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Deterministic short-term wave prediction for directional sea-states in real-time using Artificial Neural Network

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11 November 2019

Introduction

- Deterministic short-term wave prediction is required to enchance operational efficiency, such as
  - Installation and decommissioning of marine and offshore structures
  - Active control of wave energy converters
  - Route planning for autonomous or remotely-operated vessels
- Real-time prediction is challenging, because
  - Linear model is limited to low steepness
  - Nonlinear model is limited by computational cost

Source: Golden Energy Offshore

Objective

- Provide an approach for real-time deterministic short-term wave prediction
  - Given : Far-field waves captured by a radar on a ship
  - Predict : Near-field waves around the ship

- Establish the baseline performance
  - Linear Wave Theory (LWT) – real-time physics-based model
  - Artificial Neural Network (ANN) – real-time data-driven model

Linear Wave Theory (LWT)

- Assume each component propagates independently

- Express the wave field as

$$\eta(\vec{x}, t) = \mathrm{Re}\left[\sum_{n=0}^{N-1} A_n \exp(i\vec{k_n} \cdot \vec{x} - i\omega_n t + \phi_n)\right]$$

- All parameters are computed based on measurement
- Linear dispersion relation is assumed

Artificial Neural Network (ANN)

- A universal function *F* that maps input to output
  - Input: Measured surface elevation
  - Output: Reconstructed wave field
- A set of weights to be tuned using training data

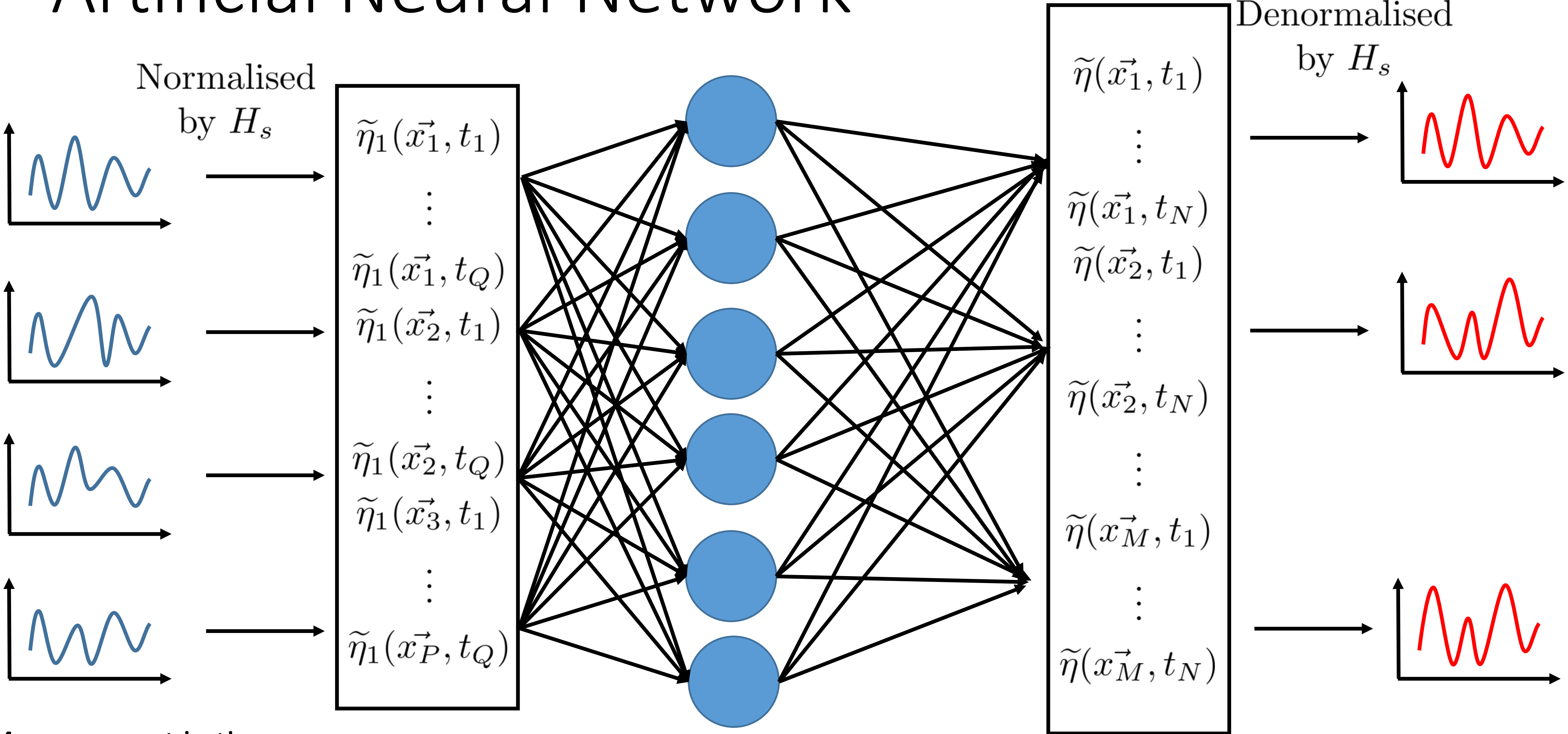
Weight to be trained using training data

$$\{\eta(\vec{x_i}, t_j)\}_{i=m_1,m_2,\ldots,m_M;j=n_1,n_2,\ldots,n_N} = F(\{\eta_1(\vec{x_i}, t_j)\}_{i=p_1,p_2,\ldots,p_P;j=q_1,q_2,\ldots,q_Q}, \vec{w})$$

Measured surface elevation at different locations for a given interval

Reconstructed wave field at
different locations at given t

Artificial Neural Network



Normalised by H_s

$\tilde{\eta}_1(\vec{x_1}, t_1)$

$\vdots$

$\tilde{\eta}_1(\vec{x_1}, t_Q)$

$\tilde{\eta}_1(\vec{x_2}, t_1)$

$\vdots$

$\tilde{\eta}_1(\vec{x_2}, t_Q)$

$\tilde{\eta}_1(\vec{x_3}, t_1)$

$\vdots$

$\tilde{\eta}_1(\vec{x_P}, t_Q)$

$\tilde{\eta}(\vec{x_1}, t_1)$

$\vdots$

$\tilde{\eta}(\vec{x_1}, t_N)$

$\tilde{\eta}(\vec{x_2}, t_1)$

$\vdots$

$\tilde{\eta}(\vec{x_2}, t_N)$

$\vdots$

$\tilde{\eta}(\vec{x_M}, t_1)$

$\vdots$

$\tilde{\eta}(\vec{x_M}, t_N)$

Denormalised by H_s

Measurement in time at different locations

Hidden layer

Prediction of elevation in time at different locations

Prediction error

- Normalised error

Reference elevation

Predicted elevation

$$\epsilon_n(\vec{x},t) = \frac{|\eta_n^R(\vec{x},t) - \eta_n(\vec{x},t)|}{H_{s,n}/2}$$

