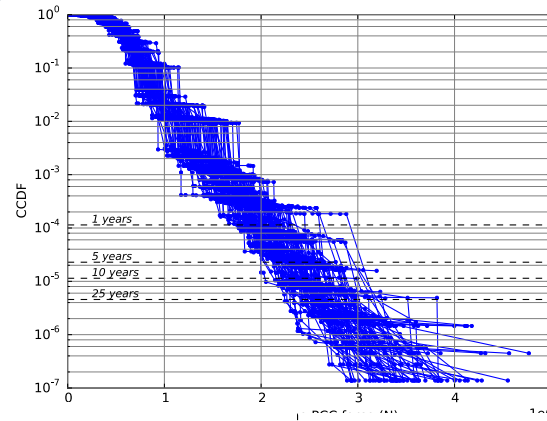
Method uncertainty and convergence



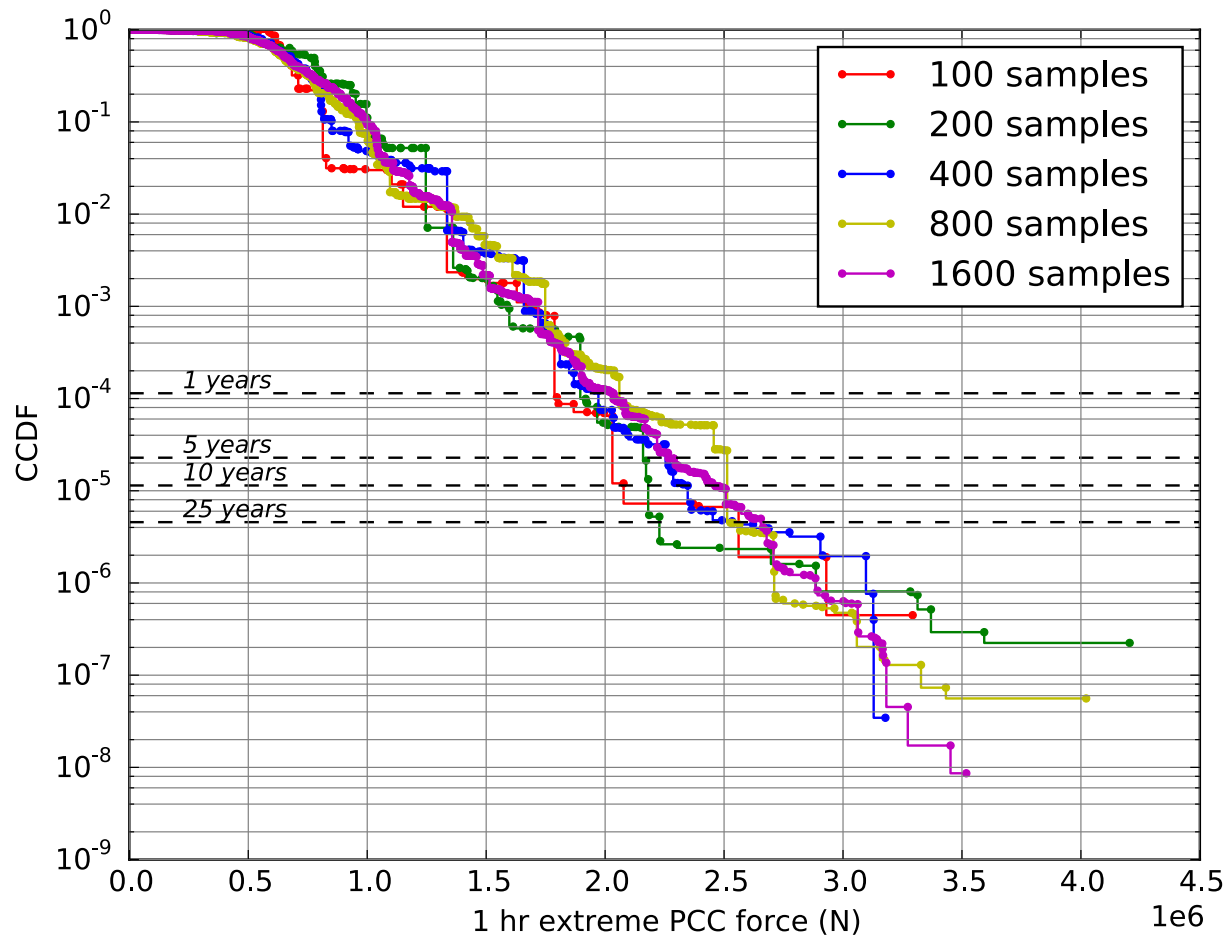
Method uncertainty and convergence



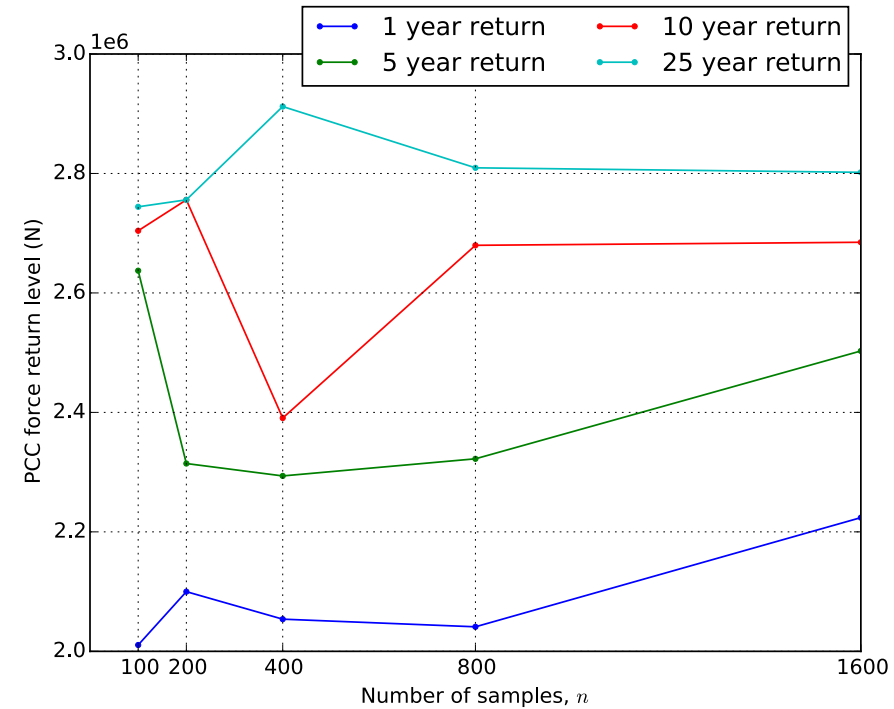
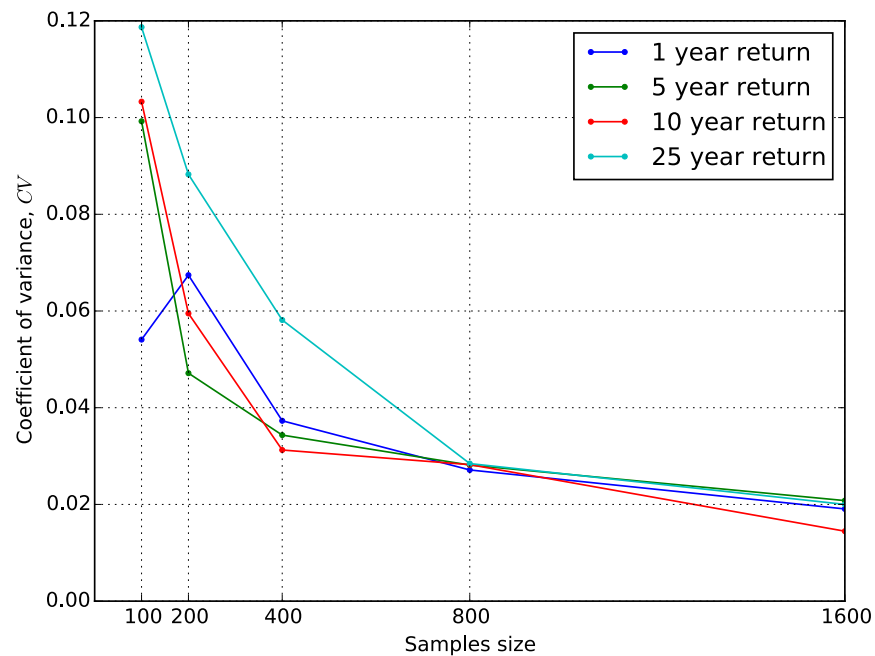
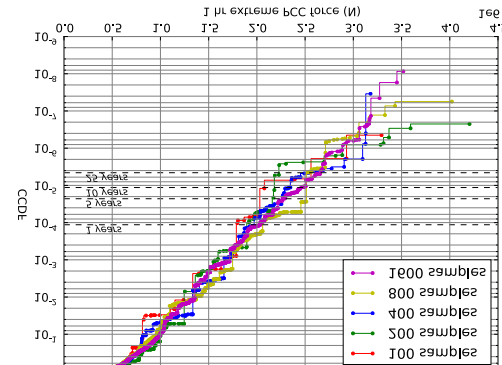
Method uncertainty and convergence



