MASTER IN RENEWABLE ENERGY IN THE MARINE ENVIRONMENT

REM

Numerical Modelling of Water Waves & Extreme Waves

Dr Thomas Vyzikas, Bilbao 17 June 2025

What describes best your background?

Expected learning outcomes

- Being able to explain what a numerical model is
- Understand its basic operating principles
- Describe the different categories of models
- Learn the basics of wave propagation
- Select the best model for each physical process

Why do we model things?

Predict the behaviour of a system
Preliminary studies
Collect more data
Design our structures better
Optimise the design

“All models are wrong, but some are useful” (George Box)

Basic principles of numerical modelling

1. Design of the model: from complex to simple
   What is the problem that I want to solve?
   Which physical processes and factors can be ignored (assumptions)?
   What are the scales and objectives of the problem?
2. Selection of governing equations and numerical schemes
3. Discretization: spatial (mesh) and temporal resolution (time step)
4. Convergence studies until stability is achieved (independence)
5. Validation* against experimental results (or to eliminate errors)
6. Calibration of the model for a specific problem to match observed data
7. Verification* for similar problems (or against physical reality)

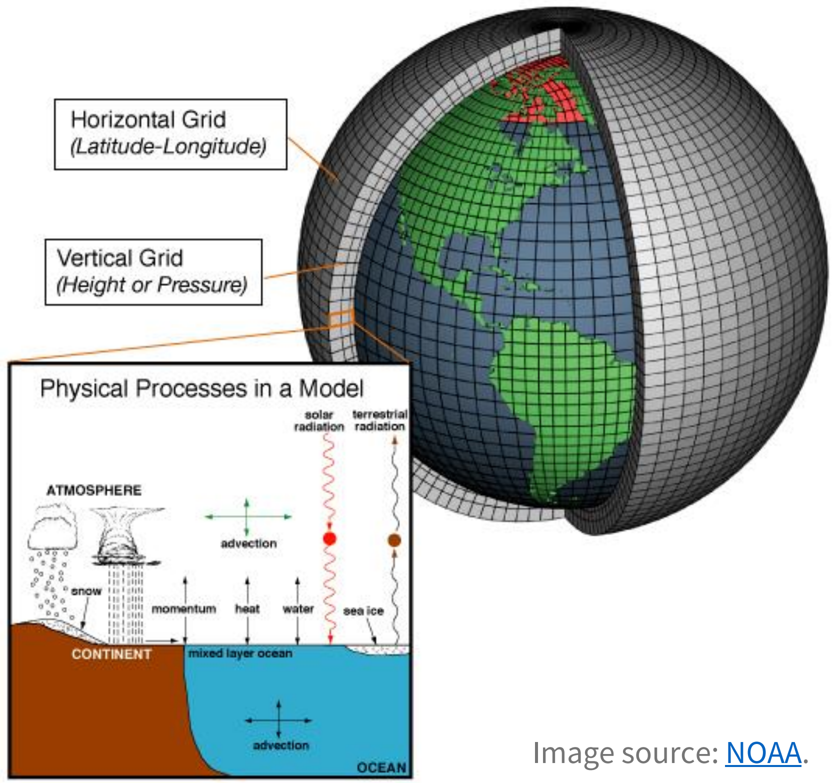
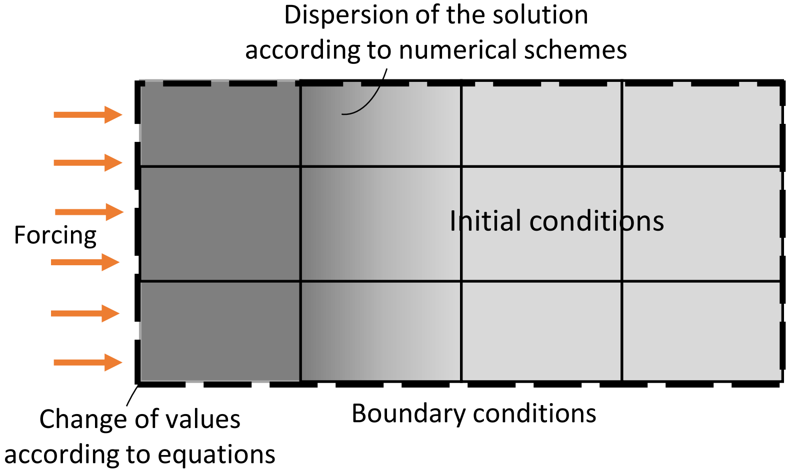
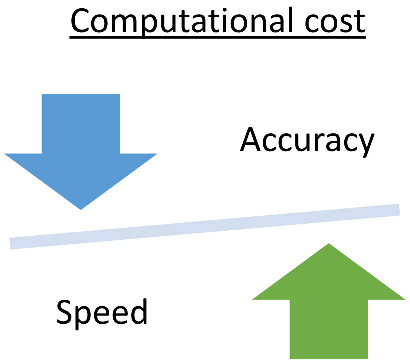
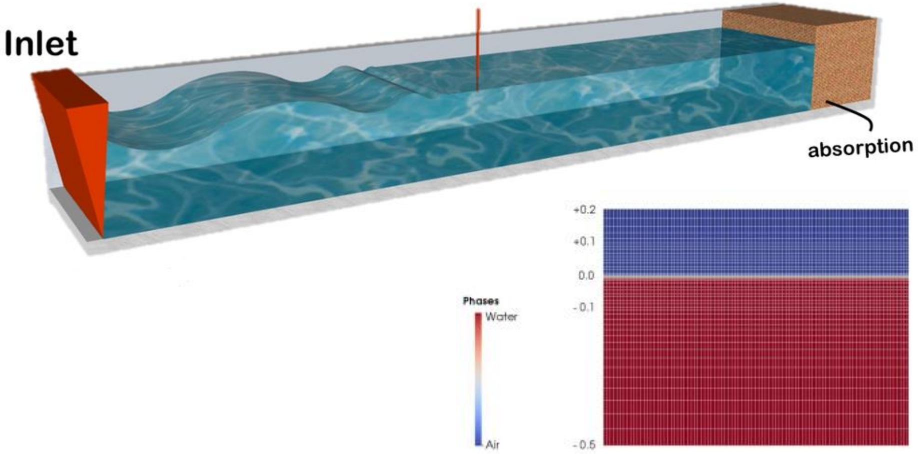


Image source: NOAA.

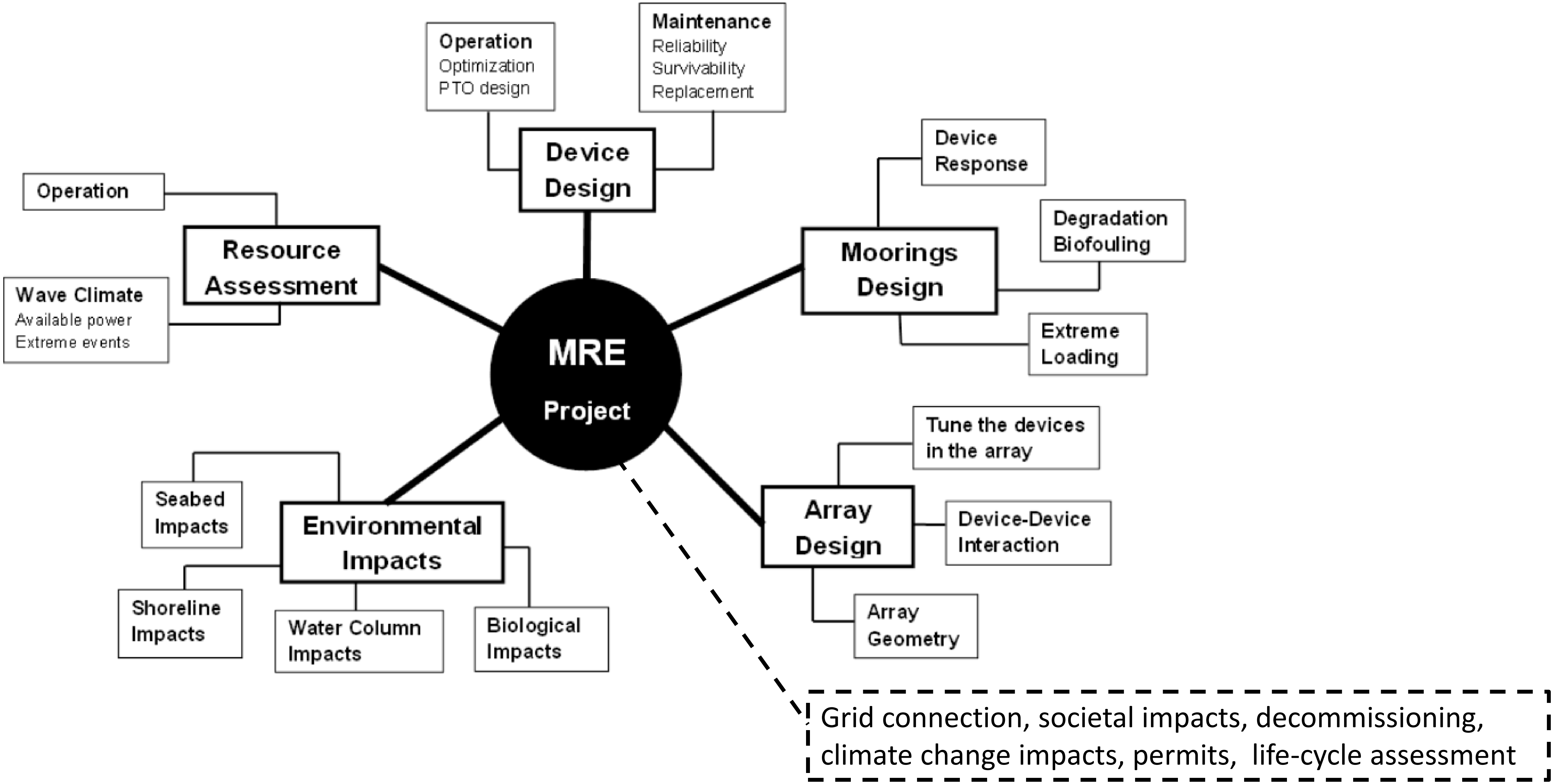




Numerical Wave Tank (NWT)



Numerical models for MRE problems



The MERiFIC project

Overarching scope: Advance the adoption of marine energy across the two regions of Cornwall and Finistère

- Marine energy resource assessment/mapping
- Policy issues and potential barriers to marine energy development
- Business and commercial opportunities for island/mainland communities
- Island/mainland interaction on appropriate infrastructure and Community and stakeholder engagement with key groups (e.g. fishing, wave farm developers, and investors)

Task: Best practice guide for numerical modelling in MRE

MERiFIC
Marine Energy in Far Peripheral and Island Communities

france (manche channel) england
interreg

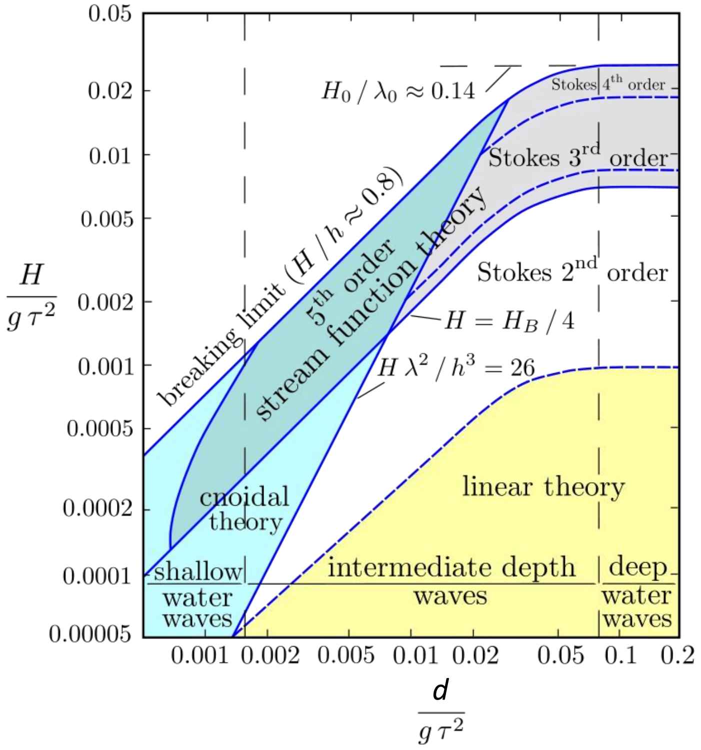
European Regional Development Fund
The European Union, investing in your future

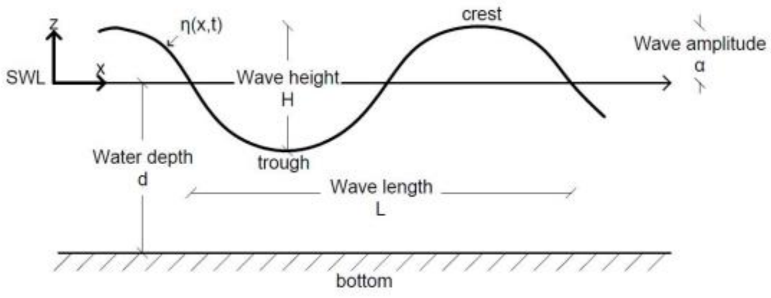
Fonds européen de développement régional
L'union Européenne investit dans votre avenir

EU INTERREG IV A, 2011-2013
http://www.merific.eu/

Wave propagation and nonlinearity

Regular waves
(Stokes / Airy theory, swell)