Hs estimated based on input

- Root-mean-square (RMS) of Normalised error

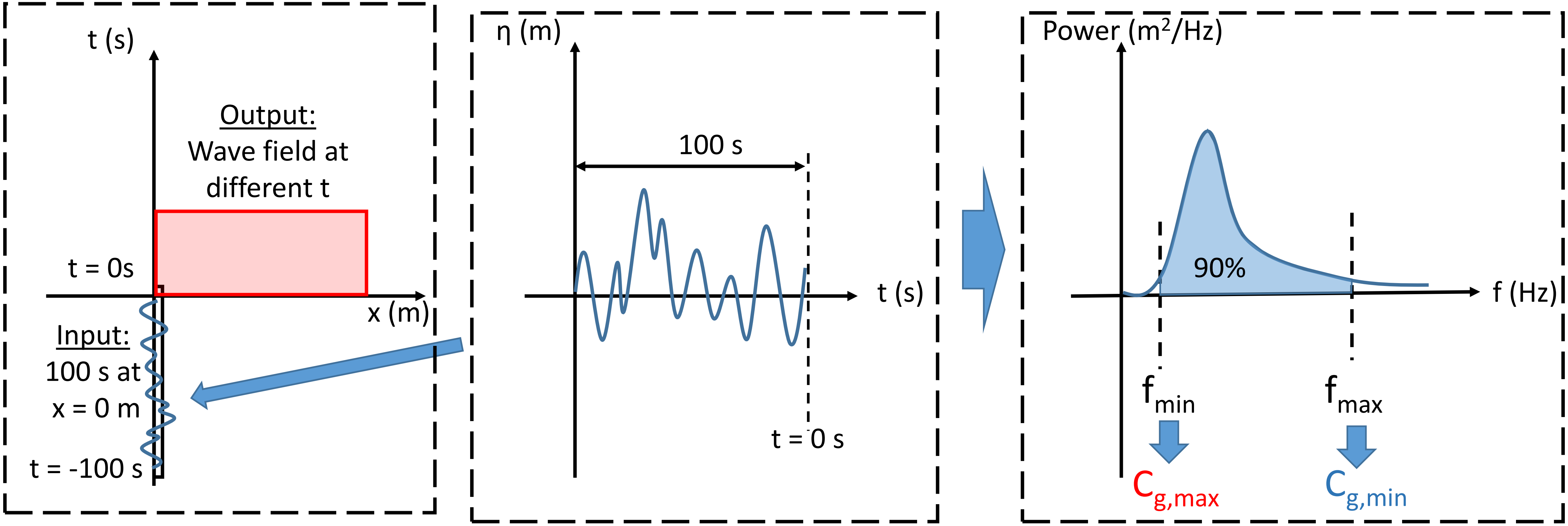
$$\mathcal{E}(\vec{x},t) = \sqrt{\frac{1}{N_s}\sum_{n=1}^{N_s}\left[\epsilon_n(\vec{x},t)\right]^2}$$

Number of samples
= 500 realisations

Application on
- Unidirectional Waves
- Directional Waves

Numerical database
- by HOS-ocean with Jonswap spectrum assumed
- $\gamma = 3.3$
- $H_s/T_p^2 = 0.06$, with Tp ranges from 7 s – 20 s
- Spreading = -45^o to 45^o for directional wave