Method uncertainty and convergence

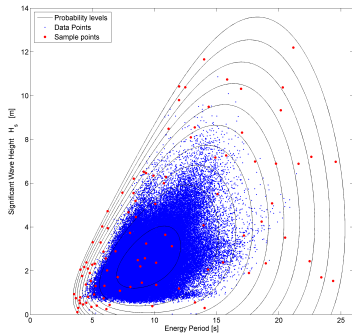


Method uncertainty and convergence

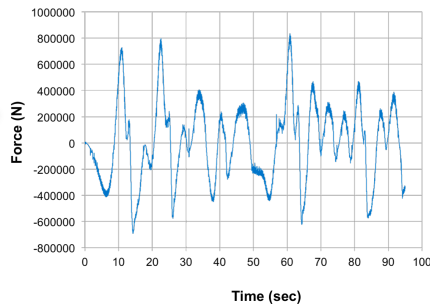


Multi-fidelity analysis

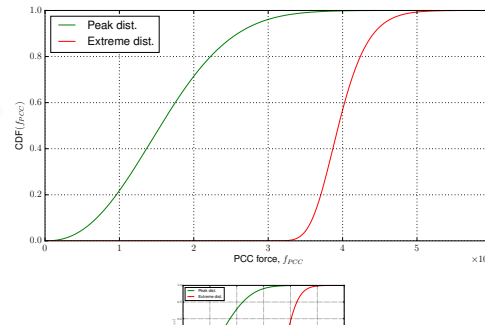
Environmental
characterization



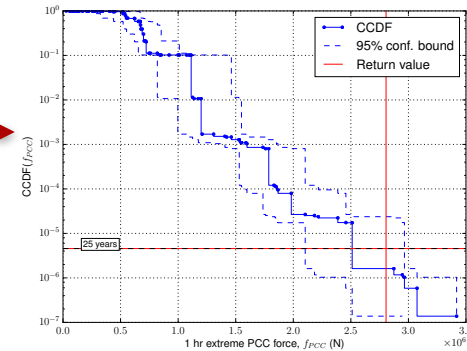
Mid-fidelity
modeling



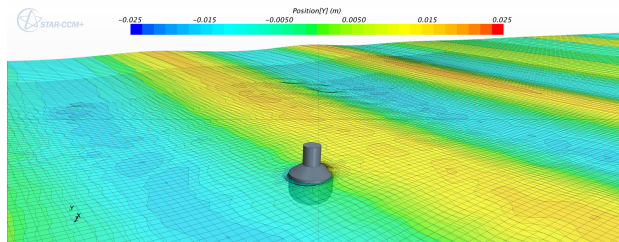
Short-term
response