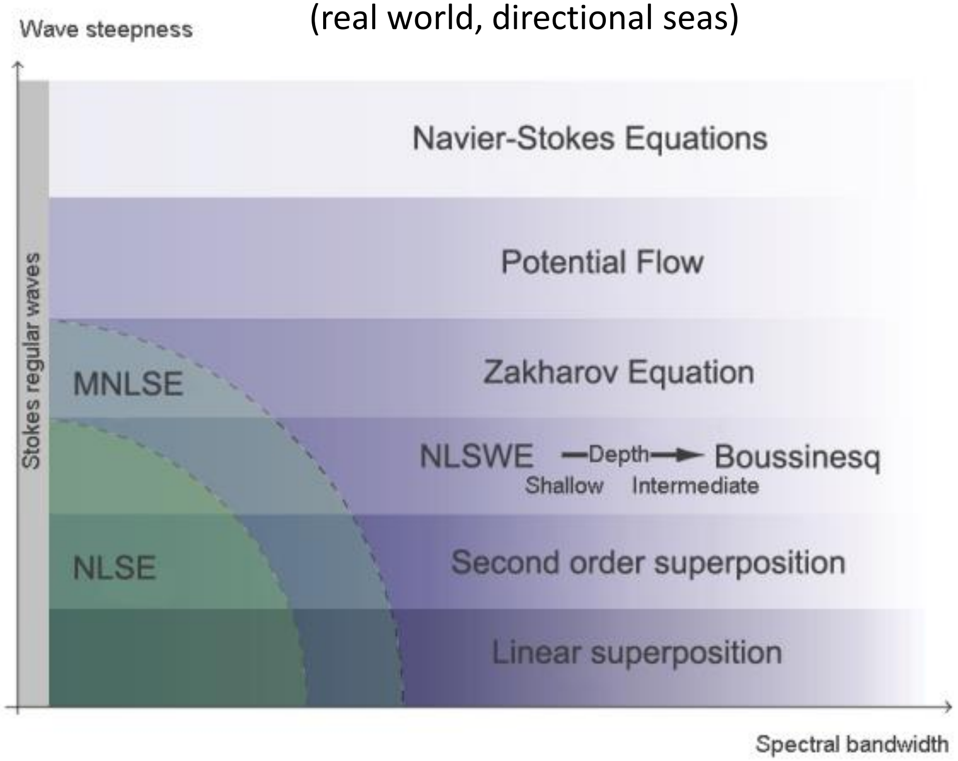


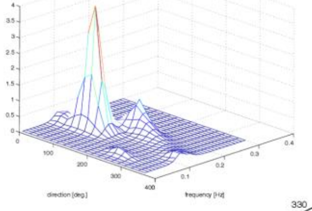
$$\mathbf{k}_i = \frac{2\pi}{L_i} = \frac{2\pi\omega_i^2}{g2\pi \ \tanh(2\pi d / L_i)}$$

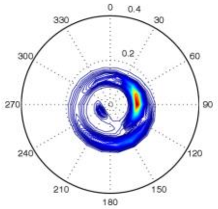
c = L / τ = ω / k

c: phase speed, ω: frequency,
k: wave number

Irregular waves
(real world, directional seas)







The two schools of numerical modelling

Phase-resolving models

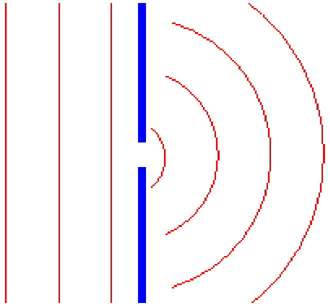
- Each individual wave component is included in the simulation (*phase*, amplitude, wavelength)
- Irregular waves result from superposition of individual (regular) waves which result in a velocity and pressure field
- Deterministic representation of the free surface
- Resolve the Navier-Stokes equations or simpler versions under certain assumptions (e.g., turbulence, depth, irrotational, incompressible fluid)
- The wave form propagates 'naturally' according to the resolved velocity fields at scale of the grid
- Rely on fewer simplifications / parameterisations
- Suitable for more nonlinear problems
- Used for smaller spatial and temporal scales
- Can handle wave-structure interaction problems
- Computationally heavy

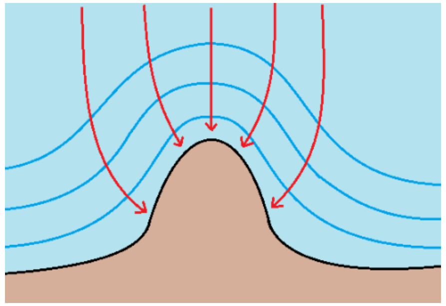
Phase-averaged models

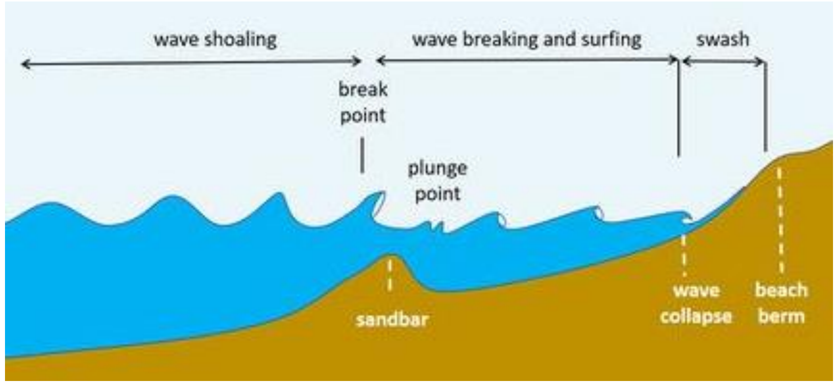
- Waves are represented by their energy and direction at certain frequencies
- Irregular seas can be considered a Fourier-type process of superposition of linear waves that form an energy spectrum (spectral models)
- Stochastic representation of sea state
- The spectrum propagates according to wave action equation (energy balance) and wave group dispersion
- Cannon model phenomena at scales smaller than the wavelength
- Parameterise complex physical processes with source terms and sinks
- Often calibrated to specific regions and phenomena
- Suitable for large scale problems (e.g., ocean circulation and meteorological models)
- Computationally efficient

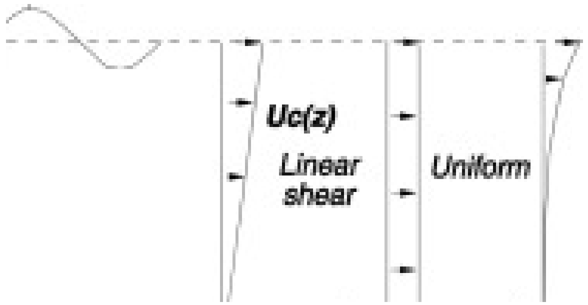
Importance of physical processes at different depths

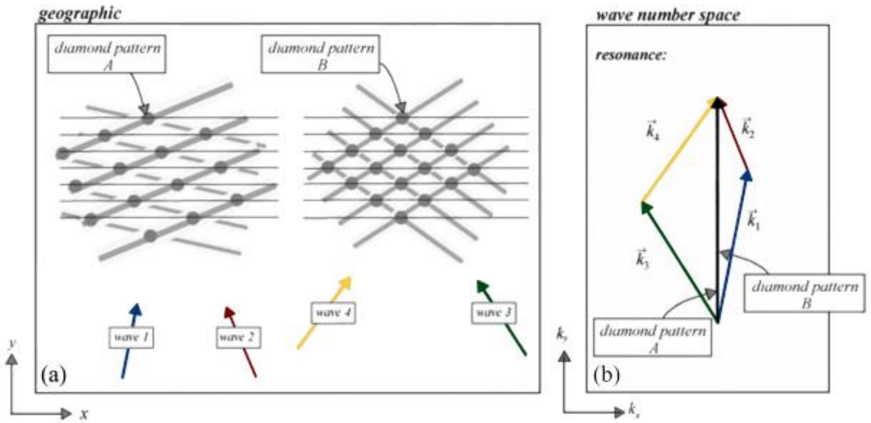
Physical Process	Deep Oceans	Shelf Seas	Shoaling Zone	Harbours
Diffraction	*	*	**	****
Depth refraction/shoaling	*	***	****	***
Current refraction	*	**	***	*
Quad Wave Interactions	****	****	**	*
Triad Wave Interactions	*	**	***	**
Atmospheric Input	****	****	**	*
White-capping	****	****	**	*
Depth Breaking	*	**	****	*
Bottom Friction	*	****	**	*

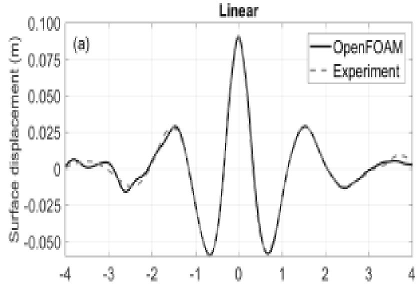


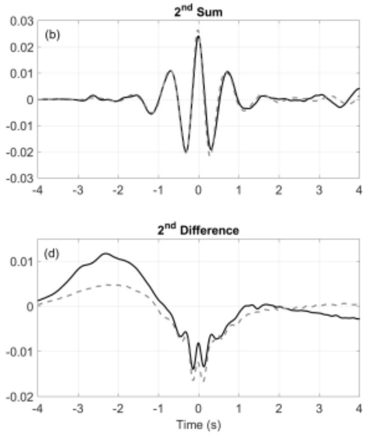












Capacities of numerical solvers for physical processes

Physical process / Numerical models	Formulation/ Numerical Methods	Wave Diffraction	Wave Refraction	Wave Dispersion	Wave Non-linearity	Wave Breaking	Wave Run-up	Over-topping	Turbulence	Wave-Structure Interaction	Wave-Current Interaction
Navier-Stokes (CFD)	FVM or FEM FDM SPH	**** **** ****	**** **** ****	**** **** ****	**** **** ****	**** **** ****	**** **** ****	**** **** ****	**** **** ****	**** ***(1) ****	**** **** ****
Hydrostatic	FDM or FVM	****	****		**				***		**(2)
Potential flow	BEM FEM FDM	**** **** ****	**** **** ****	**** **** ****	*** *** ***	*(3a) (3c) (3d)	*** *** ***	* *		***(3b) *** **	
Shallow Water Equations	FDM or FEM	****	****		***	**	***	*+	*+	*+	*+(4)
Boussinesq	Standard High-order	**** ****	**** ****	** ***	**+ ***	**+ ***	*** ***	*+ *+	*+ *+	*+ *+	** **(5)
Mild Slope Equations	Elliptic (6a) Hyperbolic (6b) Parabolic (6c)	**** **** ***	**** **** **	**** **** ***+	* * *	* * *			+ + +	*+ *+ +	** ** *
Spectral	Wave Energy Wave Action	+ +	**** ****	**** ****	** **	** **+			** **		***

Comments: (1) Cut-cell, Virtual Boundary Force, or their kinds used; (2)Mainly for current simulation only and solved in the σ-coordinate; (3a) For initiation of wave breaking only; (3b) For large structures only; (3c) Adaptive mesh or σ-coordinate; (3d) σ-coordinate; (4) Current module only in a coupled model; (5)For coupled wave-current simulation; (6a)For steady wave field only; (6b)For transient wave field; (6c)Waves with primary propagation direction.

Notes: 1) The number of stars represents the level of suitability of a particular model for the corresponding wave phenomenon; + represents half star .
**** highly suitable; *** moderate suitability; ** poorly suitable; * not suitable; no star indicates incapability of the model to replicate the physical process.

Requirements and efficiency of numerical models

	Required Skill	Computational Cost	Solver	
			Complexity	Stability
Navier-Stokes (CFD)	High	****	Complex	Possibly unstable
Hydrostatic	Medium	**	Simple	Stable
Potential Flow	Low – High[1]	**	Simple[3]	Stable[4]
Shallow Water Equations	Medium	*	Simple	Stable
Boussinesq	Medium	**	Simple	Possible unstable
Mild Slope Equations	Low	**	Simple	Stable
Spectral	Low – High[2]	*	Simple	Stable

[1]There are four types of potential flow models which require different level of skills: a) linear BEM, b) semi-analytical techniques, c) time-domain formulation and d) non-Linear BEM, requiring low, high, medium and high skills respectively.
[2]Low corresponds to "supra-grid" models and High corresponds to "sub-grid" spectral models
[3]Potential flow models with nonlinear BEM are characterized as complex.
[4]Time-domain potential flow models can be unstable.

Commonly used solvers

	Navier-Stokes (CFD)	Hydrostatic	Potential flow	Shallow Water Equations	Boussinesq	Spectral
OpenFOAM	✓			✓		
ANSYS CFX	✓					
DualSPHysics	✓					
SHYFEM				✓		
TELEMAC-MASCARET		✓				
FUNWAVE					✓	
Delft3D		✓		✓		✓
ANSYS AQWA			✓			
QALE-FEM			✓			
OrcaFlex			✓			
POM		✓				
COHERENS		✓				
WAM						✓
WAVEWATCH III						✓
SWAN						✓
MIKE 21		✓				✓
WAMIT			✓			

Suitability of numerical models for MRE problems

"Suitability = capacity x efficiency"

	Device Design				Array Design				
	Operation	Maintenance	Moorings		Resource	Device-Device Interaction	Array Geometry Optimization	Annual Energy Production	Environmental Impacts
			Response	Extreme					
Navier-Stokes (CFD)	***	****	****	****	*	****	*	**	**
Hydrostatic	*	**	**	**	***	***	***	**	****
Potential Flow	* to ****[1]	***	****	**	*	***	****	**	*
Shallow Water Equations	*	*	*	*	***	**	**	***	****
Boussinesq	*	*	**	*	***	**	**	***	***
Mild Slope Equations	*	*	*	*	***	**	**	***	***
Spectral	*	*	*	*	****	*	***	***	****

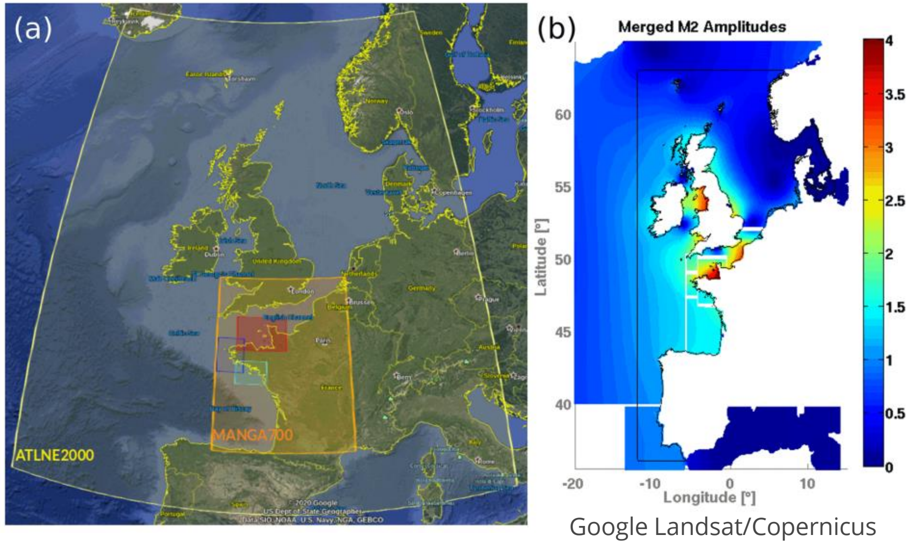
[1]Rating according to the different discretization methods, i.e.: a) linear BEM, b) semi-analytical techniques, c) time-domain formulation and d) non-Linear BEM.