Unidirectional Waves

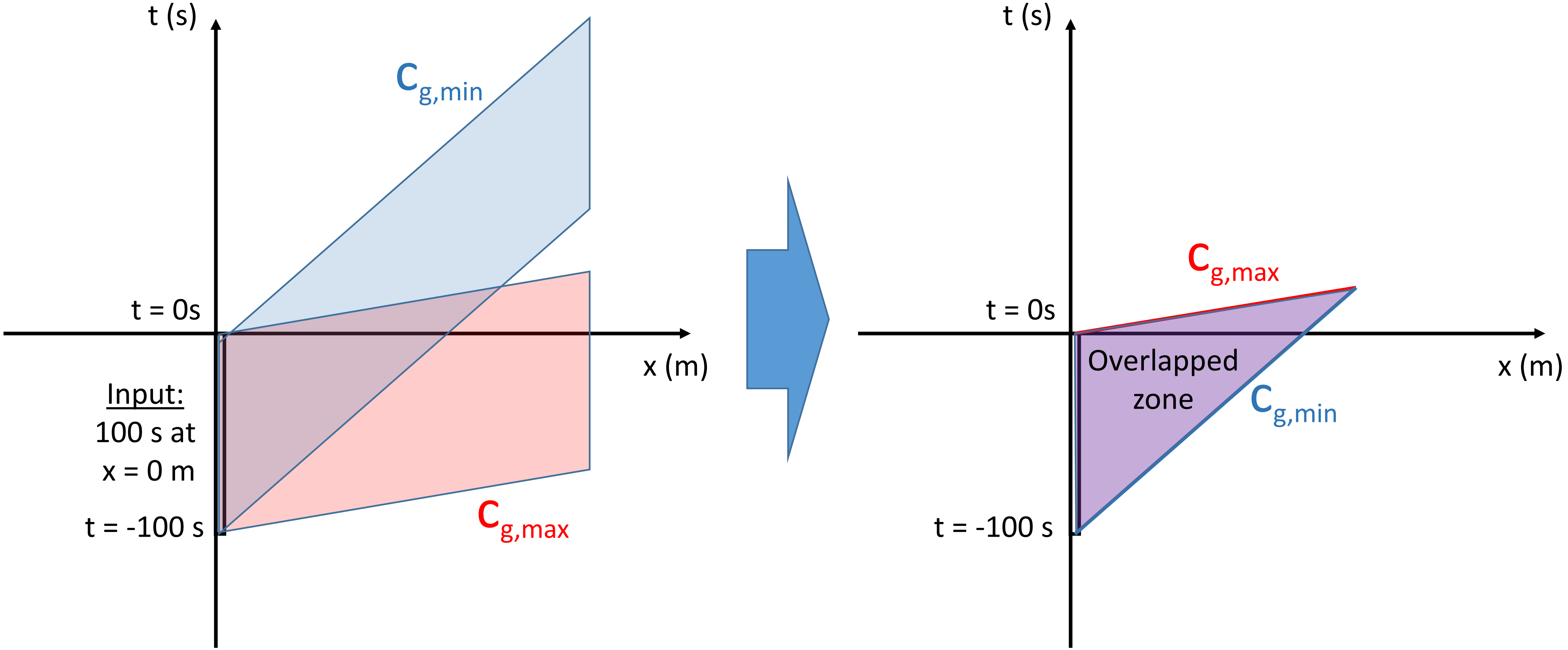


Space-time representation

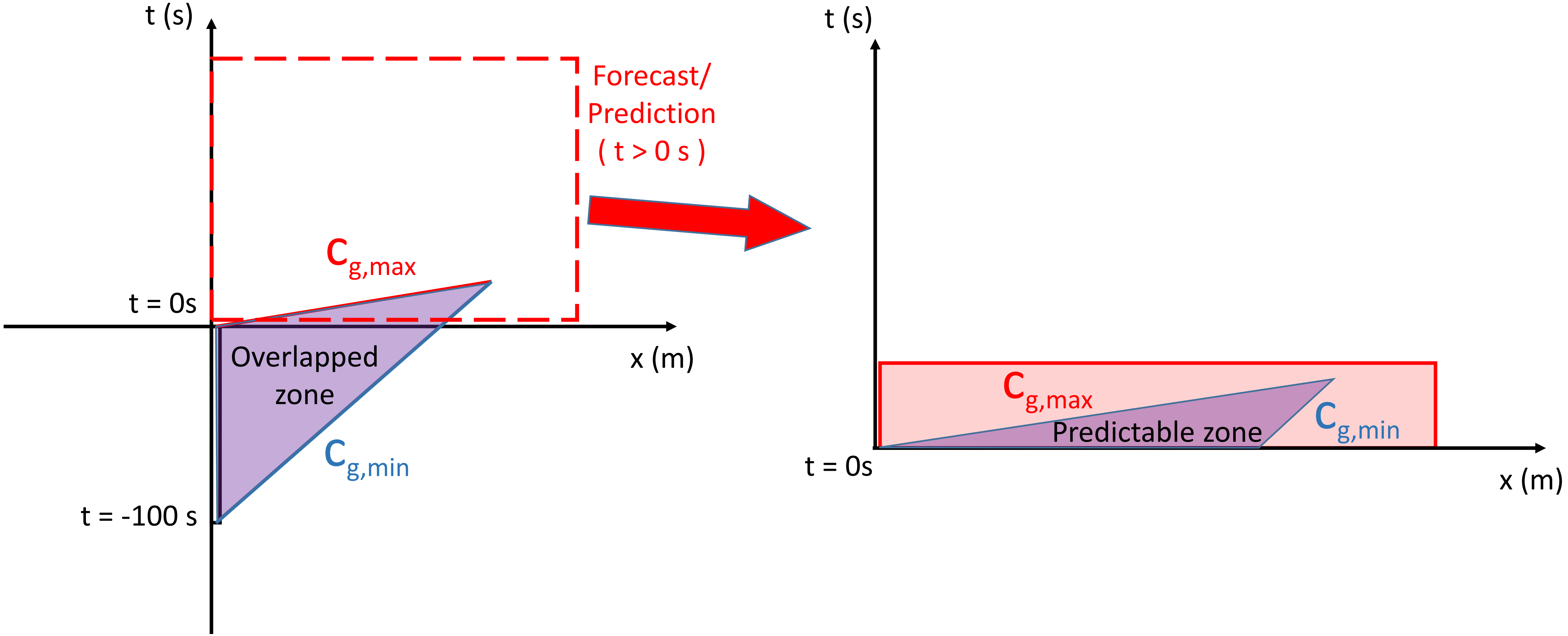
Upstream measurement

Power Spectrum

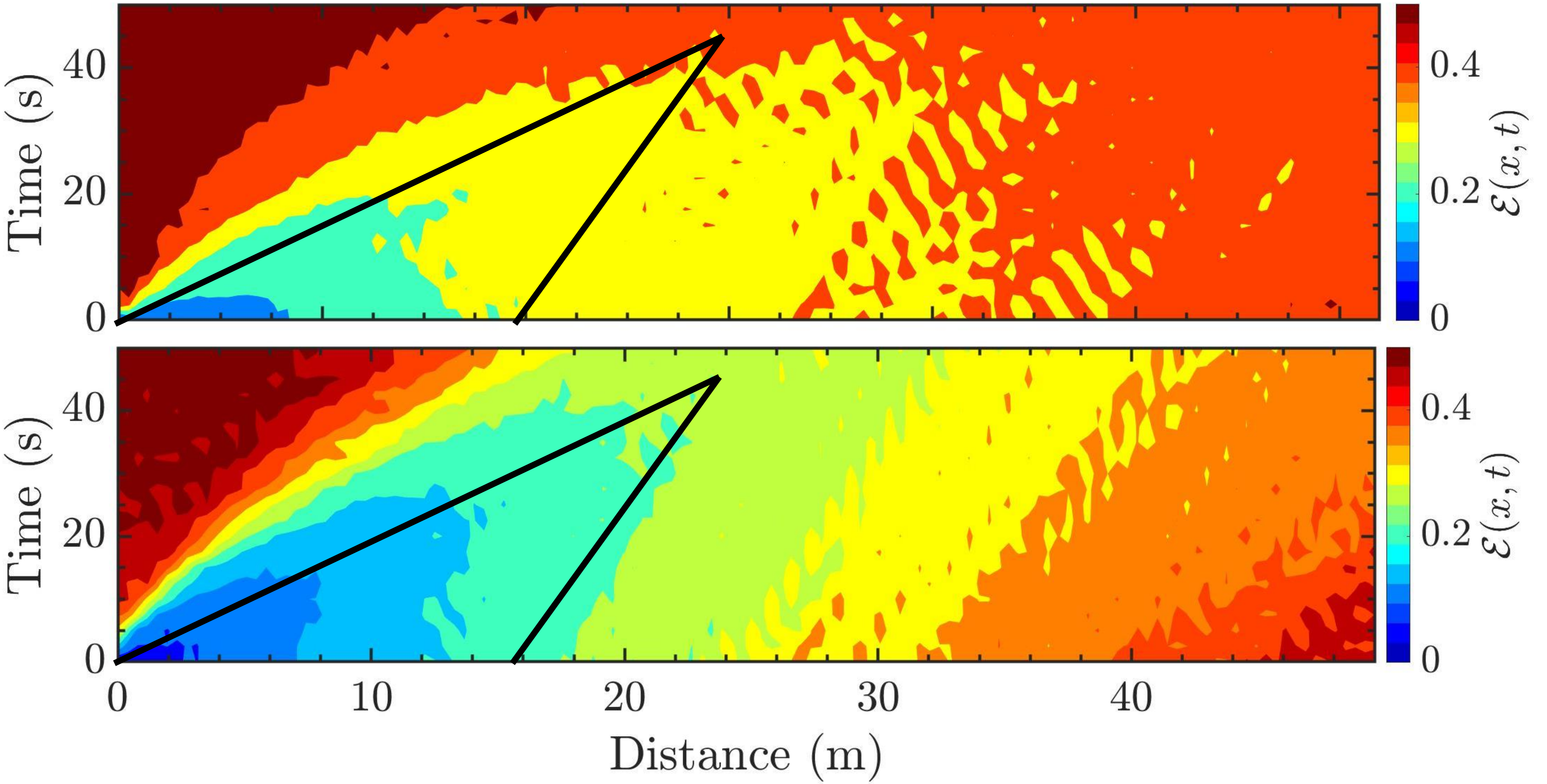
Unidirectional Waves