Long-term
response



High-fidelity
modeling

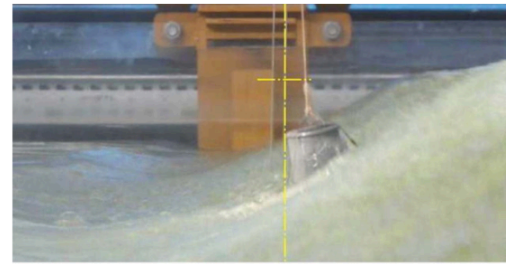
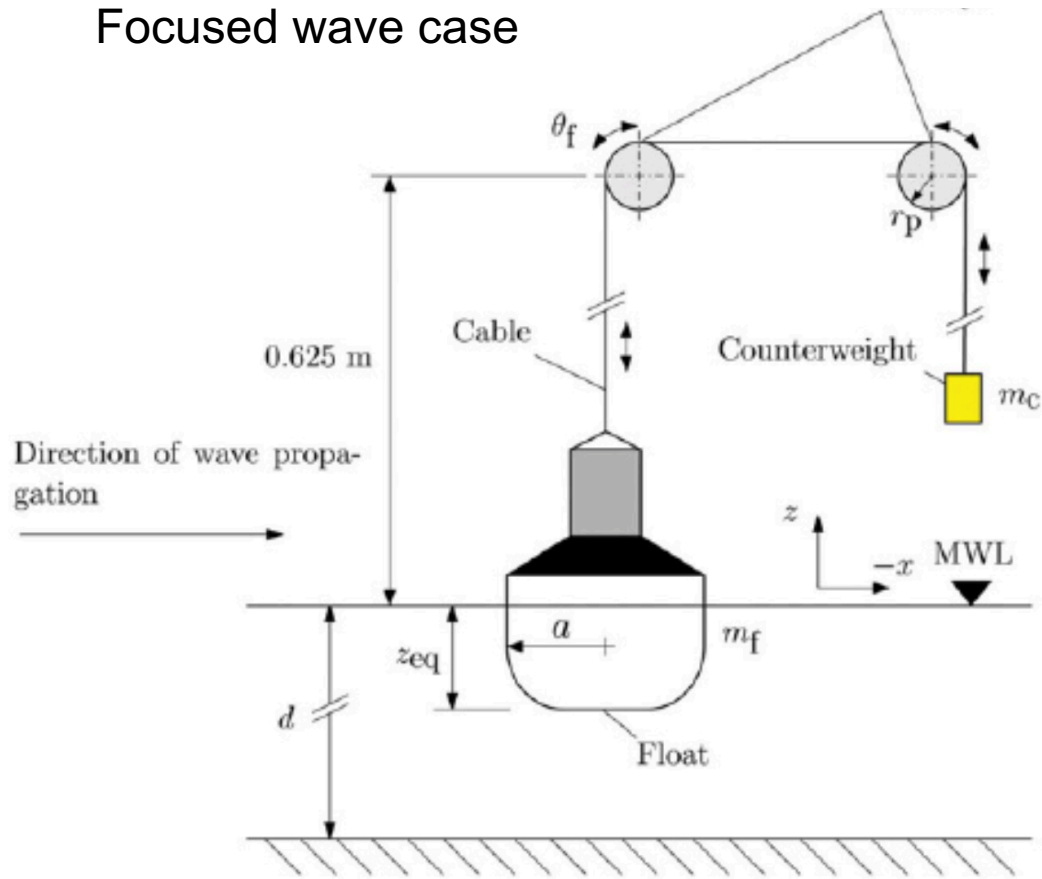


Design load
conditions

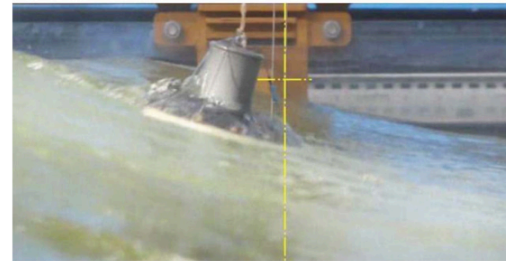
High-fidelity modeling

Simplified device studied by
Weller et al (2012)

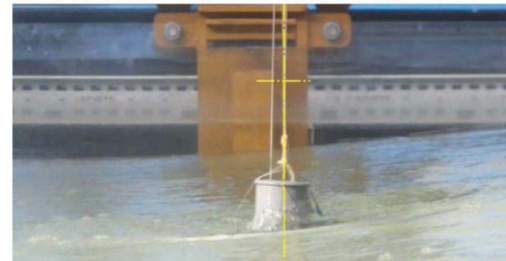
Focused wave case



(a)



(b)



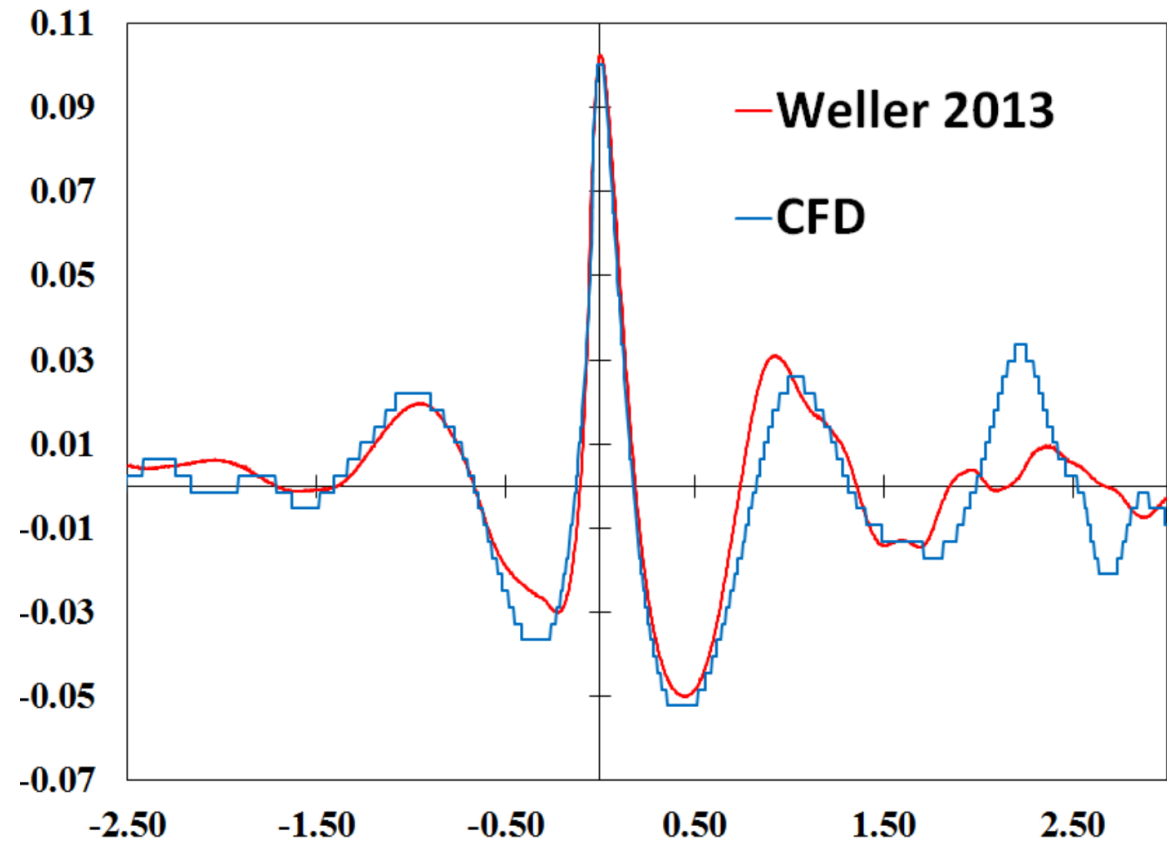
(c)