BUT

- Performance and suitability should be assessed under the same conditions, e.g., resolution, numerical schemes etc
- Capacities of models improve with updates, and models tend to evolve to modelling platforms
- Models become modular with "on and off" switches for different physical processes
- Parameterisations of physical processes improve over time or with numerical schemes, and validations
- Computational power increases (HPCs, GPUs architectures, more efficient schemes)

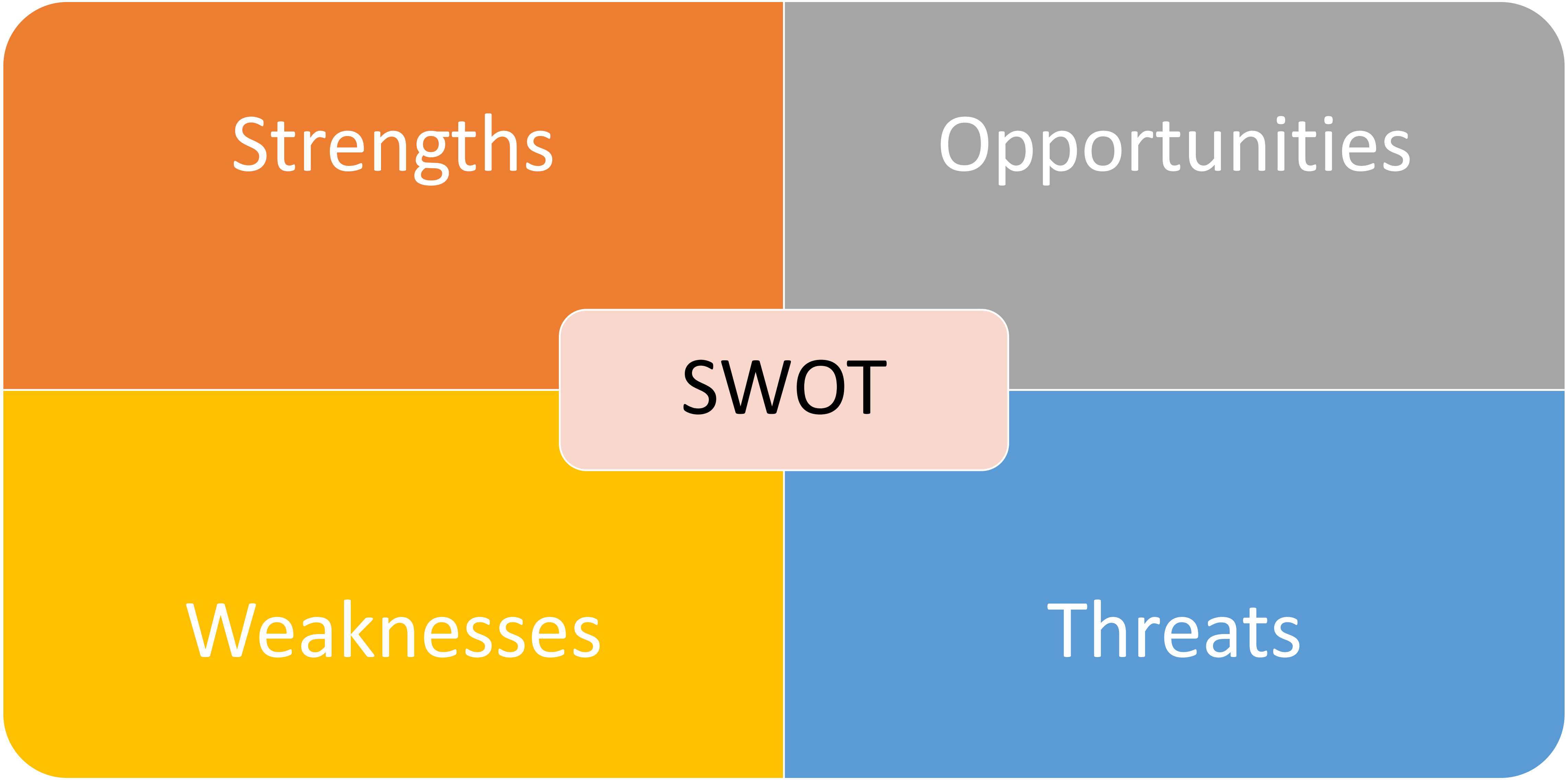
From individual models to integrated modelling

- **Integrated modelling:** Employing different models in a single platform that exchange information dynamically (coupled) while running in parallel (e.g., one-way or two-way nesting, far and near field propagation with spectral and phase resolving models). *Principle*: Use the most suitable model for each purpose.
- **Composite modelling:** It refers to the integrated and balanced use of physical and numerical modelling, which attempts to mitigate the weaknesses and make use of the advantages of the two classic modelling methods. *Principle*: Use the most suitable technique or source of data for each purpose.
- **Digital Twins:** A digital representation of the real world that allows to combine different processes or entities into a single modelling framework to simulate past, present and future scenarios for decision making (what if?). Data sources vary from demographics, financial, numerical models, to in-situ and satellite data, or even social media.
  Principle: Try to understand the interdependencies of different systems that interact with each other in real time and benefit many disciplines.
- **Artificial Intelligence:** physical processes can be to an extent predictable and repetitive. *Principle*: Machine learning can be used to avoid resolving the governing equations and gain computational efficiency.



Google Landsat/Copernicus

SWOT analysis for numerical models



SWOT analysis for numerical models

- Validated already for many physical processes
- Available documentation and user groups
- Lower cost compared to physical models (infrastructure, remote operation, person hours etc)
- Checking different conditions and configurations
- Data extraction anywhere in the computational field
- Fewer scaling issues

- Increasing computational power (CPUs, GPUs, HPCs)
- Efficiency gains from numerical schemes
- Validation for different problems / composite mod.
- Open-source codes and open data (FAIR principles)
- Becoming part of standard engineering practice
- Use of integrated systems, digital twins and AI

SWOT

- Limited validity of used parameterisations
- Wrong configurations can lead to unrealistic results
- Grid and time-step resolution dependencies
- Computational resources needed for complex models
- Time consuming for long and complex simulations
- Highly specialised personnel needed

- Misuse, beyond areas of applicability, convergence
- Unskilled modellers without experience
- Lack of validation and overconfidence in capabilities
- Loss of trust by the engineering community
- Dominance of commercial software / consultancies
- Open-source software not user friendly
- High cost (electricity / carbon footprint, personnel)

Takeaways

What are your takeaways so far?

- There are various ways to model water waves
- The two main categories of models are phase-resolving and phase-averaged
- The selection of the model should be done according to the physical problem and the available resources
- Models are constantly evolving and corrected (bug fixing or better parameterisations)
- Models are useful, but should be used with caution (e.g., convergence and validation)
- There are new opportunities and fields of interdisciplinary research arising with the emergence of Digital Twins

Short break?

Extreme Waves
The monsters of the deep

Extreme Waves: The monsters of the deep

6 deadly attacks per year

30 platforms in 2005, Gulf of Mexico



Ekofisk oil platform

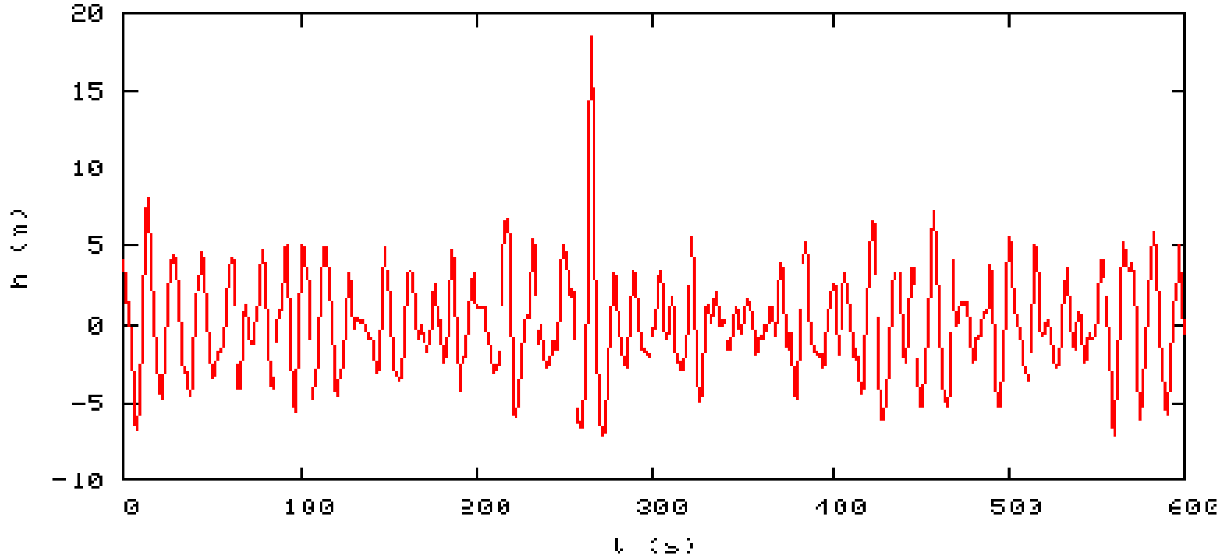
From myth to reality

From myth…

Walls of water, Holes in the sea, Pyramids, Giant Monsters, Three sisters, Mad dogs, “frozen” wave profile

…to reality

The Draupner wave 25.6m – New Year’s Day 1995, North Sea



Extreme/freak/rogue waves definition: Random individual events, not expected for the surrounding sea state

$$\frac{\eta_c}{H_s} > 1.25 \quad \text{and/or} \quad \frac{H_{max}}{H_s} > 2$$

(empirical definition by Haver, 2000)

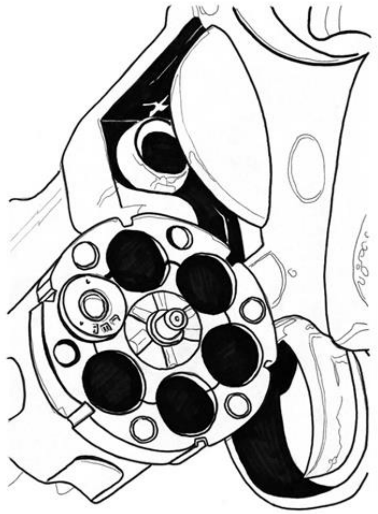
Extremes can be particularly dangerous because they can appear in a mild sea (unexpected) and propagate in oblique direction to the main one, striking from the side. But reliable measurements taken only from platforms.

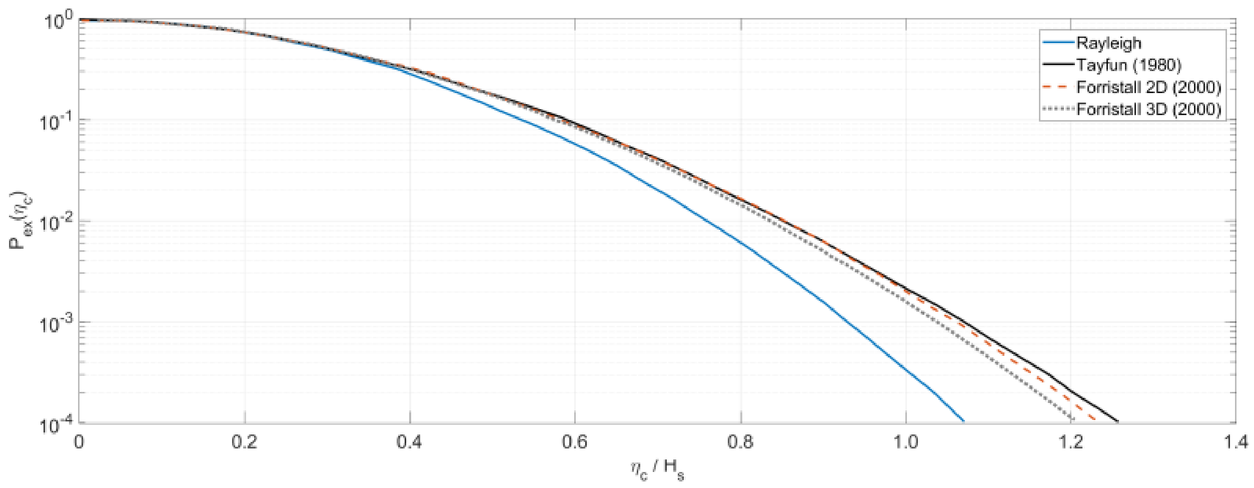
Importance of extreme waves in offshore industry

Probability of occurrence

Likelihood × Impact

- In general: “Rare” but catastrophic → Safety factor?
- How rare? Different statistical population? For engineering purposes, we need to know return period of the chosen design wave
- Most extremes belong to 2nd order probability distributions, but in measurements appear as kick-outs at the tail (filtered our as outliers!)
- Deviations depending on the steepness and directionality
- An extreme wave is expected in ≈ 10^5 waves; more common in a region
- Models capture the wave height well, but not the crest elevation





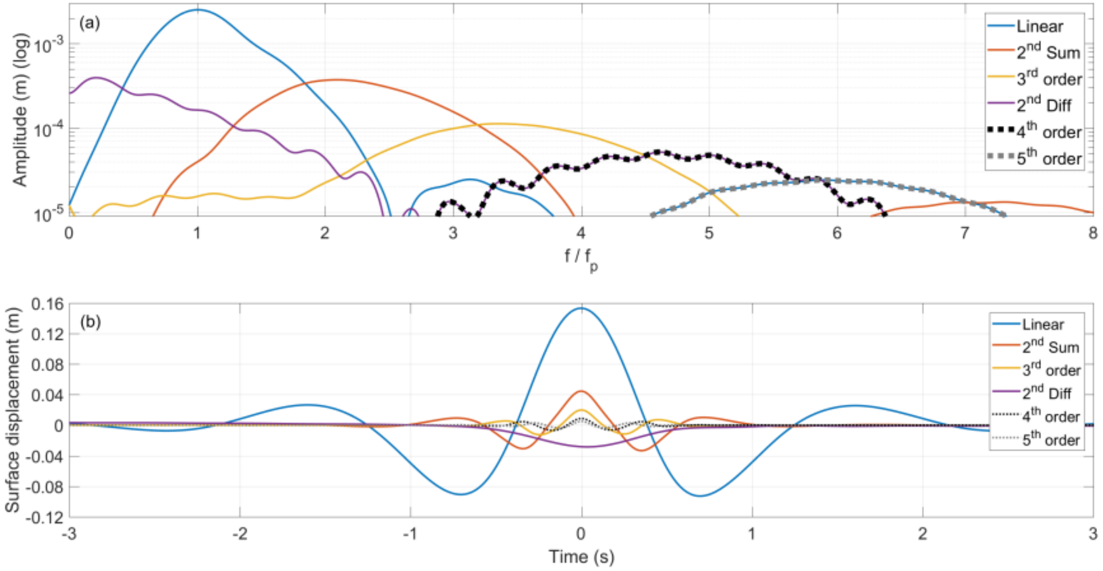
Challenges in detecting & deriving statistics