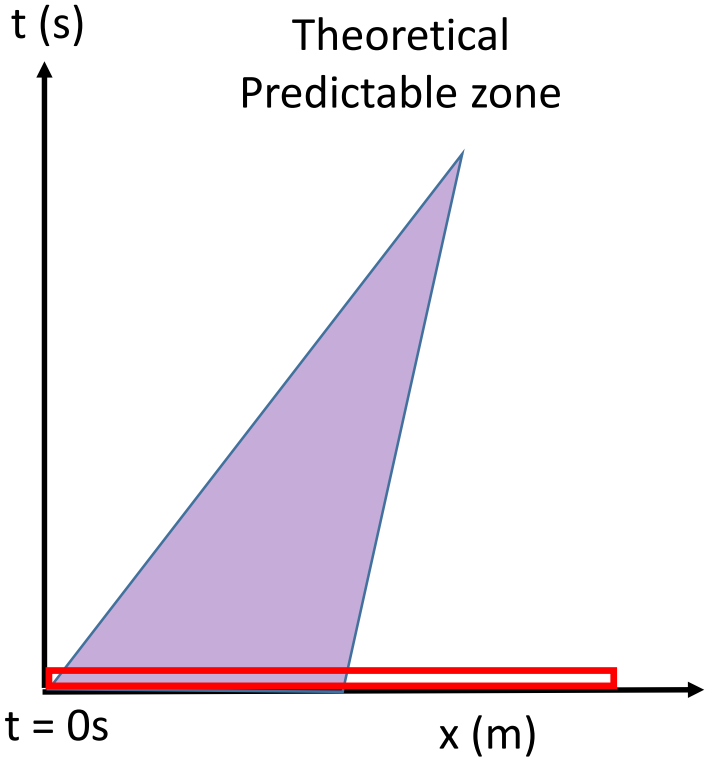
Unidirectional Waves



Unidirectional Waves
- RMS Normalised Error



Unidirectional Waves



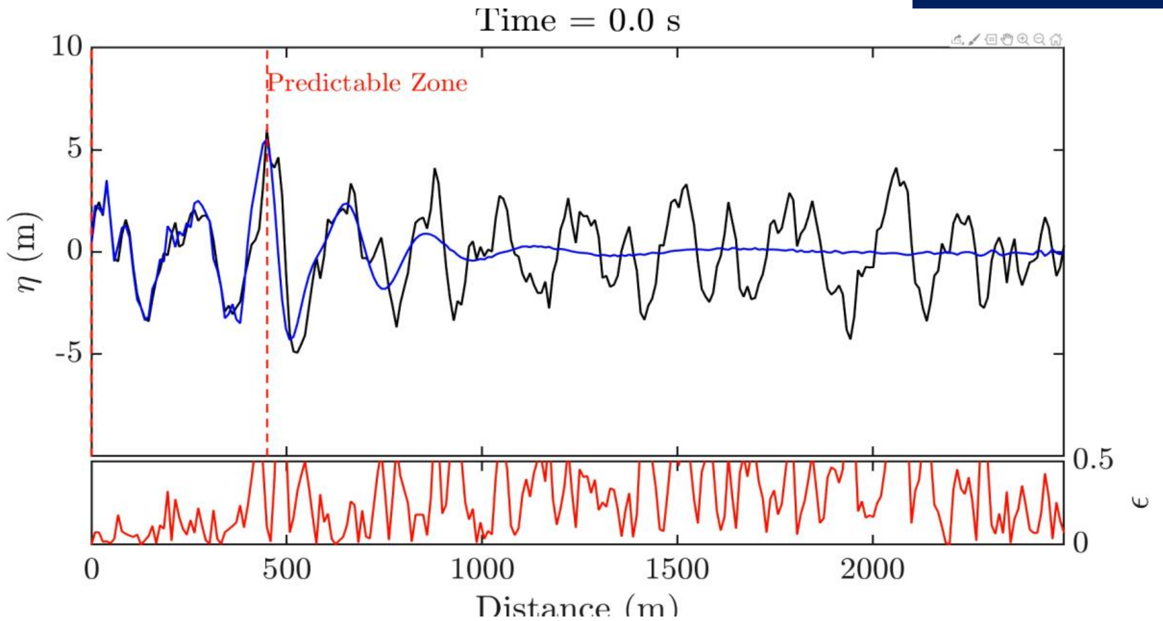
t (s)

Theoretical Predictable zone

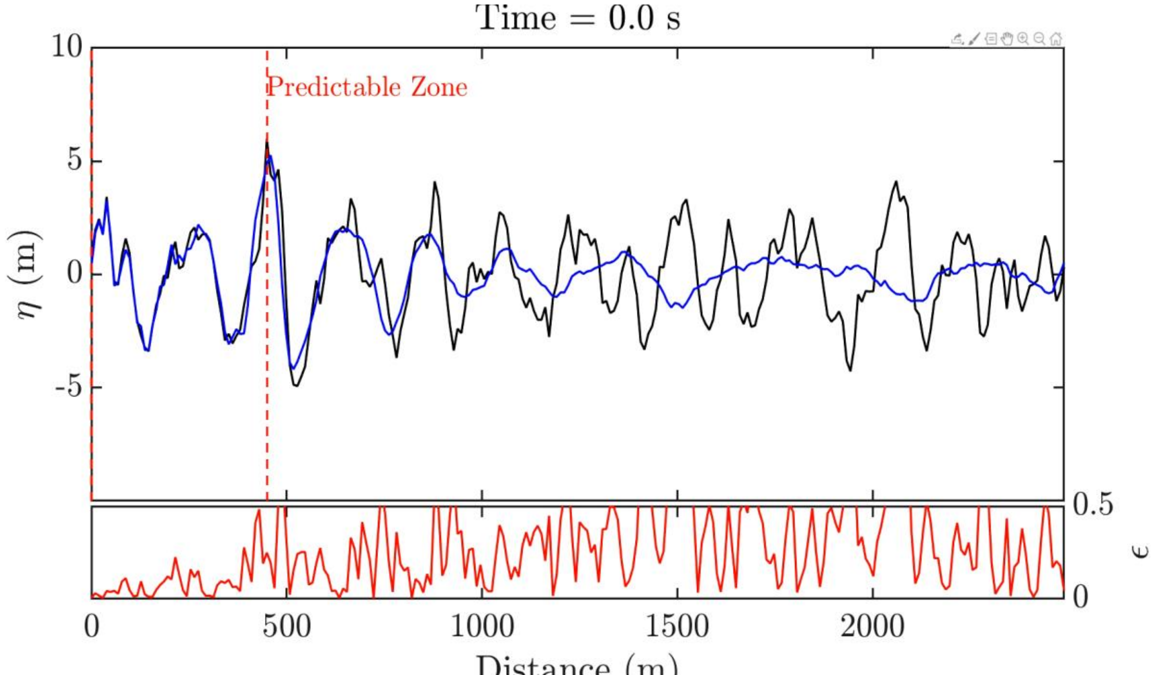
t = 0s

x (m)