(d)

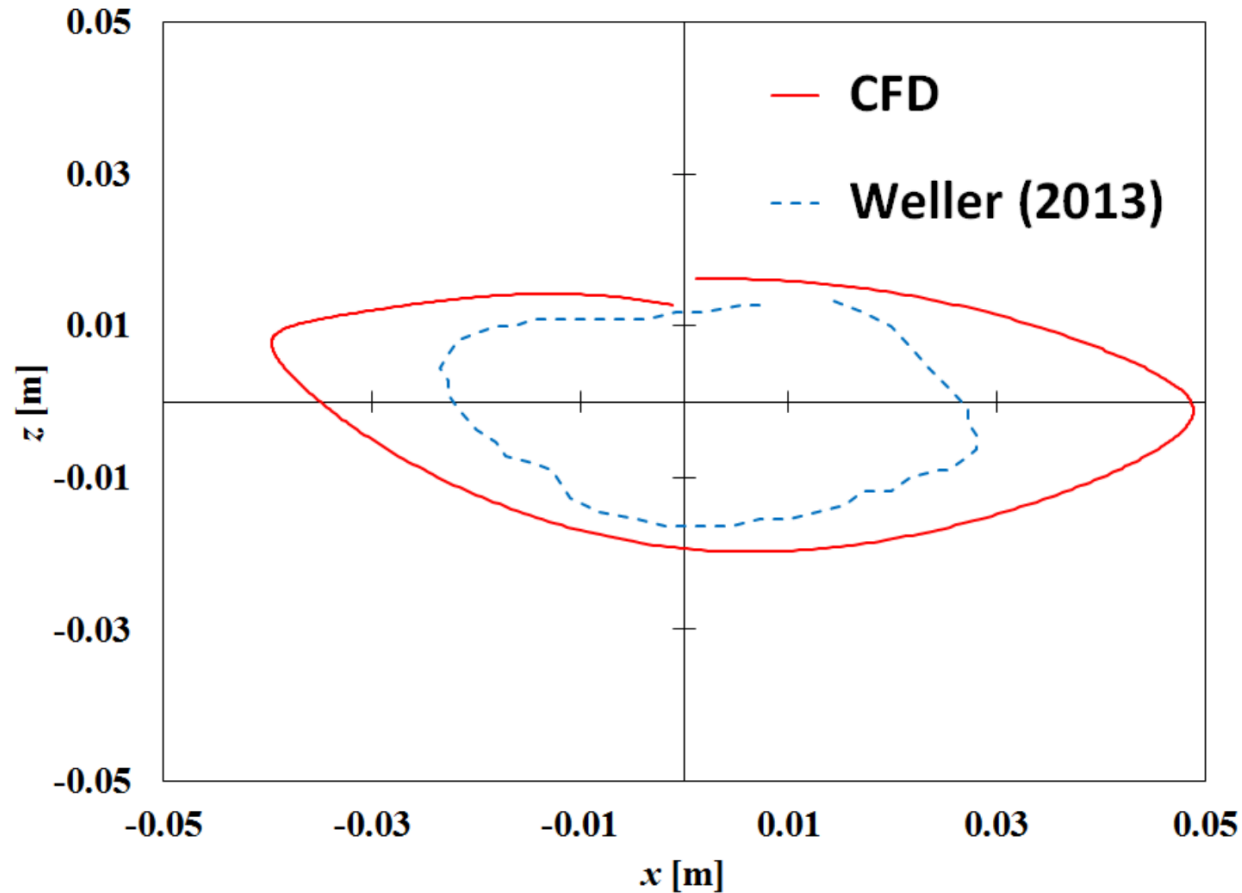
High-fidelity modeling

90 component focused-wave
wave components defined by:
(1) desired spectrum
(2) device linear response