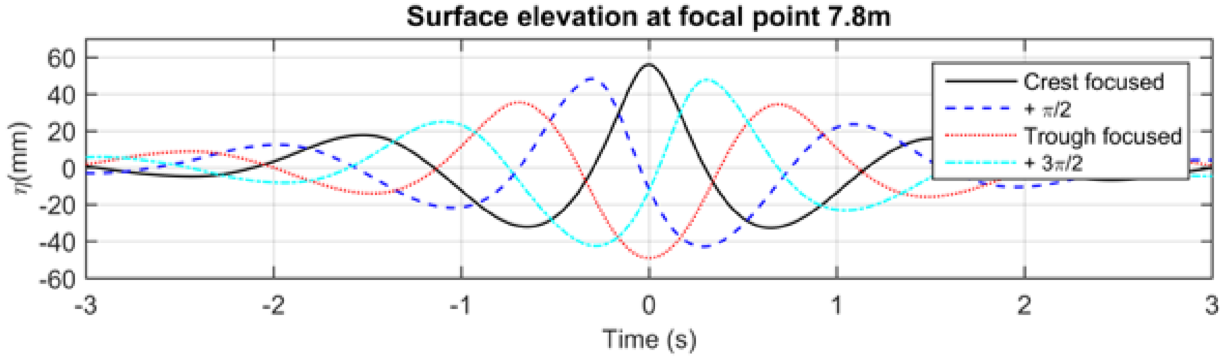
- Rare → need for long simulations / measurements
- Directionality & crossing seas
- Instrument errors at field data, sampling rate
- Apparatus can influence the measurement, e.g., Lagrangian motion of wave buoy, runup, breaking
- Breakdown of assumptions of stationary fields
- Uneven crest-troughs, wave breaking

Importance of extreme waves in offshore industry

Offshore industry

- Loading is not a “well-behaved” problem for increasing crest height affecting different parts of the structure not expecting direct impact
- Slamming: very high loads from wave impact on the deck; runup, overtop
- Shapes of extreme waves vary based on phases and directionality
- Fatigue: High harmonics cause dynamic response of structure aka ringing





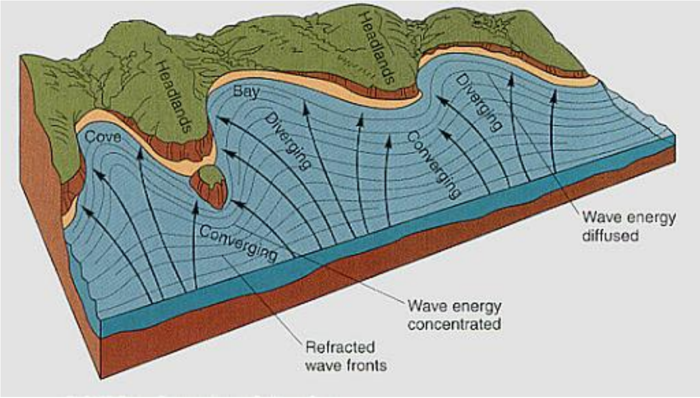
MRE industry

- Devices are located in energetic seas
- Devices have many moving parts
- Survivability of devices → De-risking

Physical Mechanisms of extreme wave generation

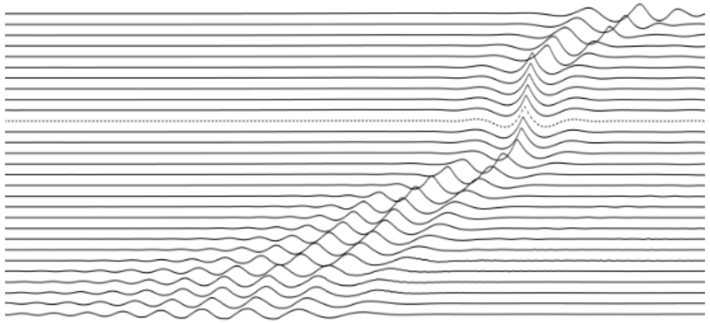
Spatial focusing

Refraction of waves in varying bottom topography or in variable/opposing currents (Agulhas current) causes local energy concentration (hot spots) and increase in steepness. Mostly captured by linear theory.
Researchers: Peregrine, Smith, White & Fornberg, Dysthe



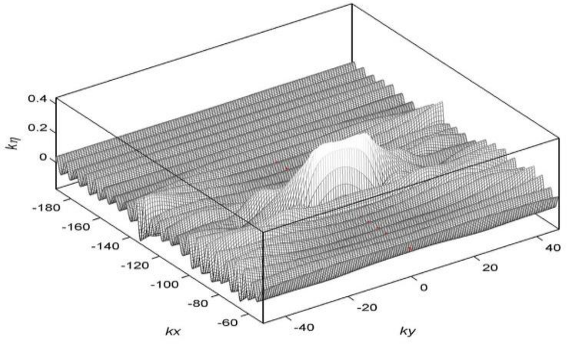
Dispersive focusing

Gravity waves are dispersive with phases and velocities proportional to the period. Phases of the wave components can be correlated to create a large wave at a specific location and time (NewWave theory). However, statistical distributions consider randomness.
Researchers: Taylor, Adcock, Baldock, Swan, Bredmose



Nonlinear focusing

Benjamin-Feir Instability, aka modulational or sideband instability, which leads to the disintegration of a wave group into isolated pulses (applications in other fields). More applicable for deep water and narrow, unidirectional spectra (not common in real ocean).
Researchers: Onorato, Toffoli, Trulsen, Dysthe

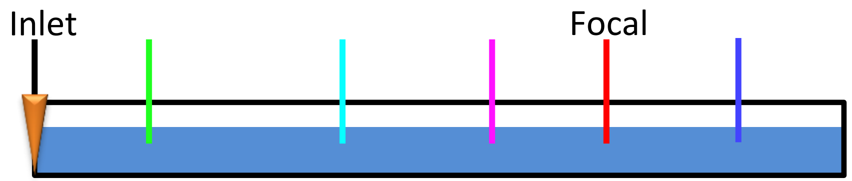


The NewWave theory

Definition: NewWave is a mathematical formulation that estimates the average shape of the largest waves and their kinematics for a given sea state if the amplitude spectrum is known (Tromans et al., 1991). Practically, the largest wave is a *focused wave group*, corresponding to the autocorrelation function of the spectrum, which is a crest focused wave (zero phases).

NewWave

→ Largest waves of a sea state → Design wave deterministic



$$\eta(x,t) = A \frac{\sum_{i=1}^{N} S(\omega_i)\cos(kx-\omega_i t)}{\sum_{i=1}^{N} S(\omega_i)}$$

Lidgren (1970)
Boccotti (1982)
Tromans et al. (1991)

Application with focused waves ⇒ **Dispersive focusing**

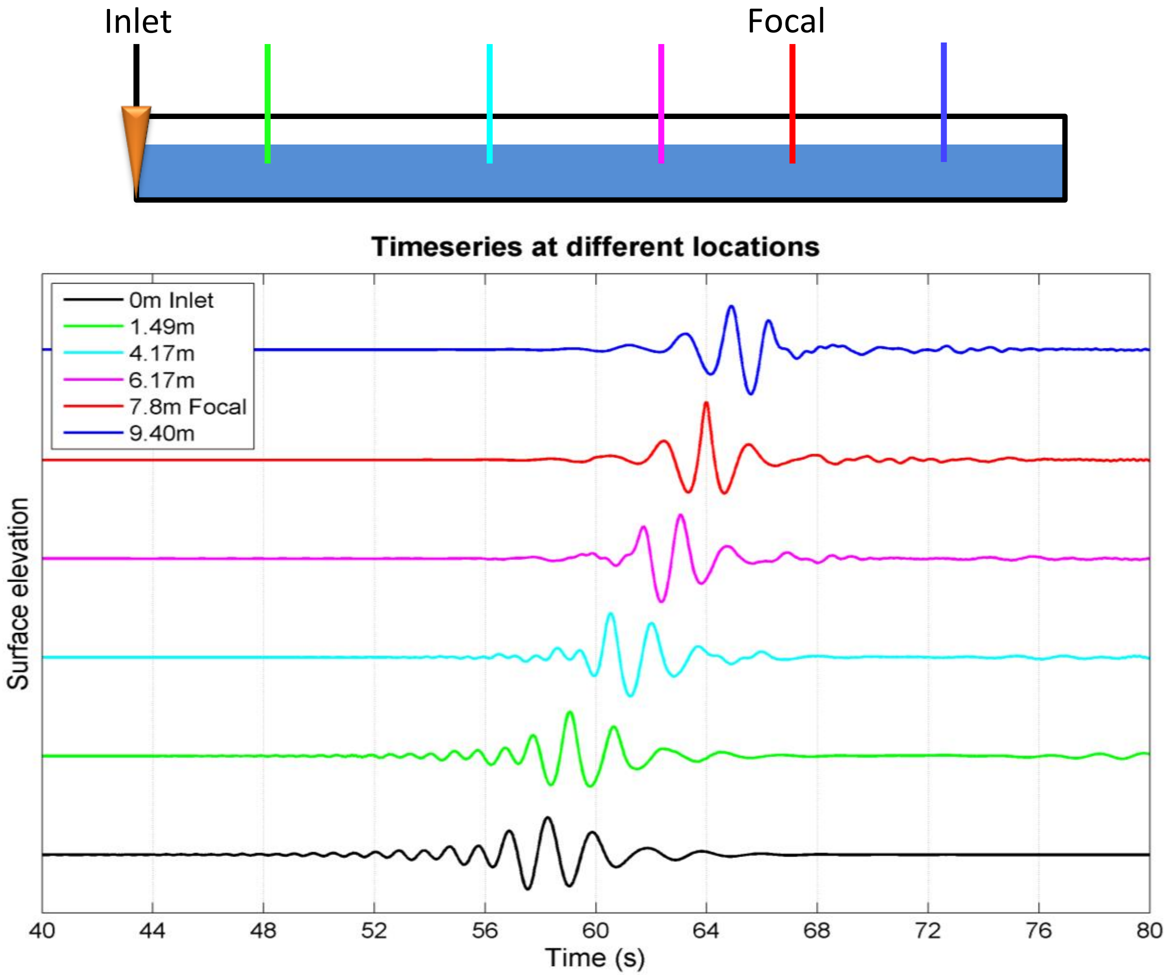
Advantages:

- ✓ It is deterministic and repeatable: we know where and when the extreme wave will occur
- ✓ No need for random simulations: significant savings in computational effort and accommodating limitations of experimental facilities (instrumentation, reflections, spurious)
- ✓ Simple to apply: extensively used physical and numerical modelling
- ✓ It can be used in different water depths and varying bathymetry
- ✓ It can produce compact wave forms of different shape for finding the design wave
- ✓ Better representation of kinematics (loading) than linear and 2nd order theory

BUT

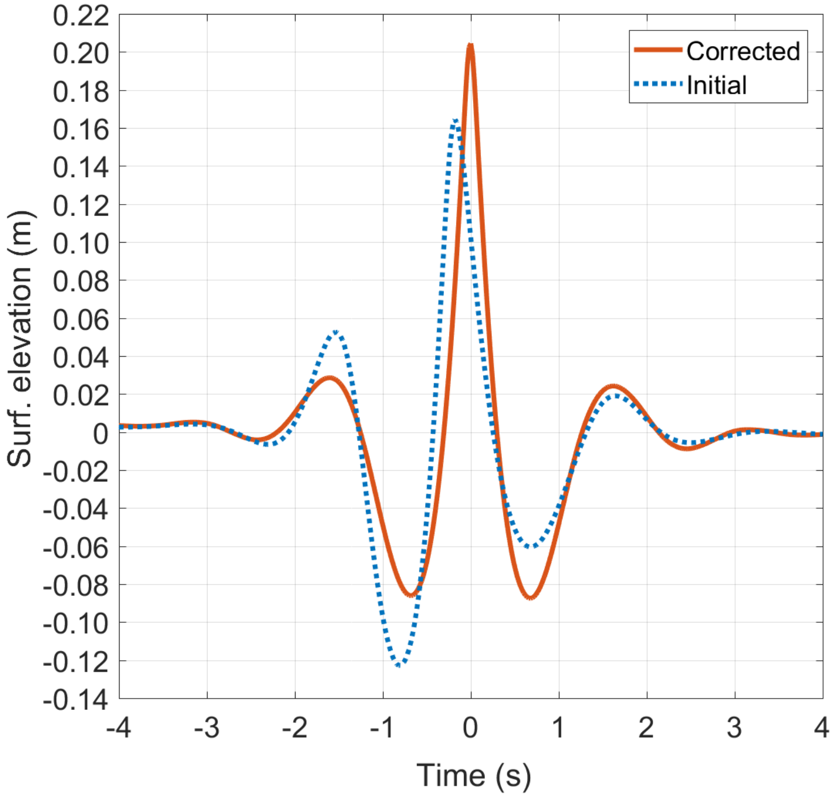
Based on linear theory….
…Large waves are steep and highly nonlinear

The effects of nonlinearities



Nonlinearities

- Change of the dispersive properties of the wave group: amplitudes and phases
- Different shape of wave form and severe underestimation of the crest height
- Missing the focusing location and time (no highest impact on the structure)
- Nonlinearities depend on the steepness



More than 20% difference at the crest

Focusing occurs due to the dispersive nature of waves.
The phases of the components are chosen at the wave inlet so that shorter waves are generated before longer in order for constructive interference of the components of the wave group to occur at the desired location.