LWT prediction



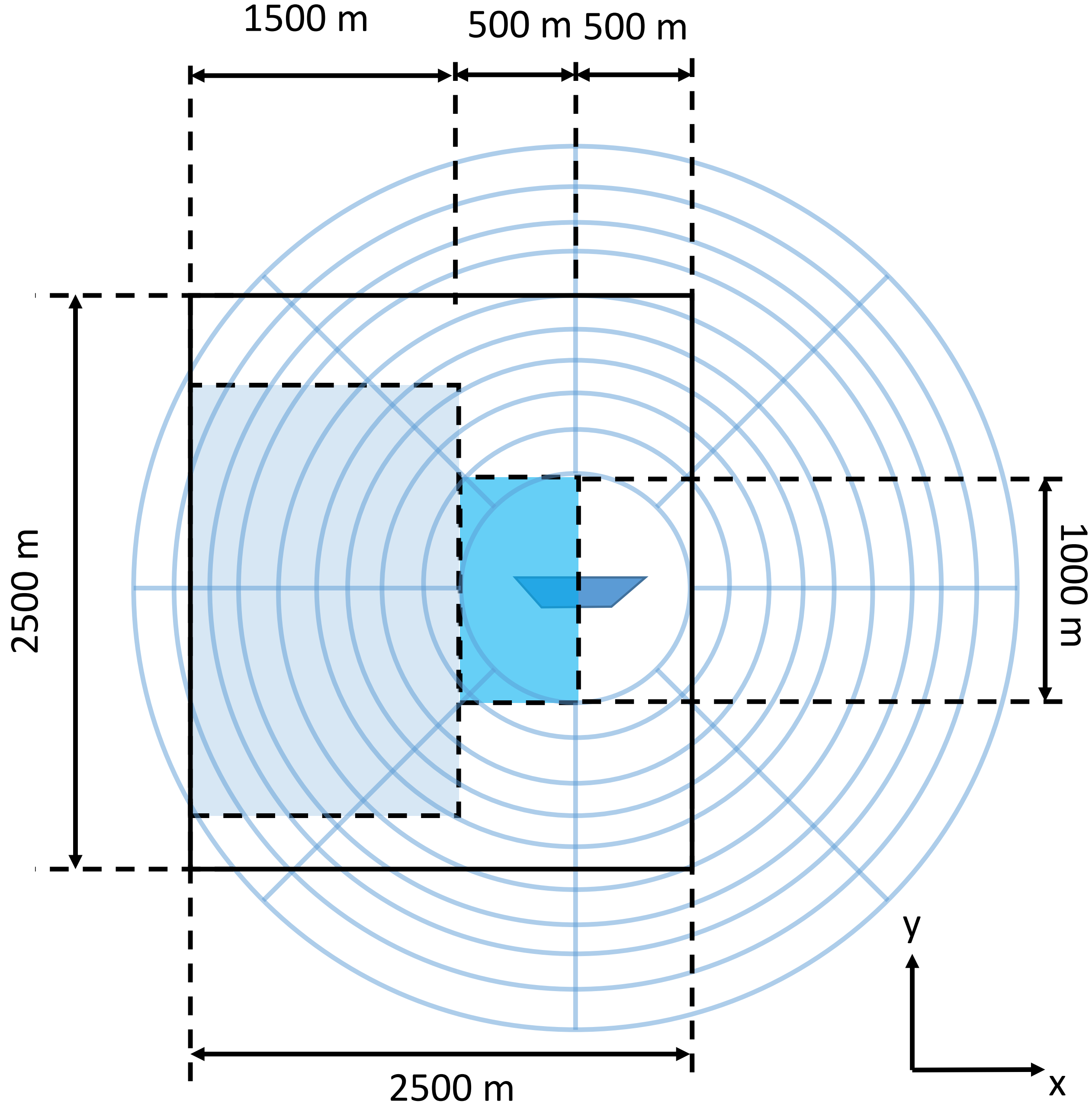
ANN prediction



Prediction of LWT and ANN for a realisation

Directional Waves

- Assuming a radar is installed on a ship
  - Covering 0.5km – 2km
  - Angular resolution of 2.5° (Δy = 88 m at 2km distance)
  - Radial resolution of ~ 20m (Δx = 20 m)
  - Sampling rate of 24 RPM (Δt = 2.5 s)
- To predict wave field in front of the ship