High-fidelity modeling

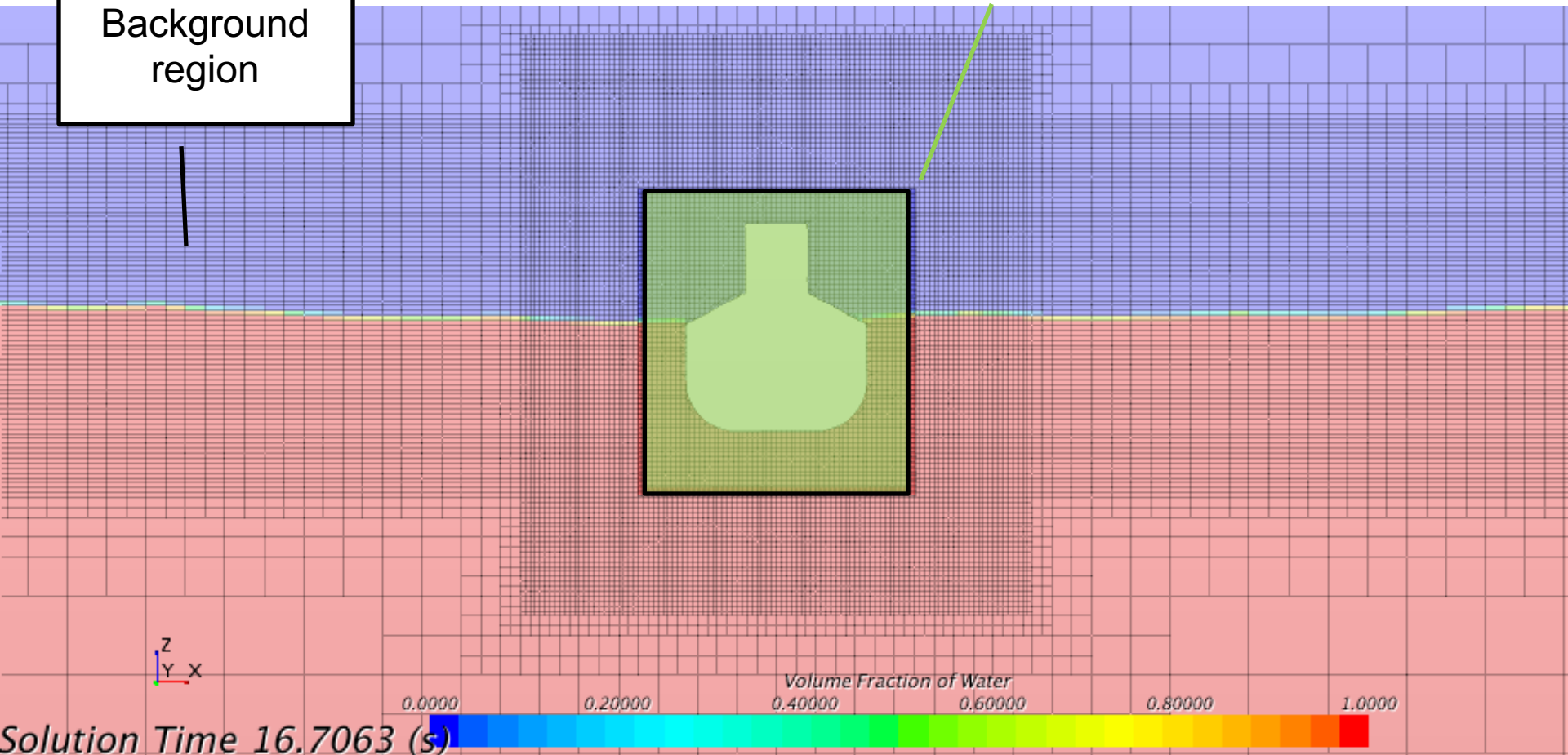
Similar to trends of Westphalen (2012) heave prediction shows better agreement than surge. Motion exaggerated by numerical methods. (Westphalen used identical modeling for pulley system.)