Improving the signal for focusing

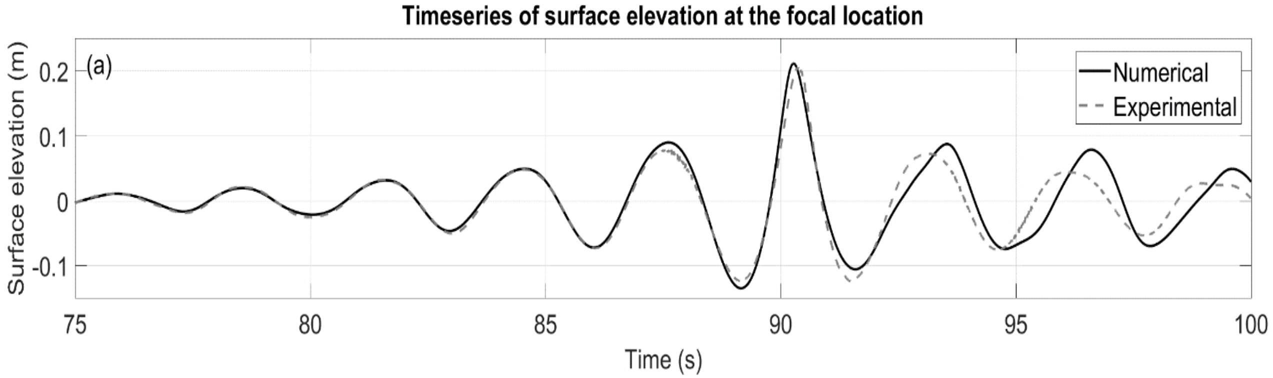
Focusing methodologies are techniques developed to cancel the nonlinear effects that cause downshifts to the focusing location and loss of symmetry with subsequent issues in the modelling of NewWave-type groups

No correction: the signal is not corrected because it is not needed (group of low steepness or dispersed), or not trivial (directional seas)
→ focusing location and time manually adjusted

Linear theory: iterative corrections using linear dispersion and FFT for returning the signal at the wavemaker. Best for low steepness, narrowband
→ focusing location and time not missed, but focusing not symmetrical

Nonlinear solvers: nonlinear models are used to return the signal from focusing to wavemaker. Best for low steepness, narrowband
→ focusing location and time not missed, but focusing not symmetrical

Trial and error: empirical adjustments of phases and amplitudes of the input signal to focus better, but not based on mathematical approach
→ focusing location and time may be missed



Phase decomposition: iterative corrections of the extracted 1st order harmonic, which is propagated backwards with linear theory
→ focusing location and time not missed, also for steep and broad spectra

The focusing methodology

Based on
Stokes expansion

Harmonic decomposition

$$\text{Linear:}\quad Af_{11}\cos\phi + A^3 f_{31}\cos\phi + O(A^5) = \frac{1}{4}\left(S_0 - S^H_{\pi/2} - S_\pi + S^H_{3\pi/2}\right)$$

$$2^{nd}\ \text{sum:}\quad A^2 f_{22}\cos 2\phi + A^4 f_{42}\cos 2\phi + O(A^6) = \frac{1}{4}\left(S_0 - S_{\pi/2} + S_\pi - S_{3\pi/2}\right)$$

$$\text{Third:}\quad Af_{33}\cos 3\phi + O(A^5) = \frac{1}{4}\left(S_0 + S^H_{\pi/2} - S_\pi - S^H_{3\pi/2}\right)$$

$$2^{nd}\ \text{diff} + 4^{th}\text{:}\quad A^2 f_{20} + A^4 f_{44}\cos 4\phi + O(A^6) = \frac{1}{4}\left(S_0 + S_{\pi/2} + S_\pi + S_{3\pi/2}\right)$$

Fitzgerald et al. (2014)
Stagonas et al. (2014)

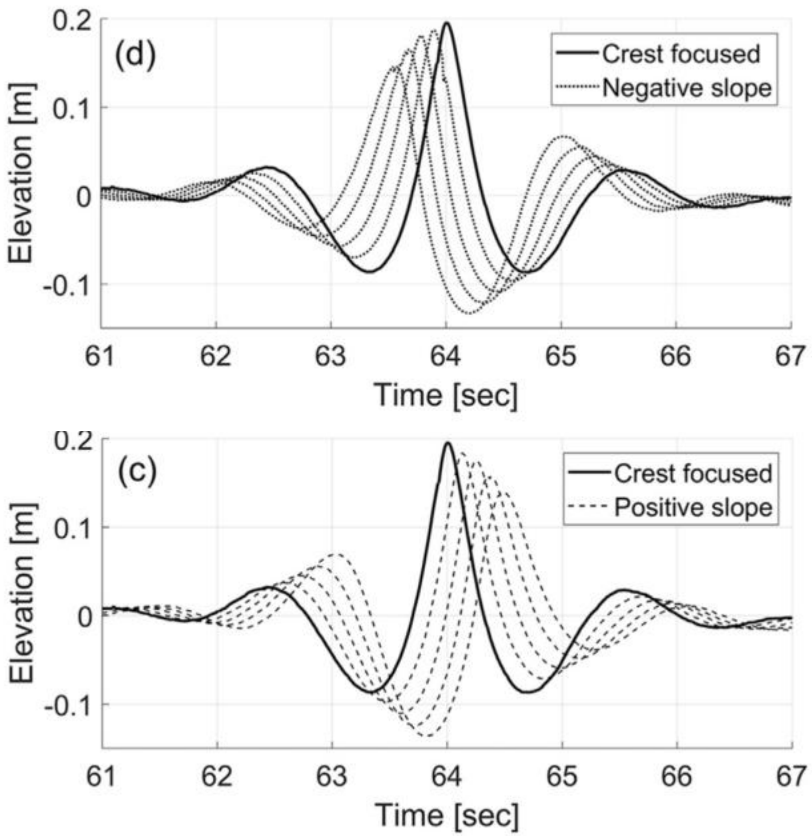
Hann et al. (2014)
12-wave decomposition

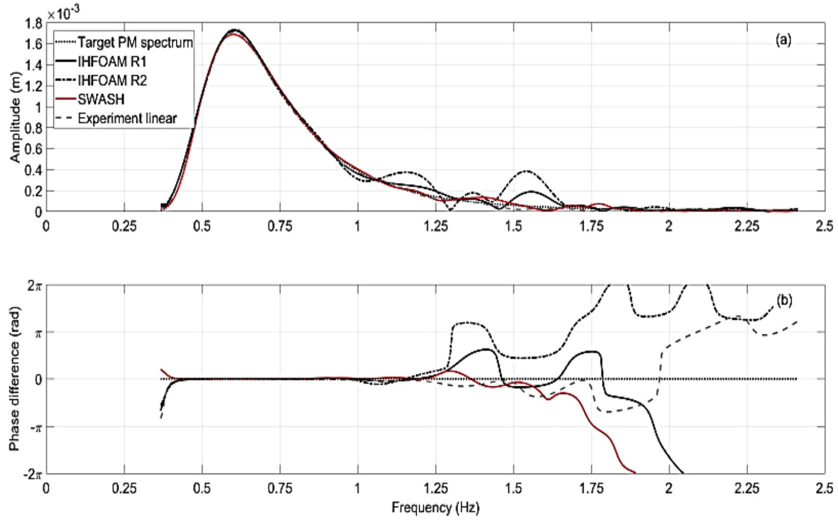
Wang et al. (2017)

Spectral analysis

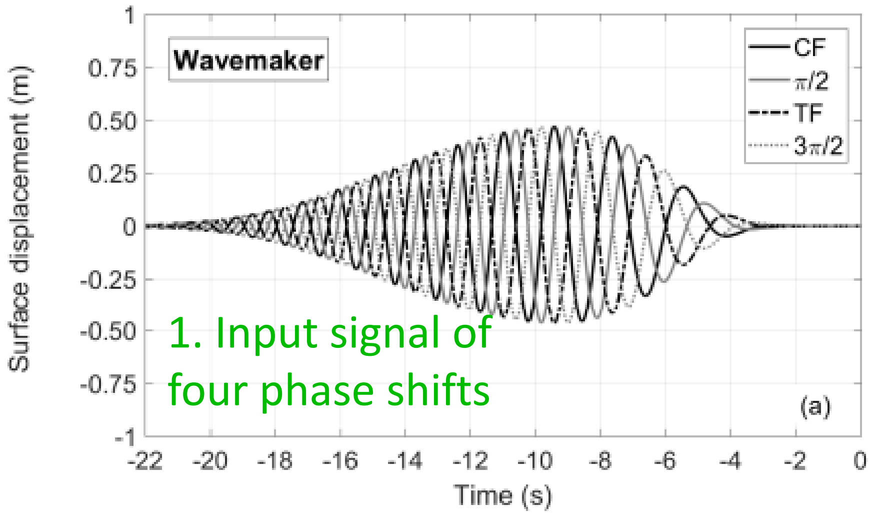
Correction

$$\alpha_{in}^{i+1} = \alpha_{in}^{i} \times \alpha_{trg}/\alpha_{out}^{i} \quad \text{and} \quad \phi_{in}^{i+1} = \phi_{in}^{i} - \left(\phi_{trg} - \phi_{out}^{i}\right)$$

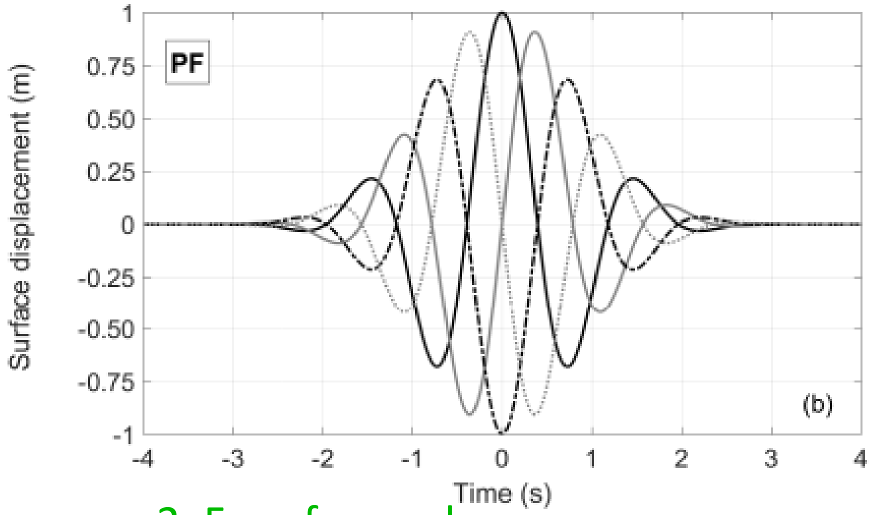




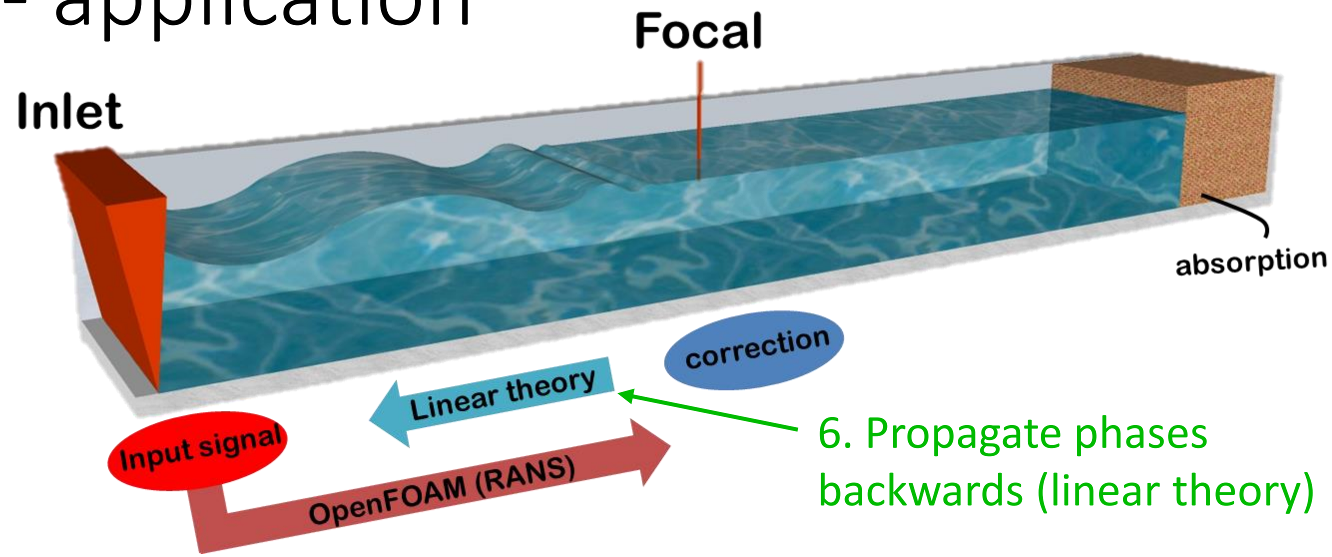
The focusing methodology - application



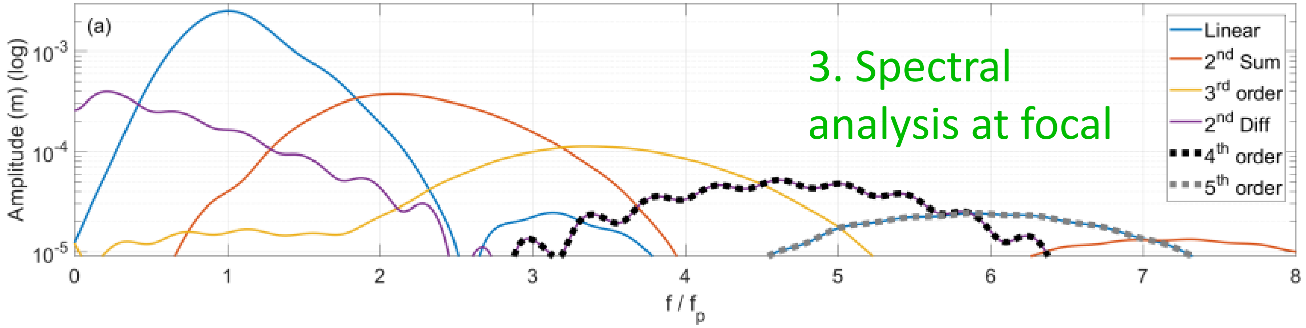
1. Input signal of four phase shifts



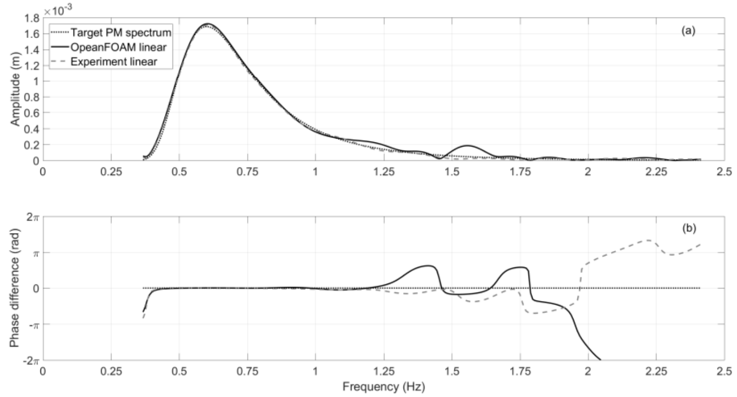
2. Four focused groups at focal



6. Propagate phases backwards (linear theory)



3. Spectral analysis at focal



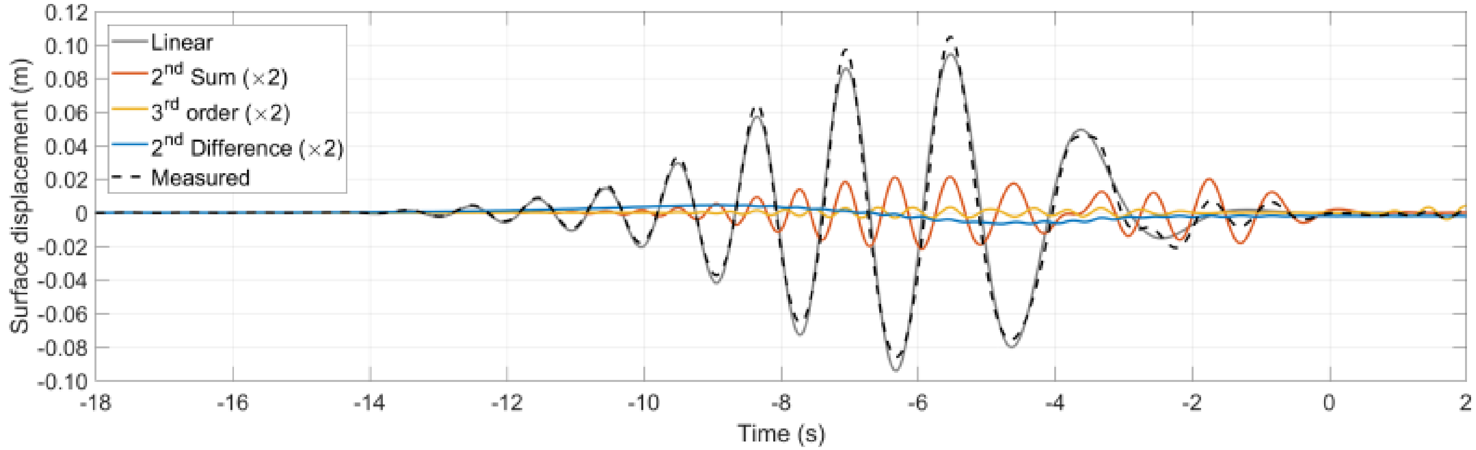
4. Amplitude correction to target spectrum

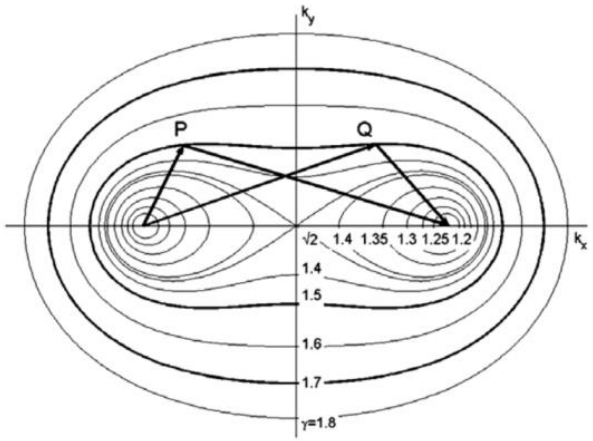
5. Phase correction to zero phases at focal

Basics on wave-wave interactions

- Free waves: obey the linear dispersion relation, propagating independently.
- Bound waves: phase-locked to the free waves, propagating with the celerity of the wave group.