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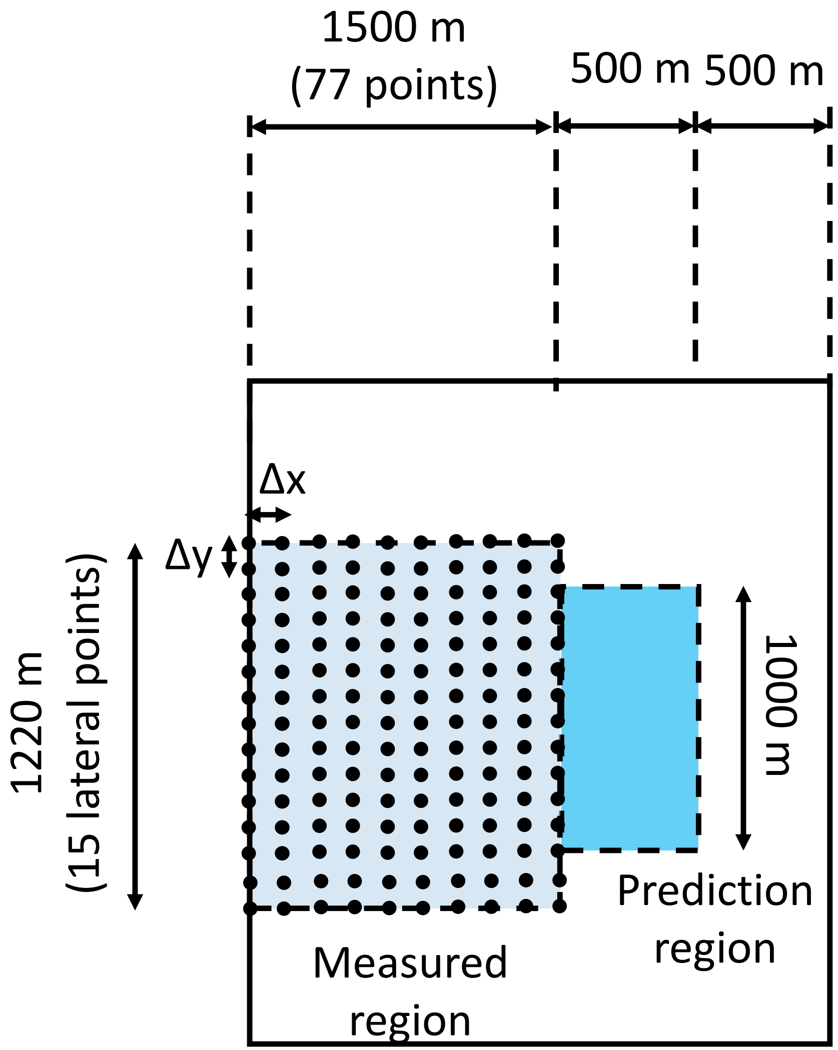
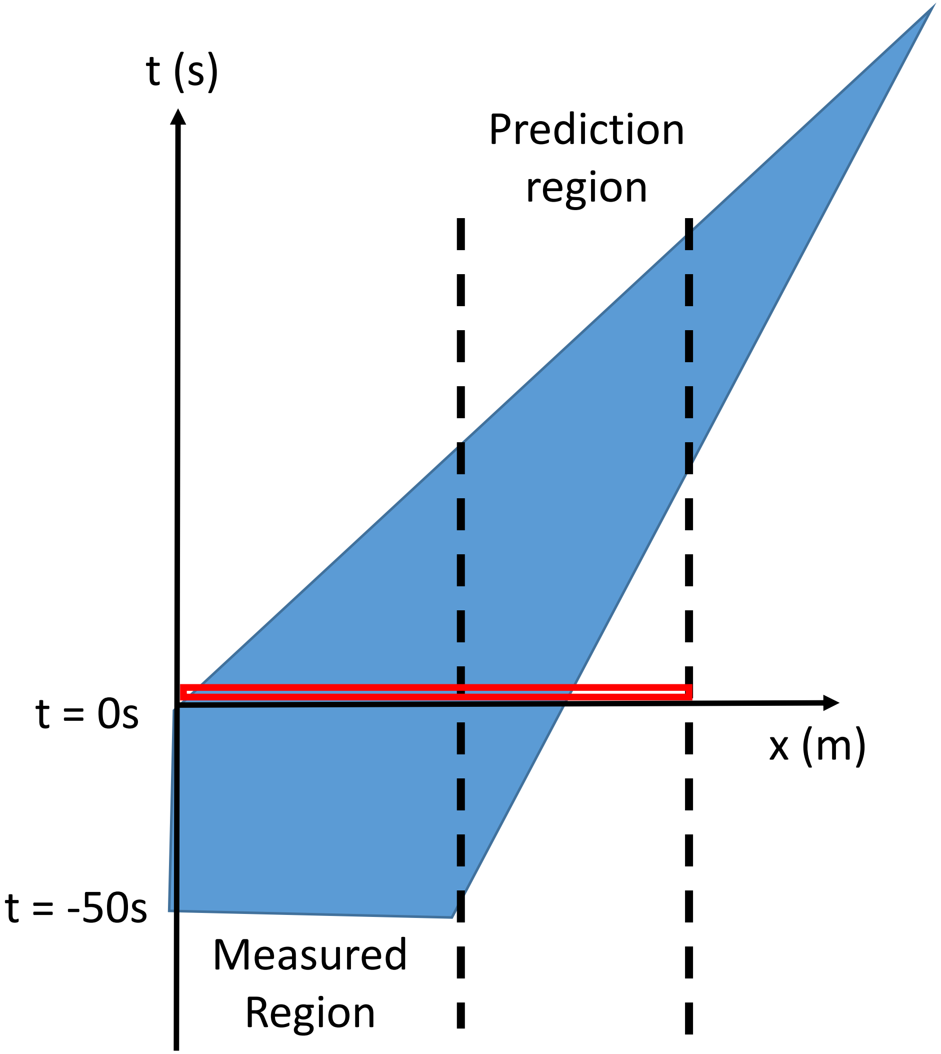
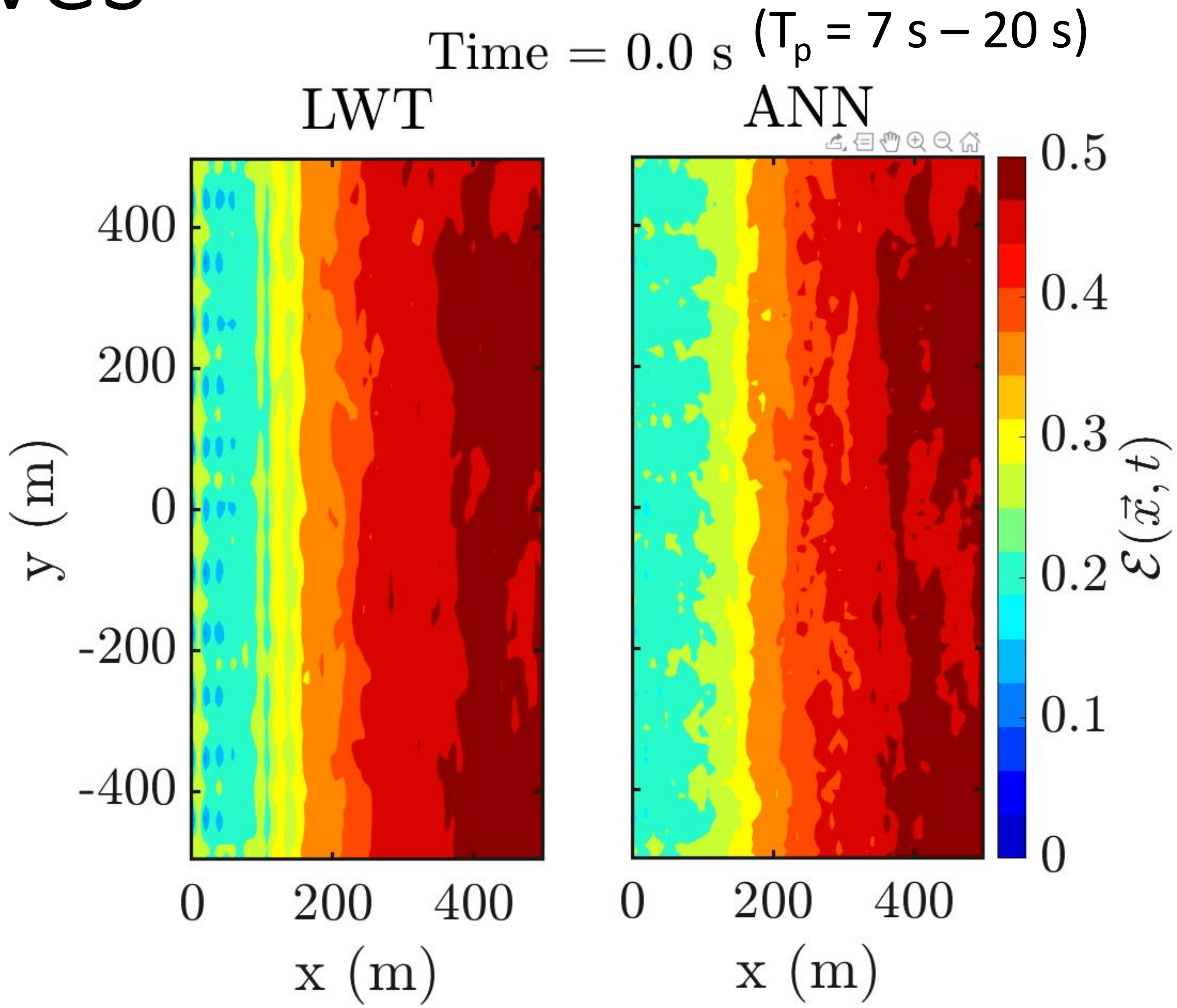
Directional Waves

- Simplify to rectangular domain
- Input
  - 15 x 77 grid points
  - Elevation measured from t = -25 s to 0 s
- Output
  - Wave field predicted from t = 0 s to 120 s