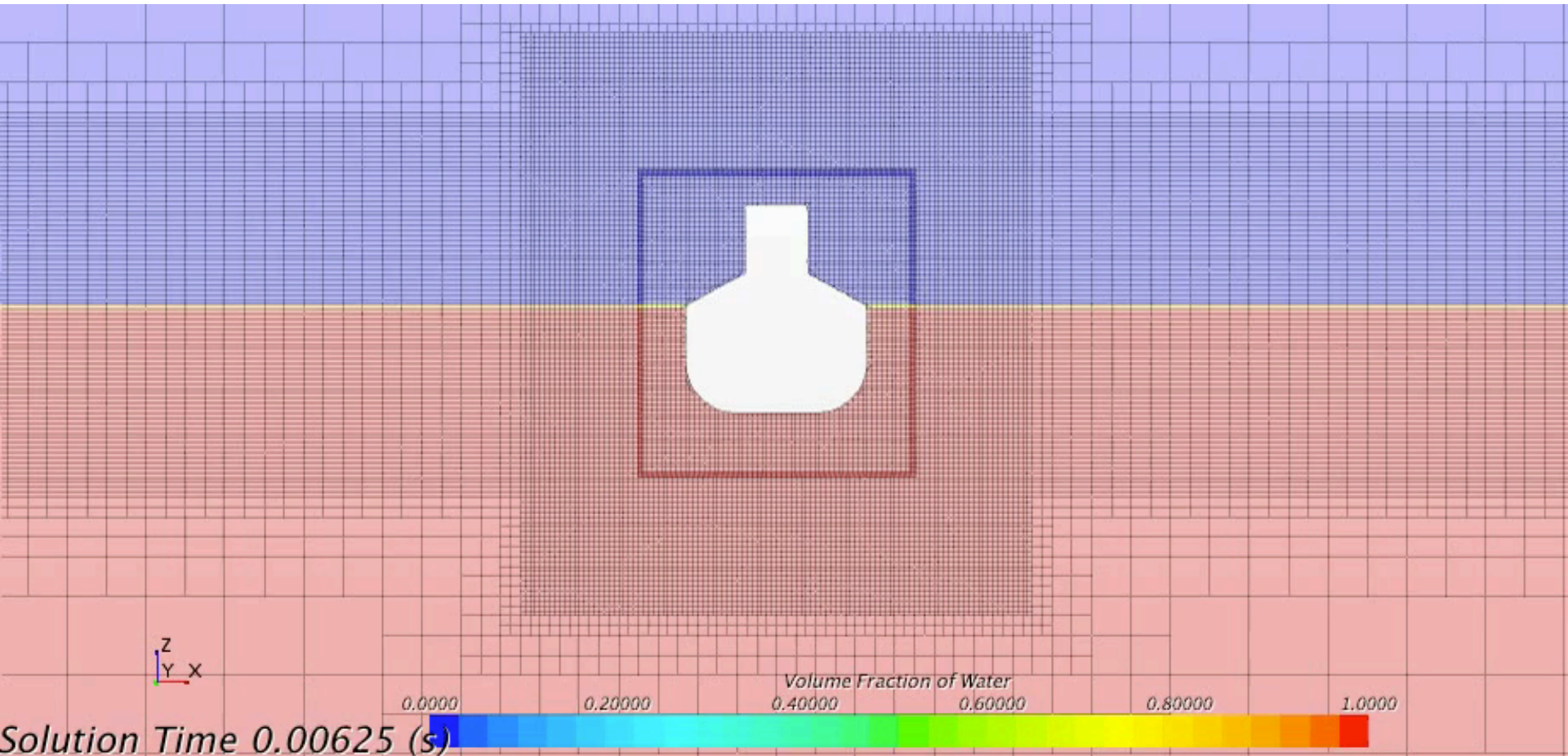
High-fidelity modeling

Overset region

Background
region

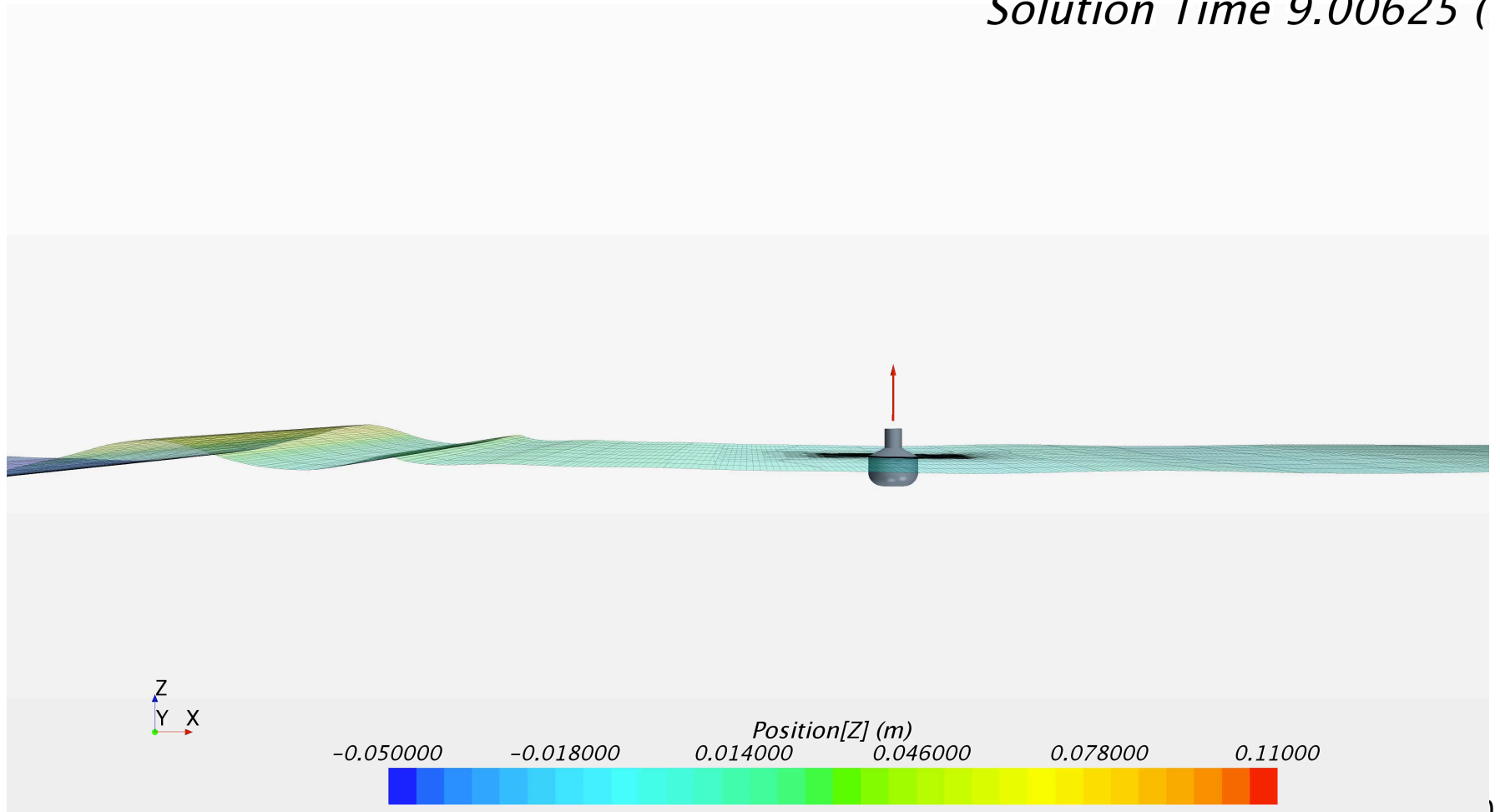


High-fidelity modeling



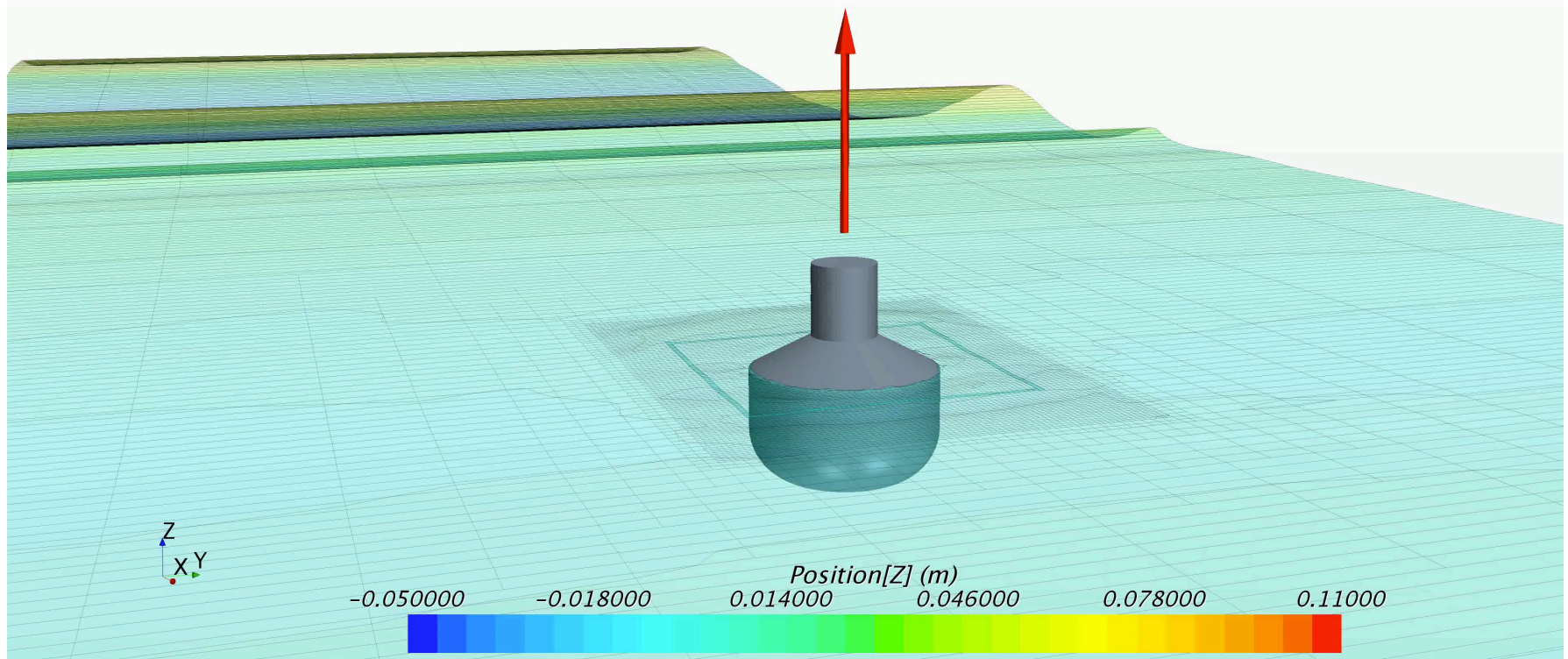
High-fidelity modeling

Solution Time 9.00625 (

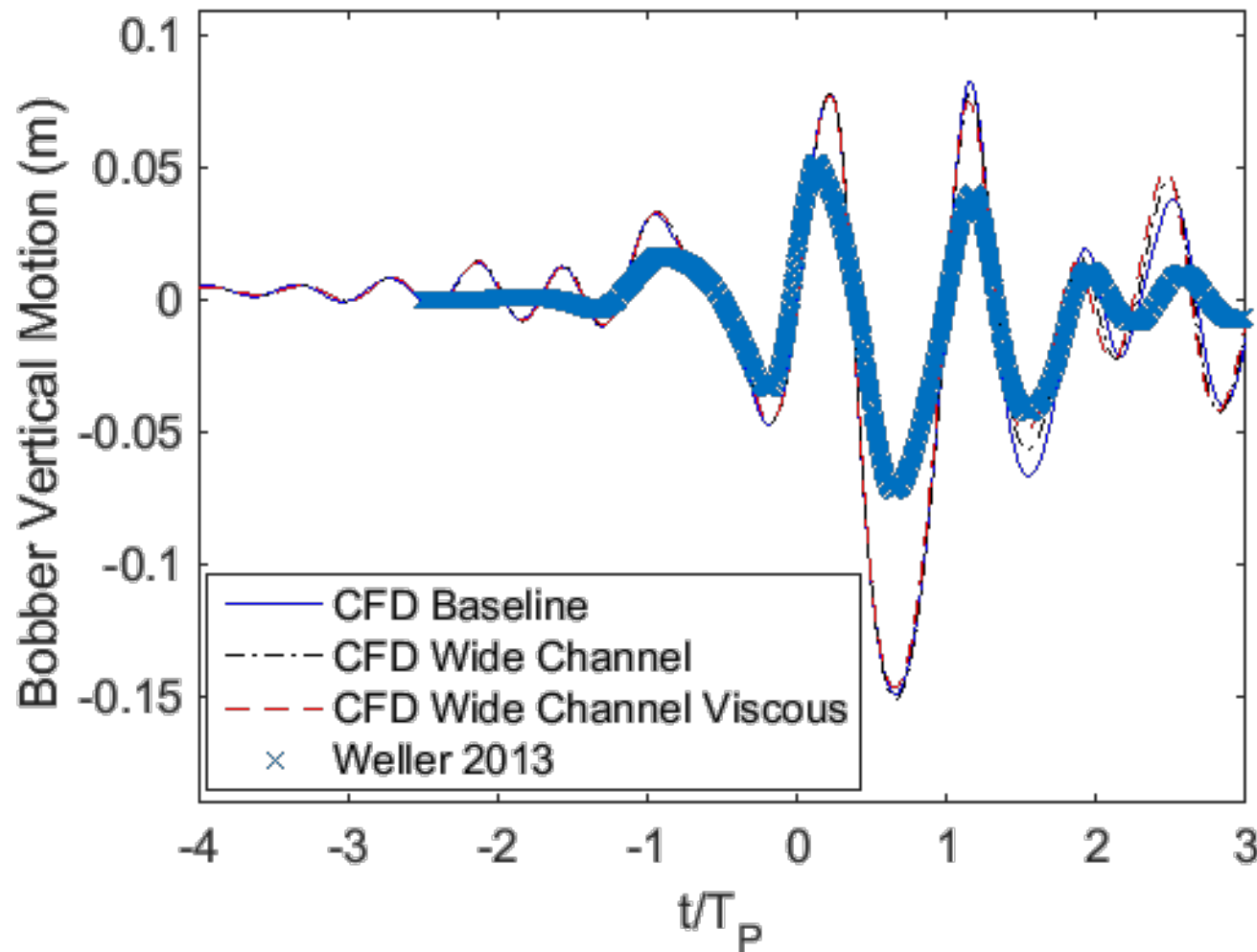


High-fidelity modeling

Solution Time 9.00625 (

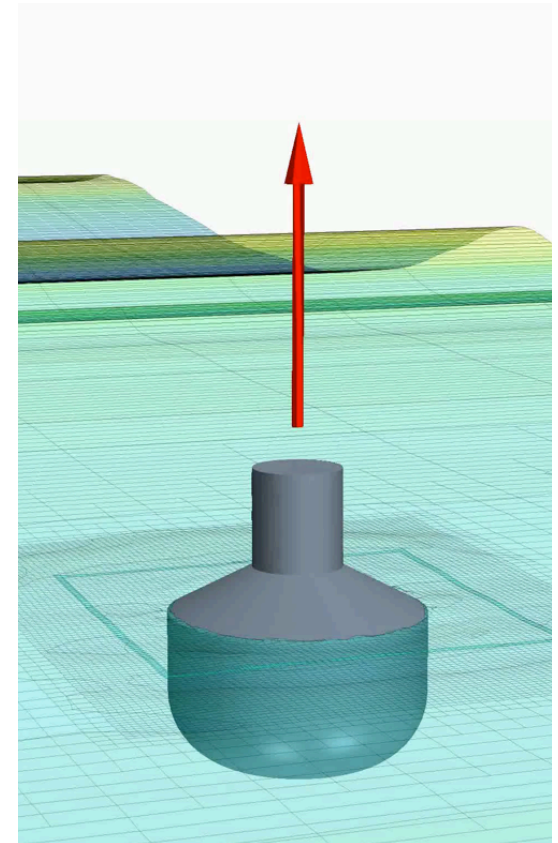
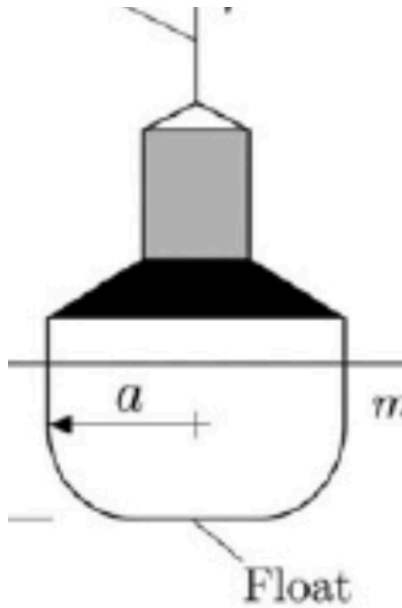
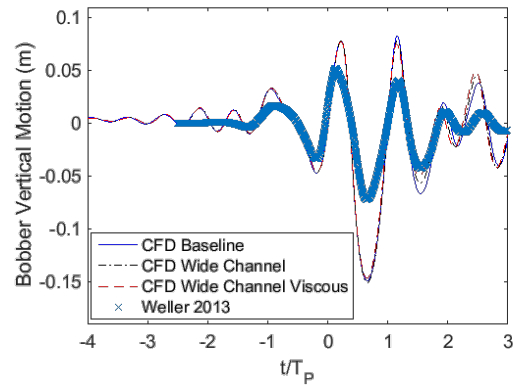


High-fidelity modeling



**Agreement is...
underwhelming**

High-fidelity modeling





Thank you.