- **Resonant interactions**: nonlinear wave-wave interactions between three or four free wave (triad and quad interactions) components that create new free wave components. Exact conditions for the frequencies and wavenumbers, which take the mathematical form of a linear resonator, must apply (Phillips, 1960).
- **Bound interactions**: nonlinear wave-wave interactions among pairs of free waves that generate bound harmonics. at multiple integers of the frequencies of free waves, referring to second, third, fourth etc harmonics. At half of the free wave frequencies, bound long waves are generated, aka as low frequency or infragravity (IG) waves
- **Near-resonant interactions**: similar to resonant interactions, but the exact conditions are not satisfied. Important for the generation of free wave in long-crested seas as well as numerical and physical flumes.
- **Non-resonant interactions**: depending on the context, may refer to bound, near-resonant or BF instabilities.





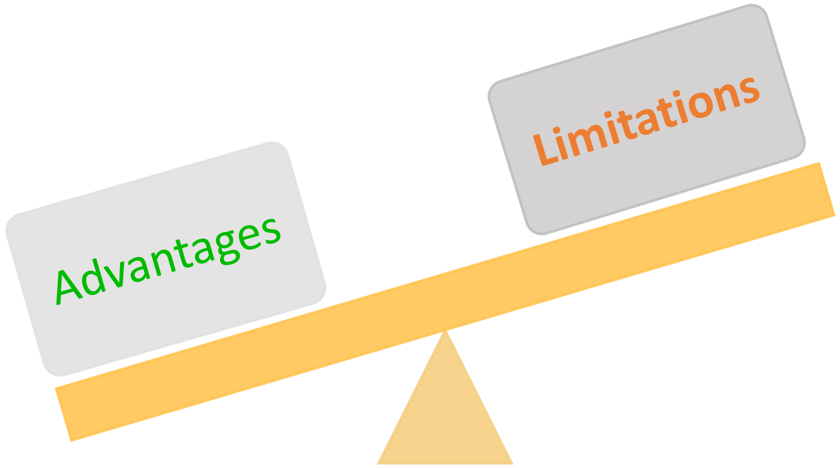
Why does the focusing methodology work?

Advantages:

a) The methodology extracts the free-wave (linear) spectrum and corrects only this. Most other methodologies correct the full nonlinear spectrum in a linear way, which is not consistent;
b) Objective focusing with a pre-defined target spectrum;
c) Accurate extraction: The linear harmonic doesn't overlap with other orders;
d) Simplicity: The linear dispersion relation is used to propagate backwards the signal from PF to the wavemaker;
e) Consistent: In most cases the transfer functions of the wavemaker are linear and when second order generation is used it is based on the free-wave spectrum;
f) It lets the nonlinear medium do the work and naturally evolve the signal to nonlinear: the nonlinear harmonics are uniquely defined by the free-wave spectrum;
g) It can be used with currents and waves.

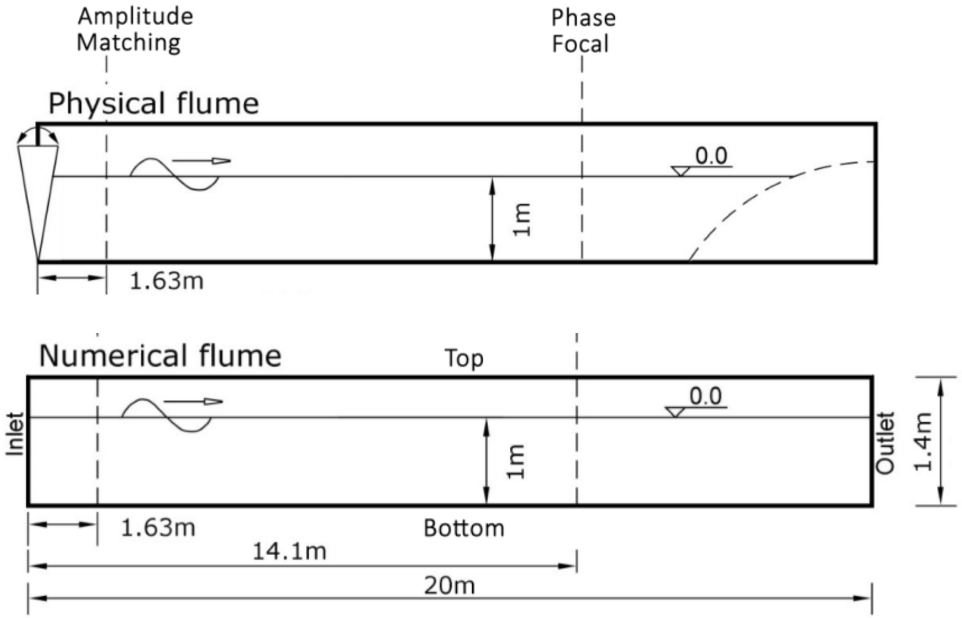
Limitations:

a) It cannot be applied to breaking waves;
b) Reflections, which are free waves at similar frequencies, can contaminate the signal and damage the corrections;
c) Computational cost: Four phase shifts are needed per correction and 3-5 corrections in total;
d) Not yet applied in directional or crossing sea states.

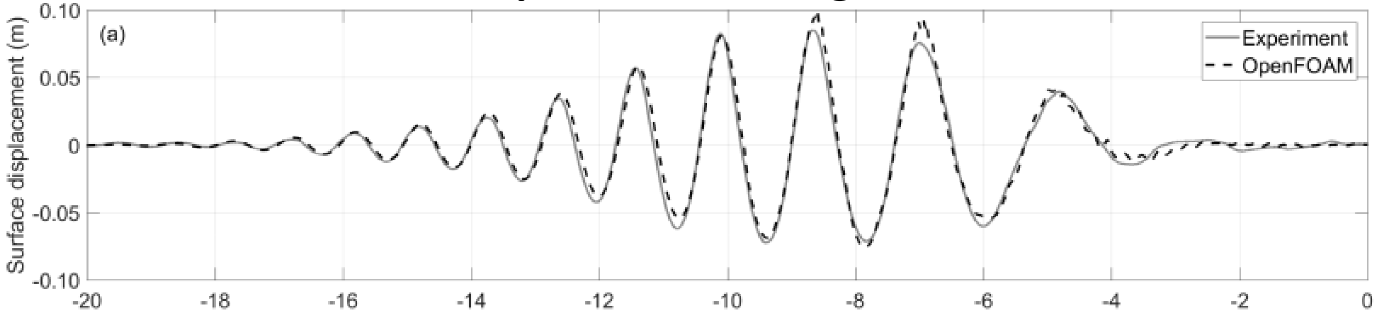


Validation of numerical models – Dispersion study

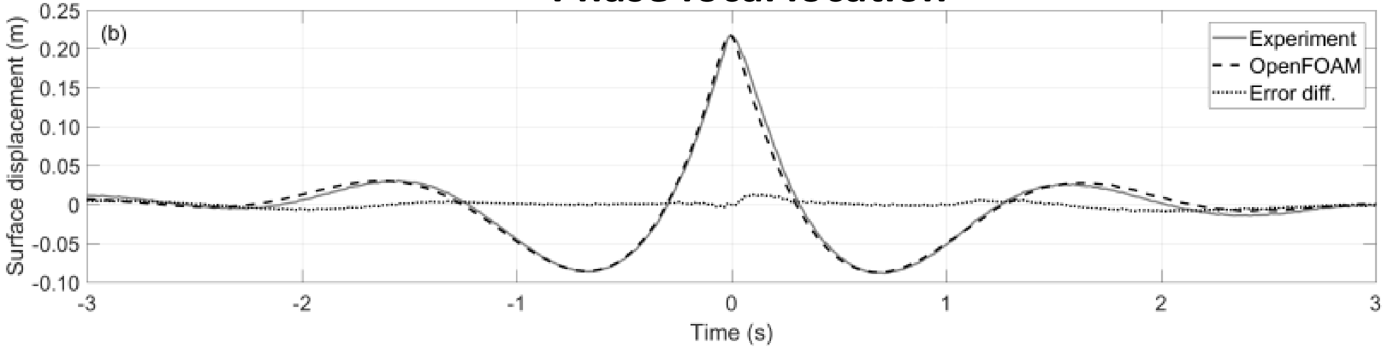
Nearly breaking wave group in physical and NWT