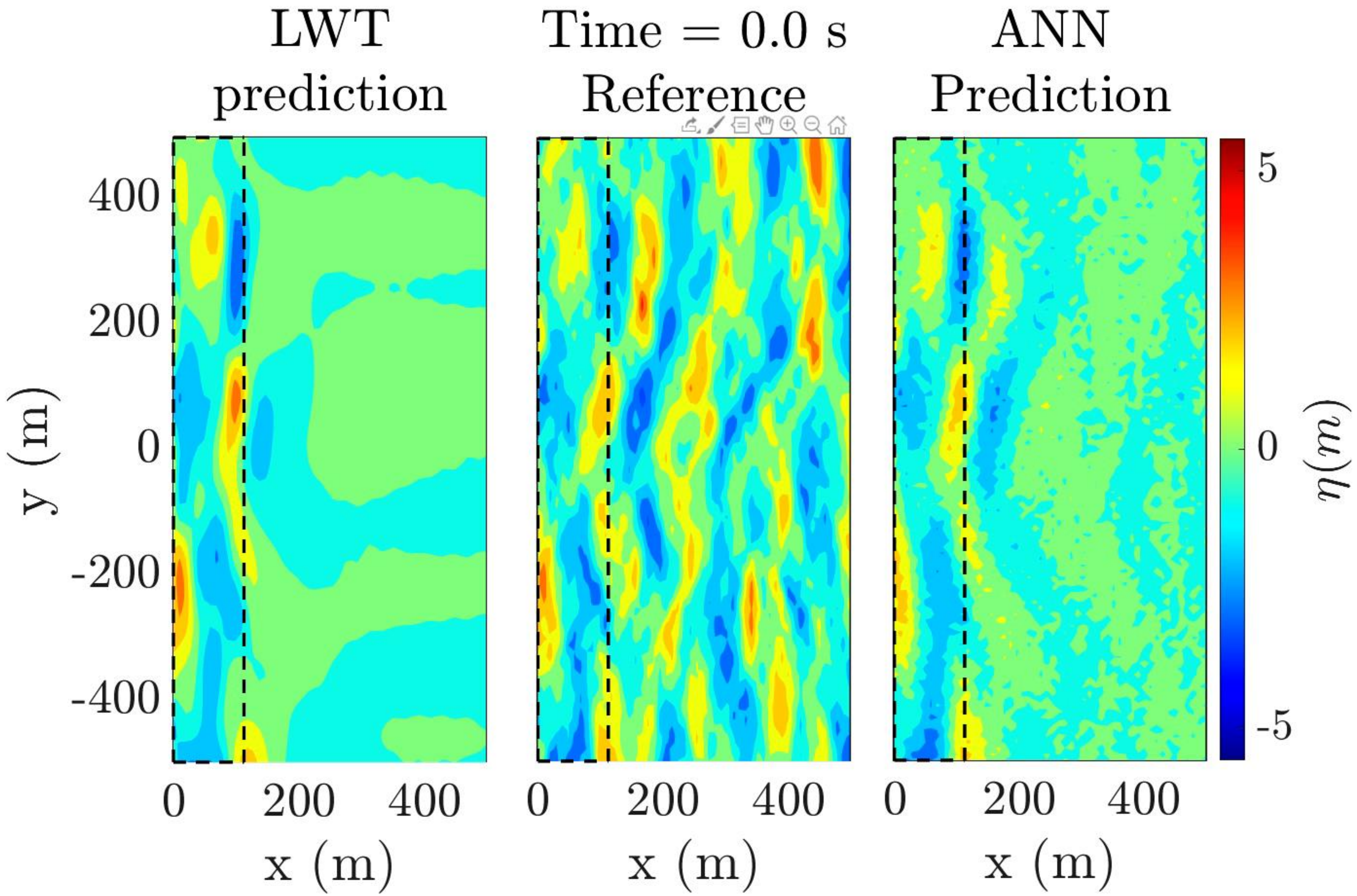


Directional Waves





Directional Waves



Summary

- A data-driven approach of real-time deterministic short term wave prediction is established
  - Based on numerical data generated using HOS-ocean
  - Data-driven model using ANN
  - Better performance compared to LWT
- Limitation of current ANN model
  - Network size become very large for larger coverage
  - Accuracy within predictable zone still need to be improved
- Extension to current ANN model
  - Explore different ANN configuration (convolutional, recurrent)
  - Include physics in ANN model to improve accuracy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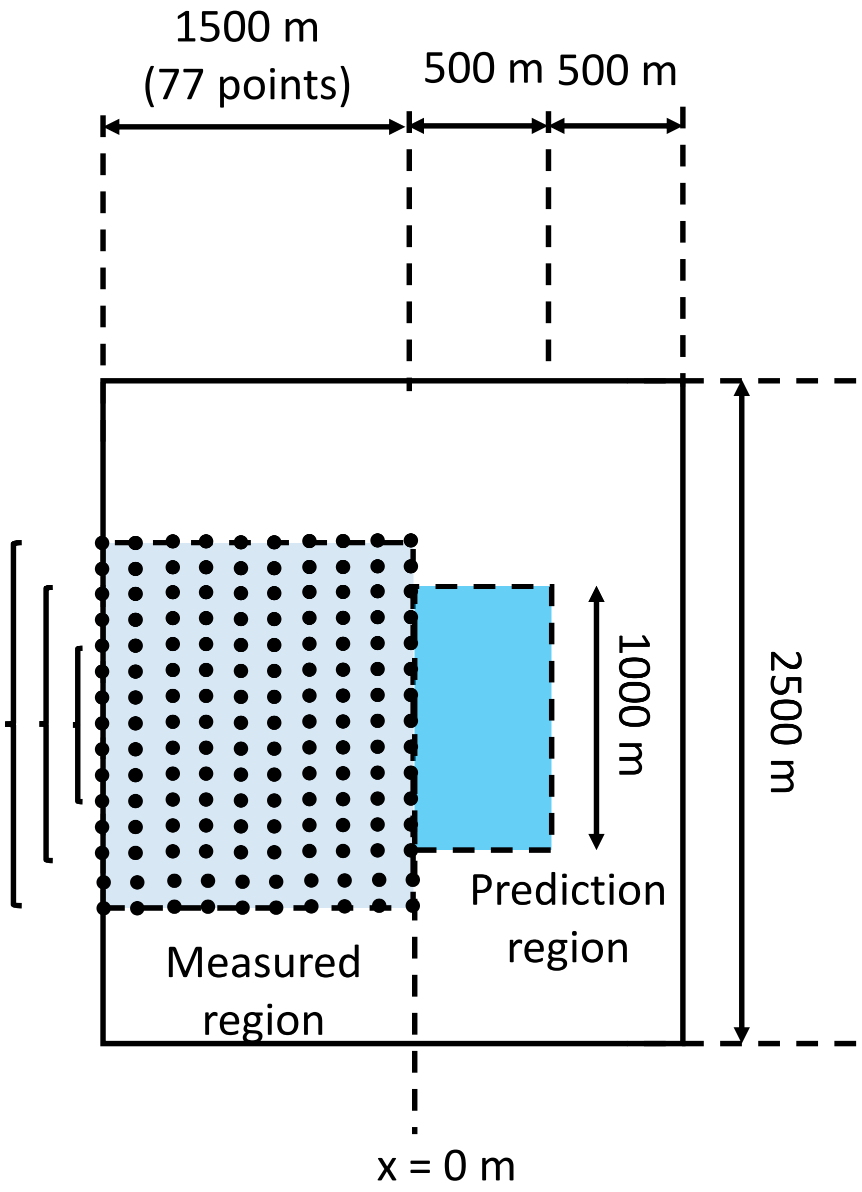
Thank You