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Collaborators

- Carlos Michelen (Sandia National Labs)
- Aubrey Eckert-Gallup (Sandia National Labs)
- Jay Lindau (Penn State Applied Research Lab)
- Yi-Hsiang Yu (National Renewable Energy Laboratory)
- Michael Lawson (National Renewable Energy Laboratory)
- Jennifer van Rij ((National Renewable Energy Laboratory)

ADVANCED WEC CONTROL

- US DOE Sponsored Controls Program
 - Multi-year Program with four major phases
 - Theoretical Development: performance model and controls
 - Experimental Validation:
 - Multiple phases
 - Each major phase is tied to a validation program to be carried out at the Carderock MASK Basin

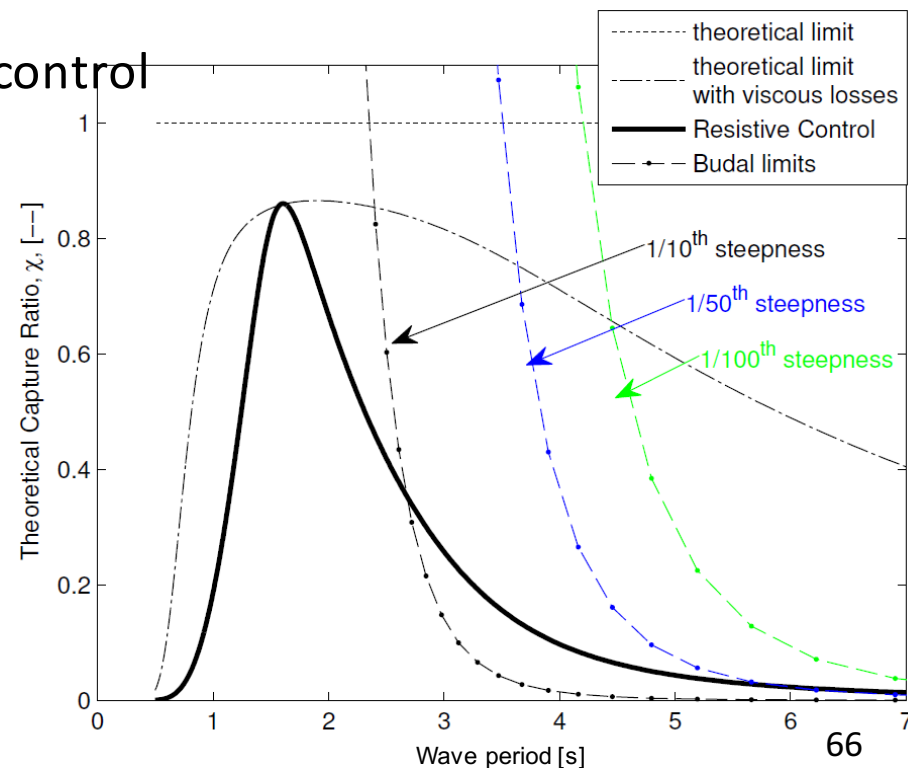
12.2-million-gallon tank in Carderock, West
Bethesda, MD
Naval Surface Warfare Center



ADVANCED WEC CONTROL

■ Goal

- What is the potential of control systems in WECs?
 - Validate the extent to which control strategies, given real world limitations, can increase the energy production of resonant WEC devices.



ADVANCED WEC CONTROL

Testing

Floating buoy

Carderock Maneuvering and Sea Keeping (MASK)
Basin – US Navy



Device overview