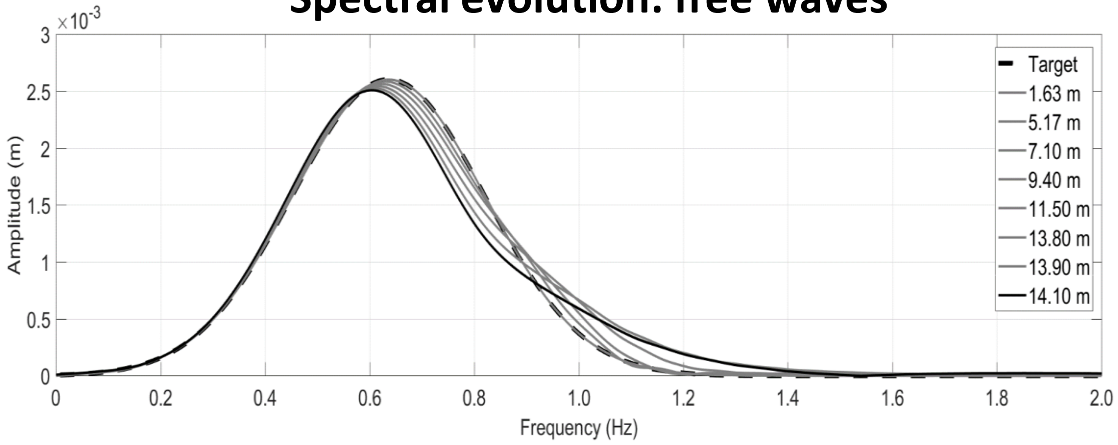
Amplitude matching location



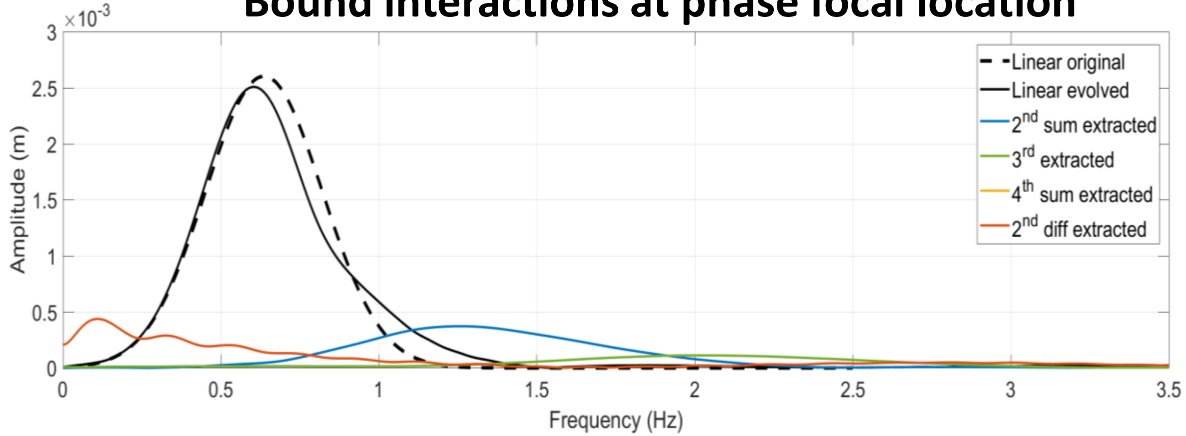
Phase focal location



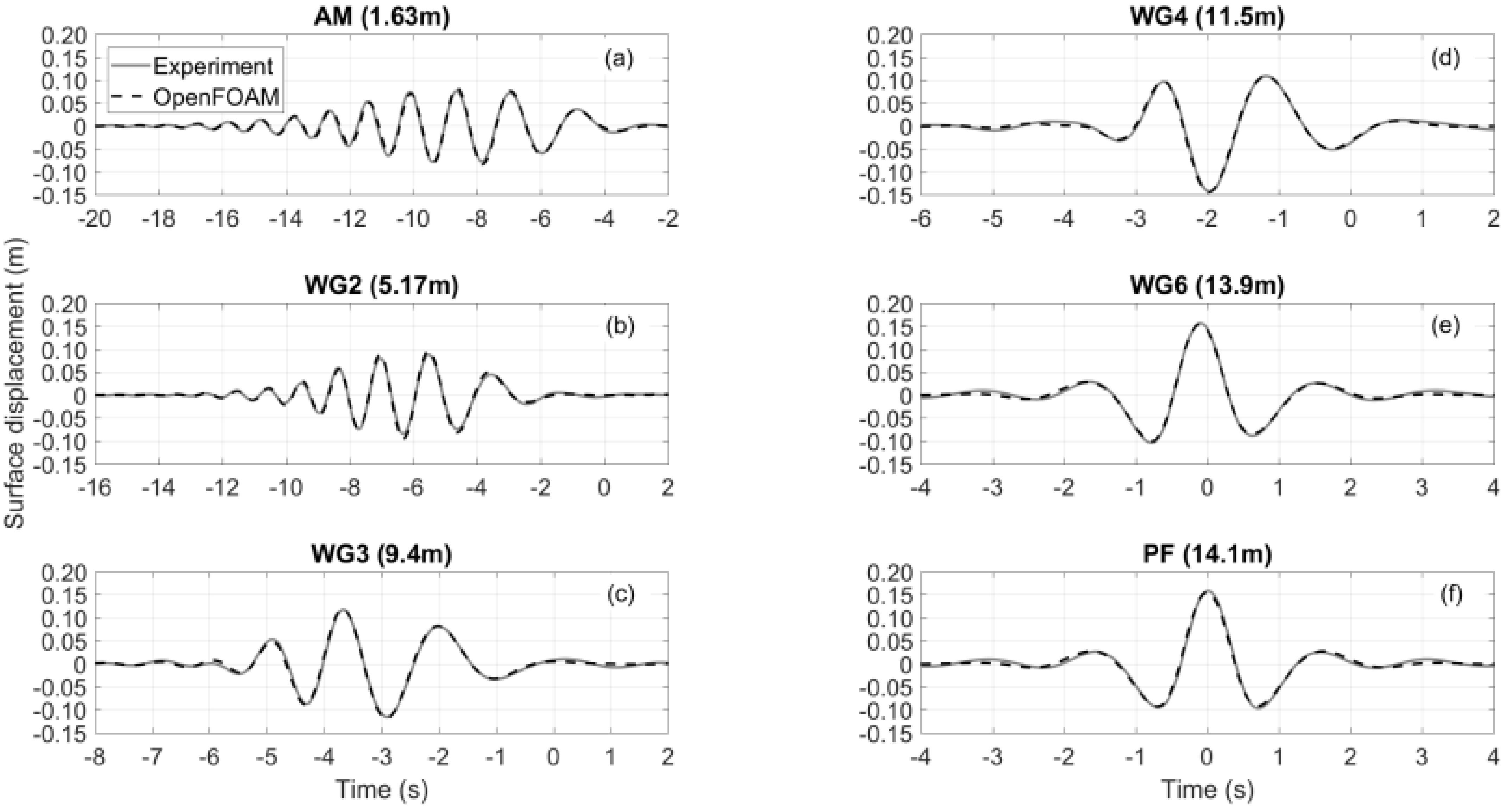
Spectral evolution: free waves



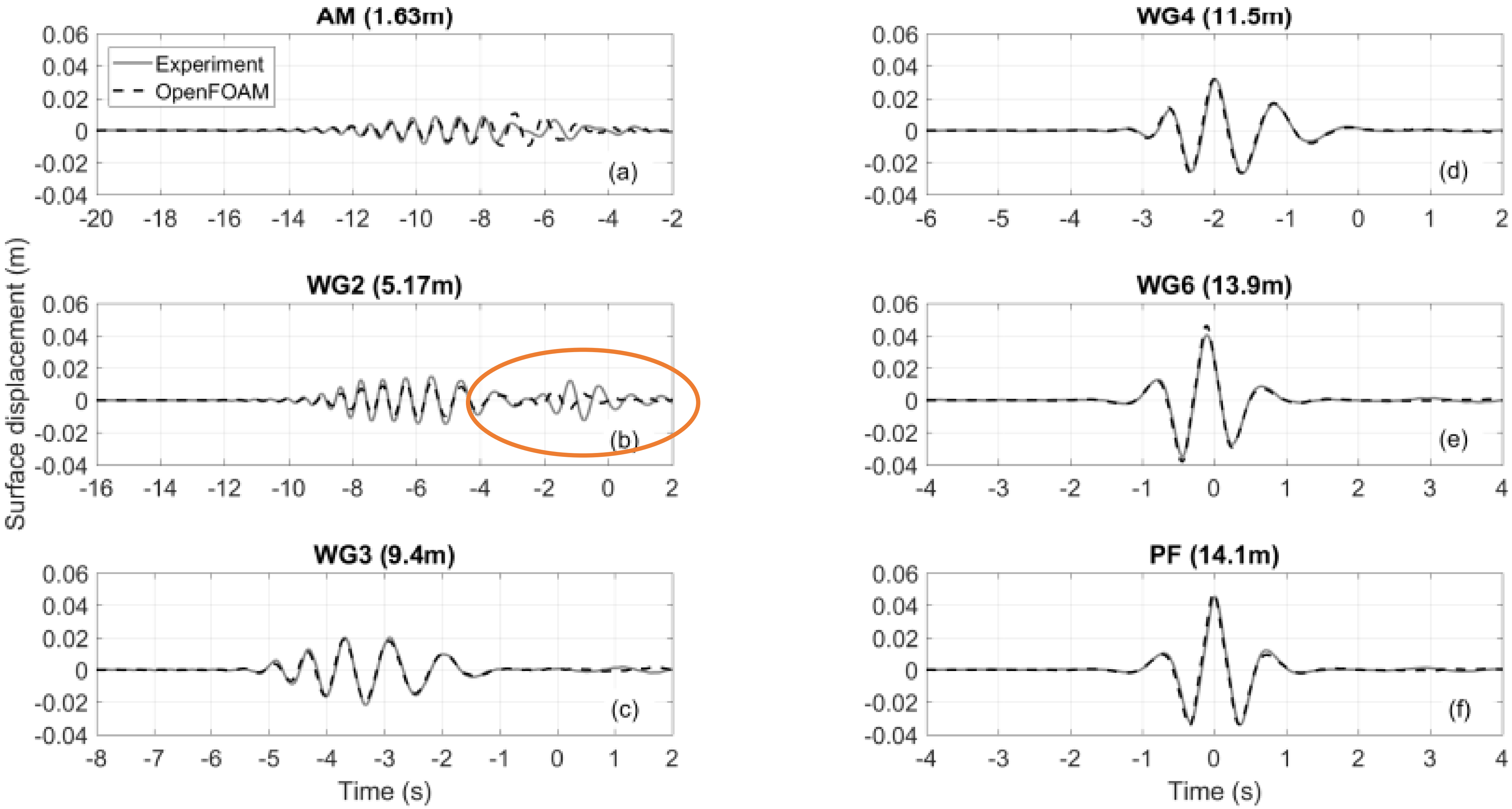
Bound interactions at phase focal location



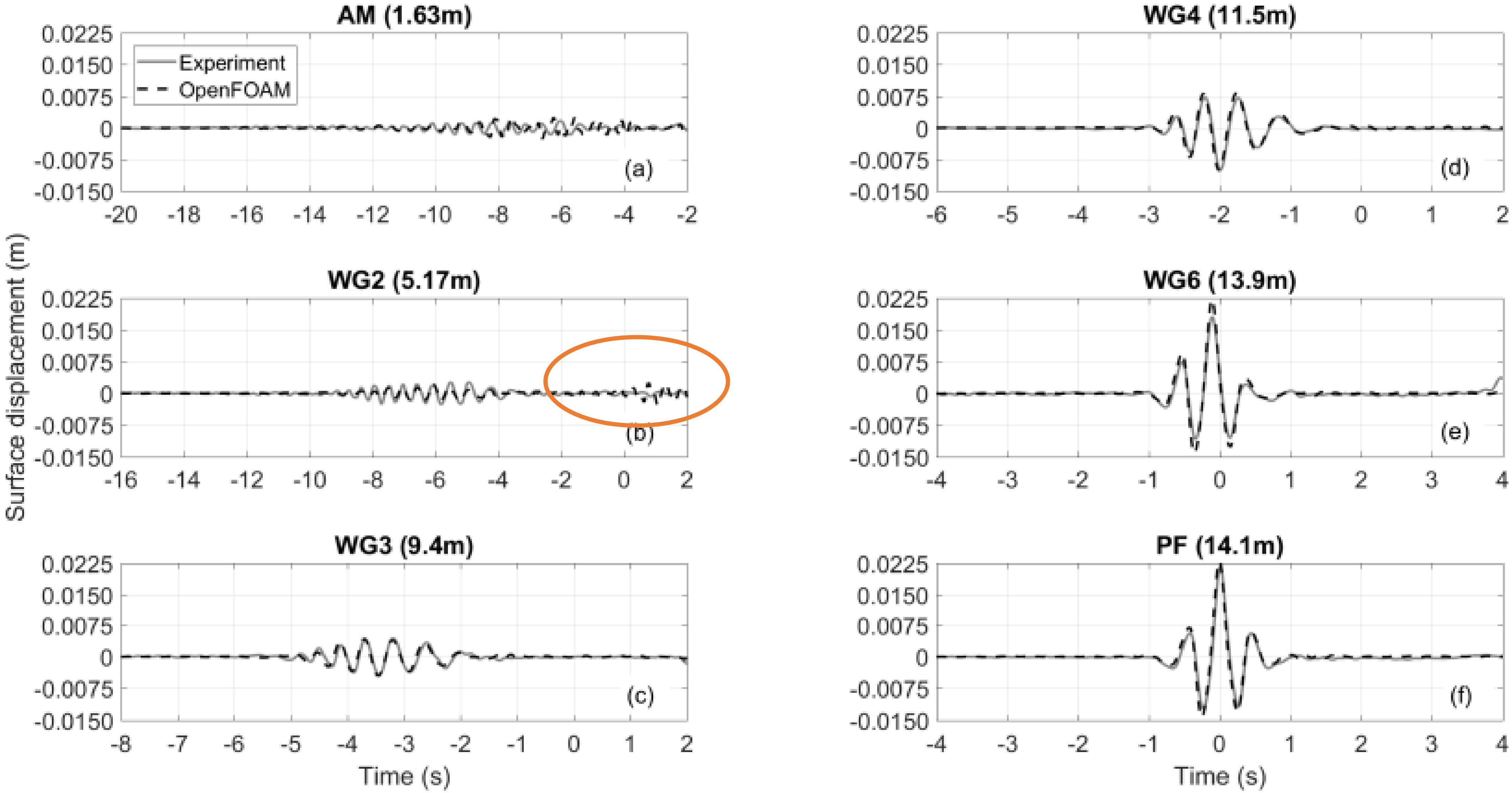
Dispersion study – linear harmonic evolution



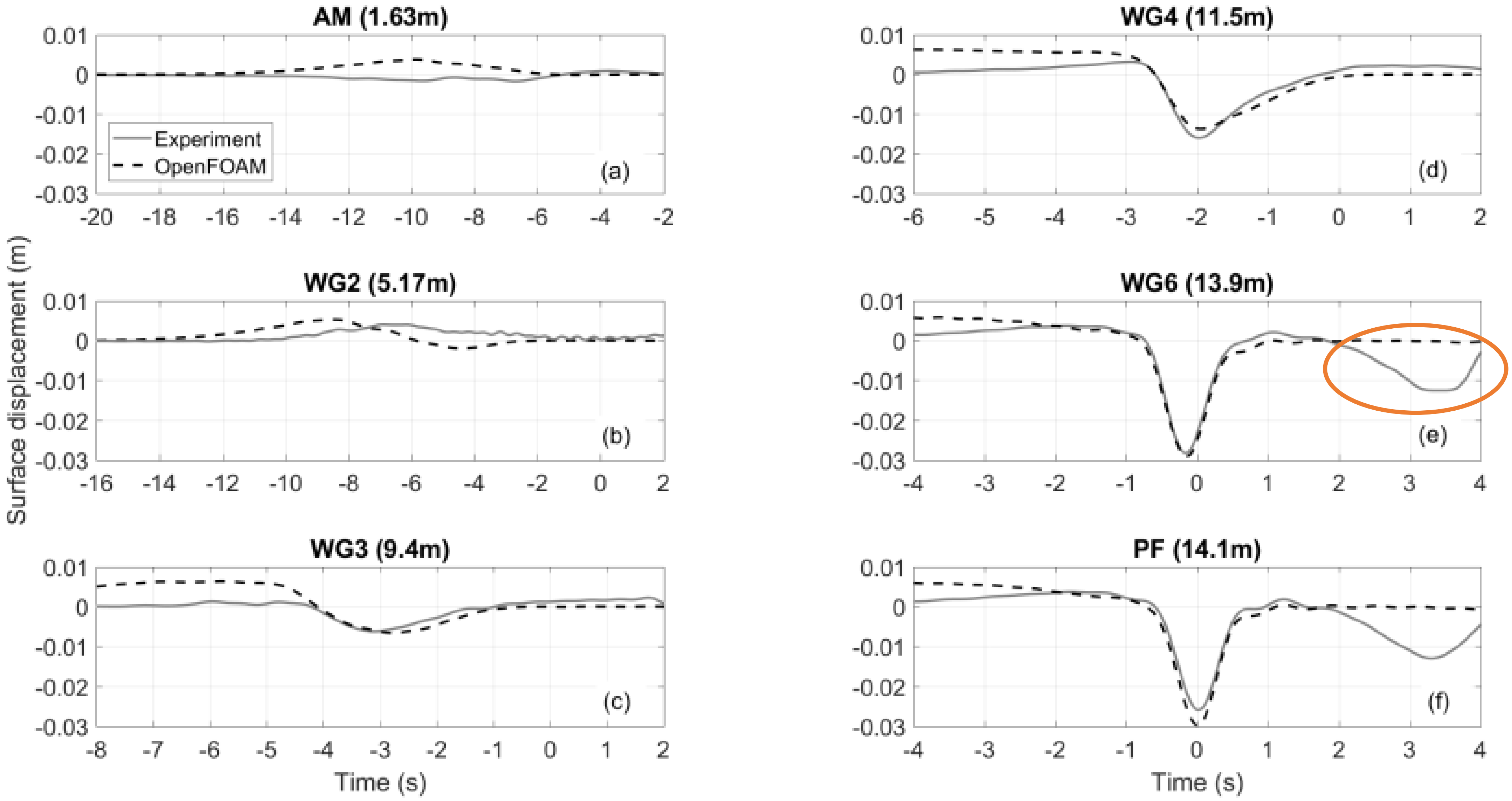
Dispersion study – 2nd order sum harmonic evolution



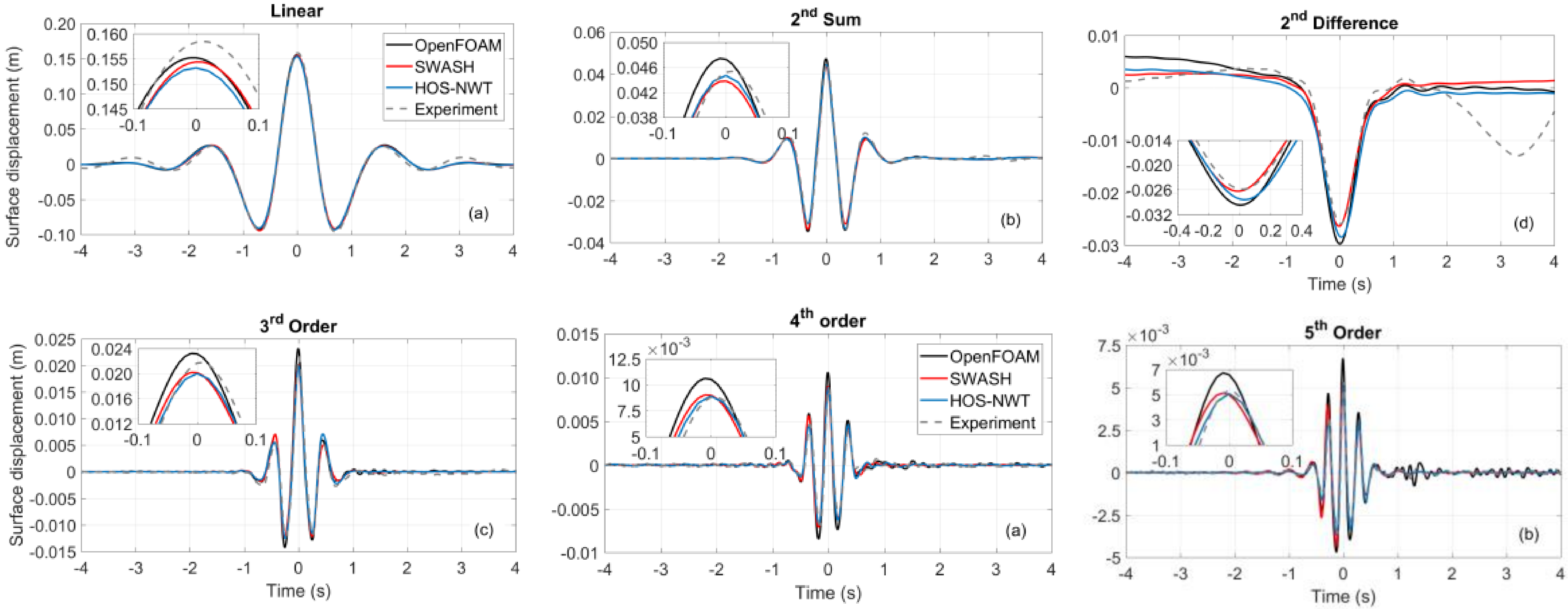
Dispersion study – 3rd order harmonic evolution



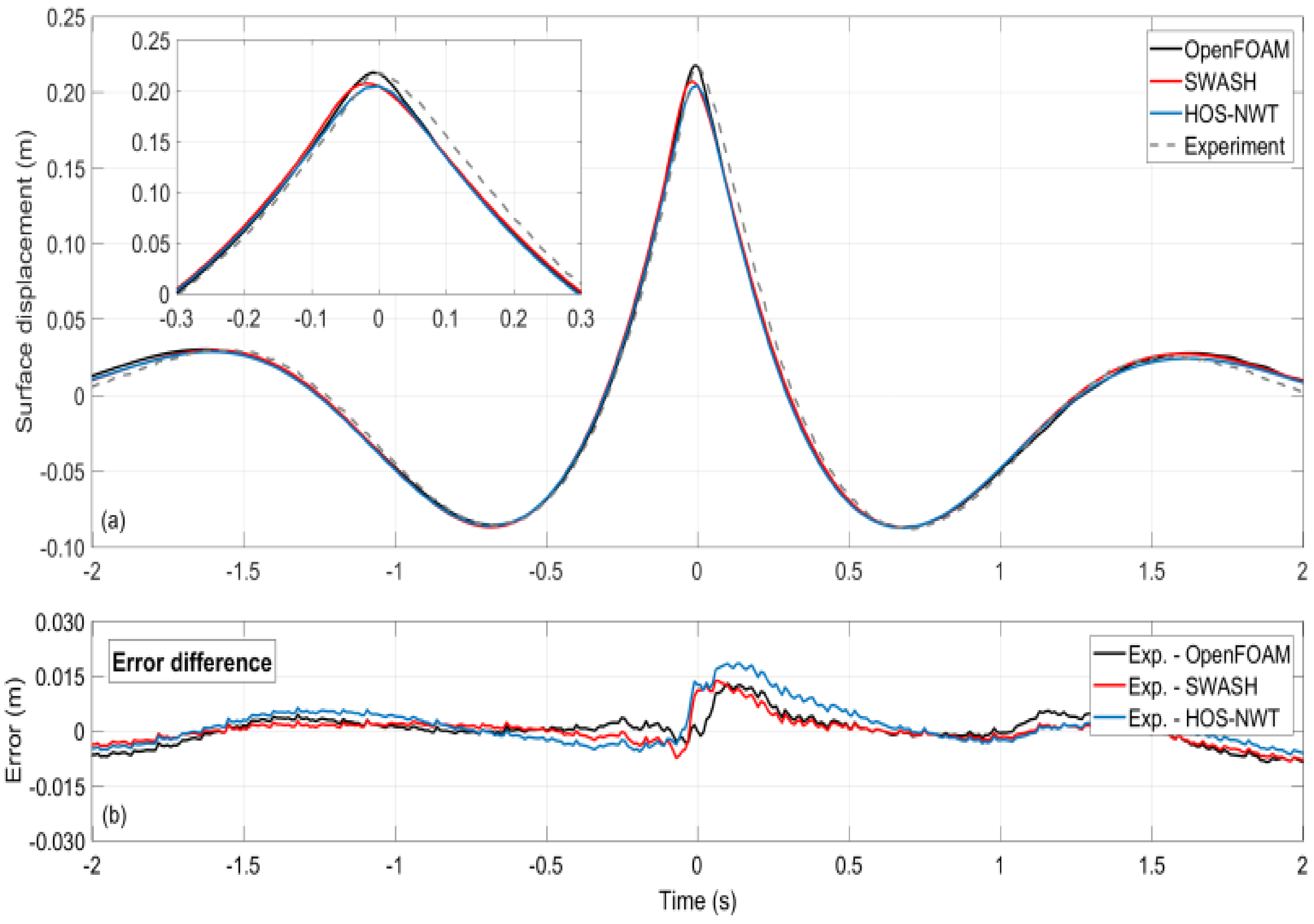
Dispersion study – 2nd difference harmonic evolution



Intercomparison of different models



Intercomparison of different models



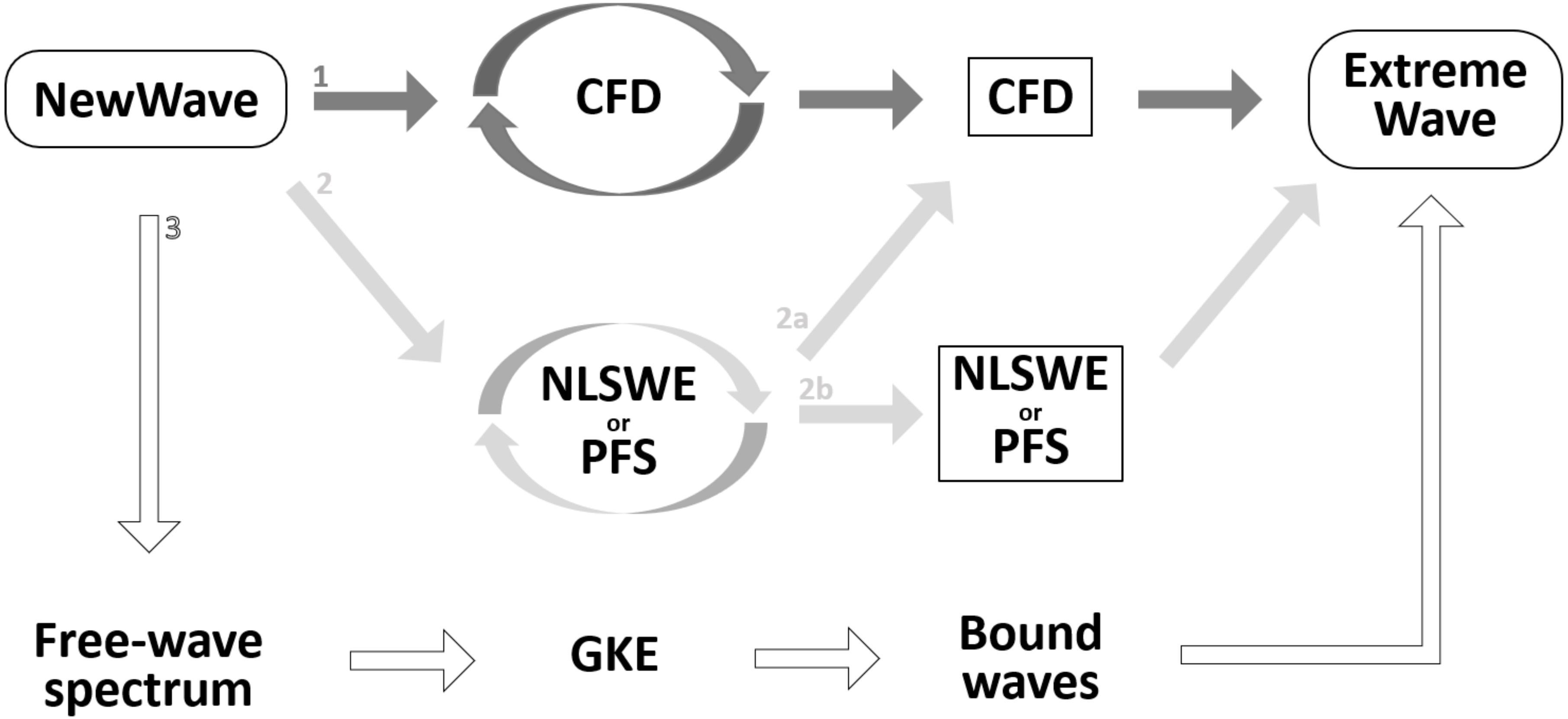
	Experiment	OpenFOAM		SWASH		HOS-NWT	
Total (measured)	217.5	0.2	0.1%	-10.5	-4.8%	-12.5	-5.7%
Linear	158.5	-3.3	-2.1%	-4.1	-2.6%	-5.3	-3.3%
2^{nd} sum	45.4	2.1	4.5%	-1.6	-3.4%	-0.7	-1.5%
2^{nd} difference	-25.9	-3.8	14.8%	-0.5	1.8%	-2.5	9.7%
3^{rd} order	21.7	1.5	6.7%	-1.6	-7.3%	-1.8	-8.1%
4^{th} order	8.8	1.8	20.2%	0.2	2.1%	0.1	1.6%
5^{th} order	5.3	1.4	26.1%	-0.2	-3.8%	-0.3	-4.8%
Sum of harmonics	213.9	-0.4	0.2%	-7.7	-3.6%	-10.3	-4.8%

- Overall, near-excellent agreement (errors at the range of wave probe accuracy)
- The differences stem from the wave generation and governing equations
- Impressive performance from models not expected to handle very steep waves
- For certain harmonics, “lower skilled” models behave better (optimised wave generation and absorption)
- The dispersion study allows validation of the evolution of the wave group, not just at one location (higher confidence for kinematics)

Reconstruction of an extreme wave profile

Accurate extreme wave generation can be achieved in a skilled model using focusing methodology

Lower cost models have similar behaviour to CFD and thus can be used for the correction methodology or themselves provide good results for extreme waves



If linear spectrum is known, nonlinear bound waves can be calculated analytically (?)

Propagate the free wave spectrum with analytical methods (resonant, near-resonant interactions)

- 2^{nd} order exact solution
- 5^{th} order approximation
- Creamer transform
- Static Krasitskii

Takeaways

- Extreme waves are rare, but can be catastrophic for structures and ships
- Extreme waves are not as rare as initially thought, and solid evidence brought them from maritime folklore to engineering studies
- Full consensus of the main aspects of extreme waves, such as definition, probability of occurrence, generation mechanisms, most appropriate way of modelling, has not been reached yet, making the study of extreme waves an exciting field of research
- There are two main "schools" for the generation of extremes: MI and dispersive focusing, which use different modelling tools, referring to envelope and hydrodynamic equations, respectively
- Recent analyses of field data showed that dispersive focusing is a valid mechanism for extreme wave generation in the real ocean
- The NewWave theory can be used to provide the largest waves based on an underlying spectrum
- Nonlinear effects deteriorate the quality of the focusing making the simulations and experiments for extreme waves challenging
- Focusing methodologies can be used for improving the accuracy of extreme wave simulations
- “De-rogueing” will eventually make extreme waves part of the engineering design process

Extreme waves in the (near) future

Climate change is expected to increase the extremes:

- More energetic sea states in intensity and frequency should increase the emergence of extremes
- Sea-level rise will expose more nearshore and coastal structures to extremes
- Sea-level rise will reduce the air-gap between the deck of offshore structures causing greater impacts
- Currents and ocean circulation patterns may change and create new hot-spots
- New shipping routes and deployments of oil & gas or offshore wind farms in areas not previously exploited may expose the structure in extremes

Understanding and knowledge in extreme waves should improve:

- Better instrumentation on offshore structures should provide better records
- Many more offshore structures deployed that can take recordings (e.g., wind energy farms)
- Satellite technologies offer better and more frequent coverage of entire areas
- More advanced modelling tools for fluid-structure interactions (e.g., hydroelasticity solvers)
- Better understanding of the physics and the generation mechanisms through research
- Use of AI for detection and prediction of extreme waves
- Development of early warning systems in forecasting services for safety at sea

PhD Thesis Vyzikas, T., 2018,Numerical Modelling of Extreme Waves: The Role of Nonlinear Wave-Wave Interactions, University of Plymouth, http://dx.doi.org/10.24382/987

Vyzikas, T., Stagonas, D., Buldakov, E. and Greaves, D. (2017). The evolution of free and bound waves during dispersive focusing in a numerical and physical flume, Coastal Engineering 132, pp. 95-109. https://doi.org/10.1016/j.coastaleng.2017.11.003

Vyzikas, T., Greaves, D., Simmonds D., Maisondieu C., Smith H. and Radford L. (2014). Best practice report: Task 3.4.4 of the MERiFIC project: Application of numerical models and codes. University of Plymouth, February 2014. https://archimer.ifremer.fr/doc/00324/43550/43111.pdf

Homework for tomorrow

Factors for selecting a job -> What is success?

Workshop

Look for a job vacancy in Euraxess or at EU Careers
- What skills / knowledge do you need to develop to get it?
- What skills will you develop after 3 years in the job?
- How does it contribute to your longer-term career path and how can it influence it?

Job	Sector	Skills required	Skills gained	Long-term plan

Workshop technical & soft-skills

Technical skills		Soft skills	