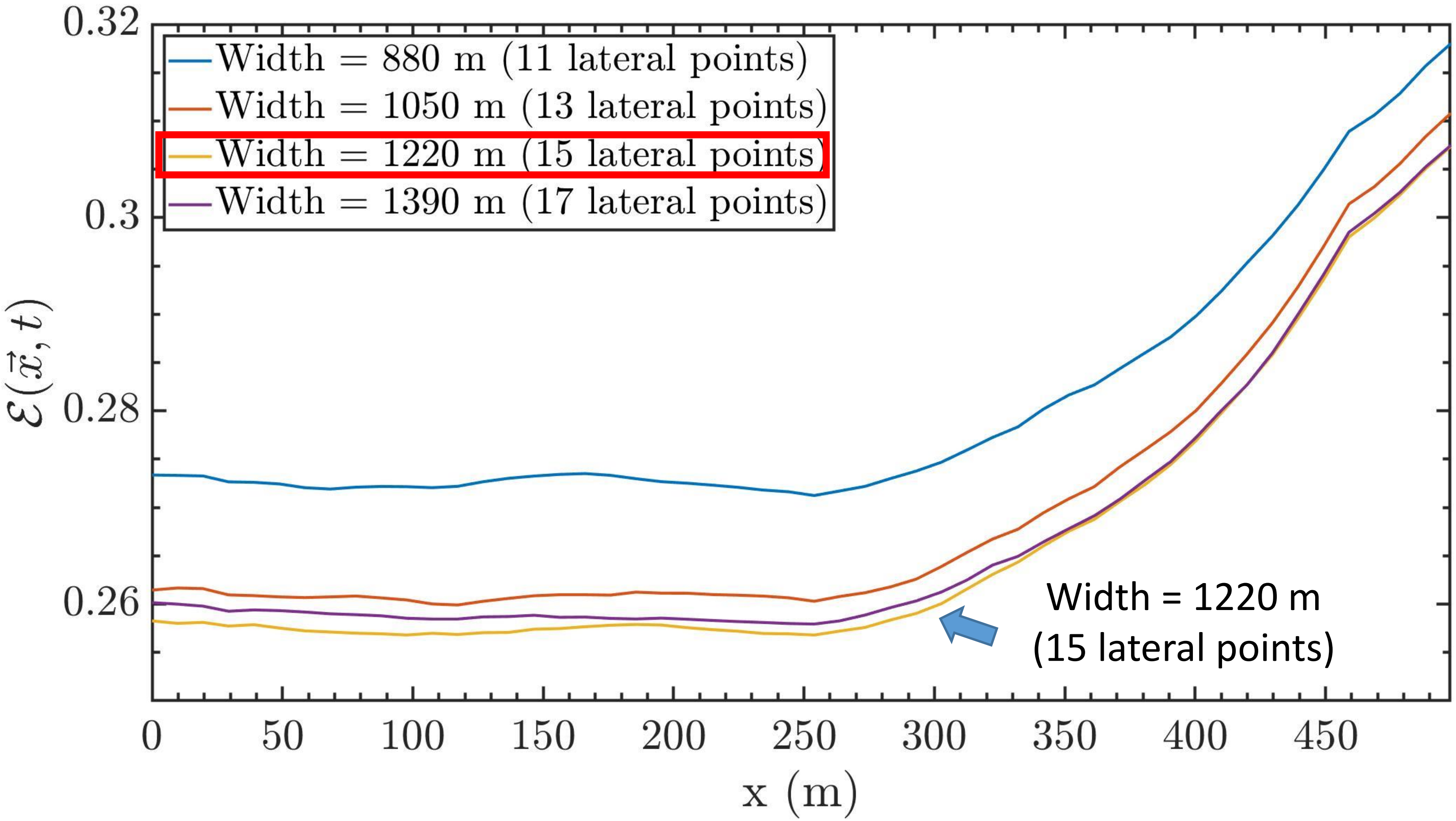
Directional Waves

- First step is to determine with of the measured region required
- Input:
  - Varying width of measured region
  - Elevation measured from t = -25 s to 0 s
- Output:
  - Wave field predicted at t = 60 s



Directional Waves
- ANN Prediction Error in the prediction region

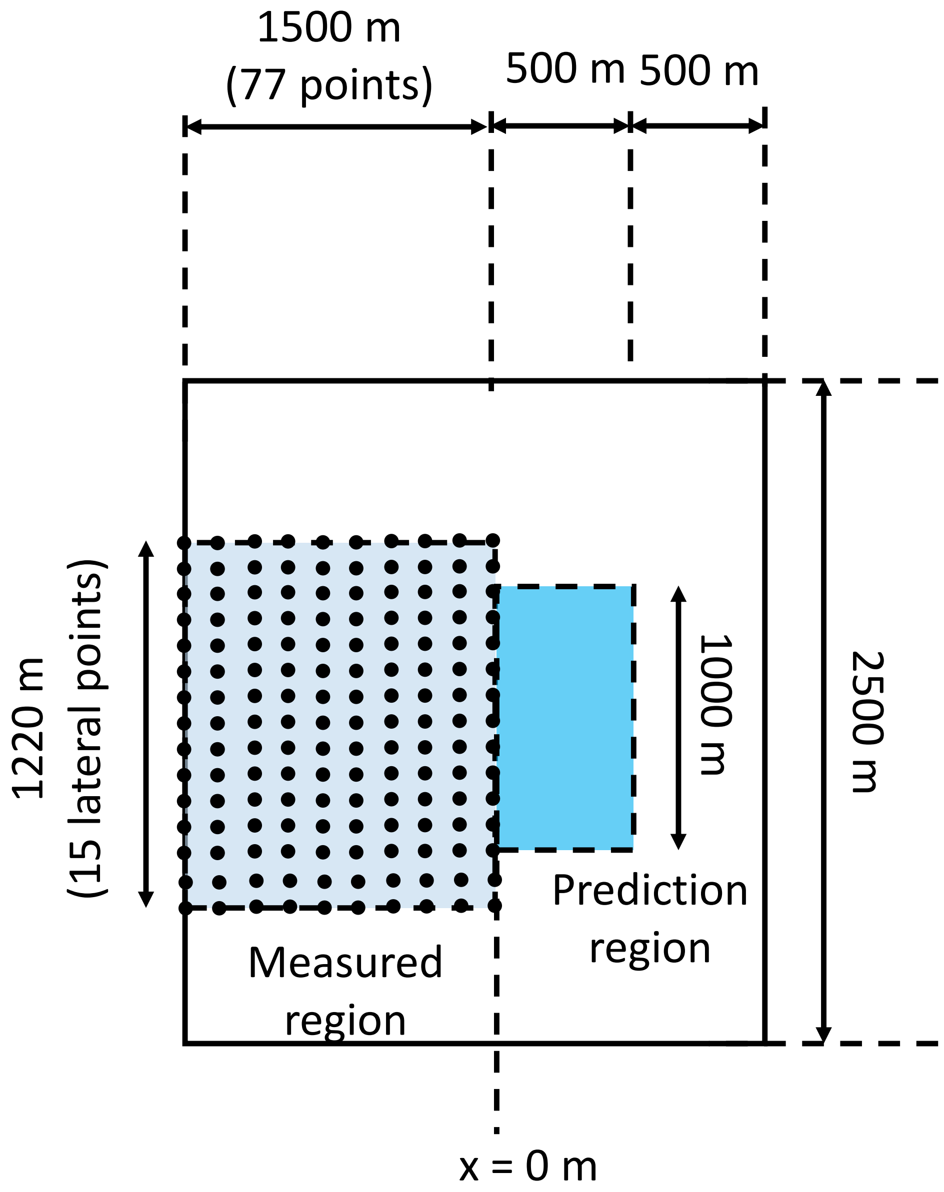
Mean error along x in prediction region



Width = 1220 m
(15 lateral points)

Directional Waves

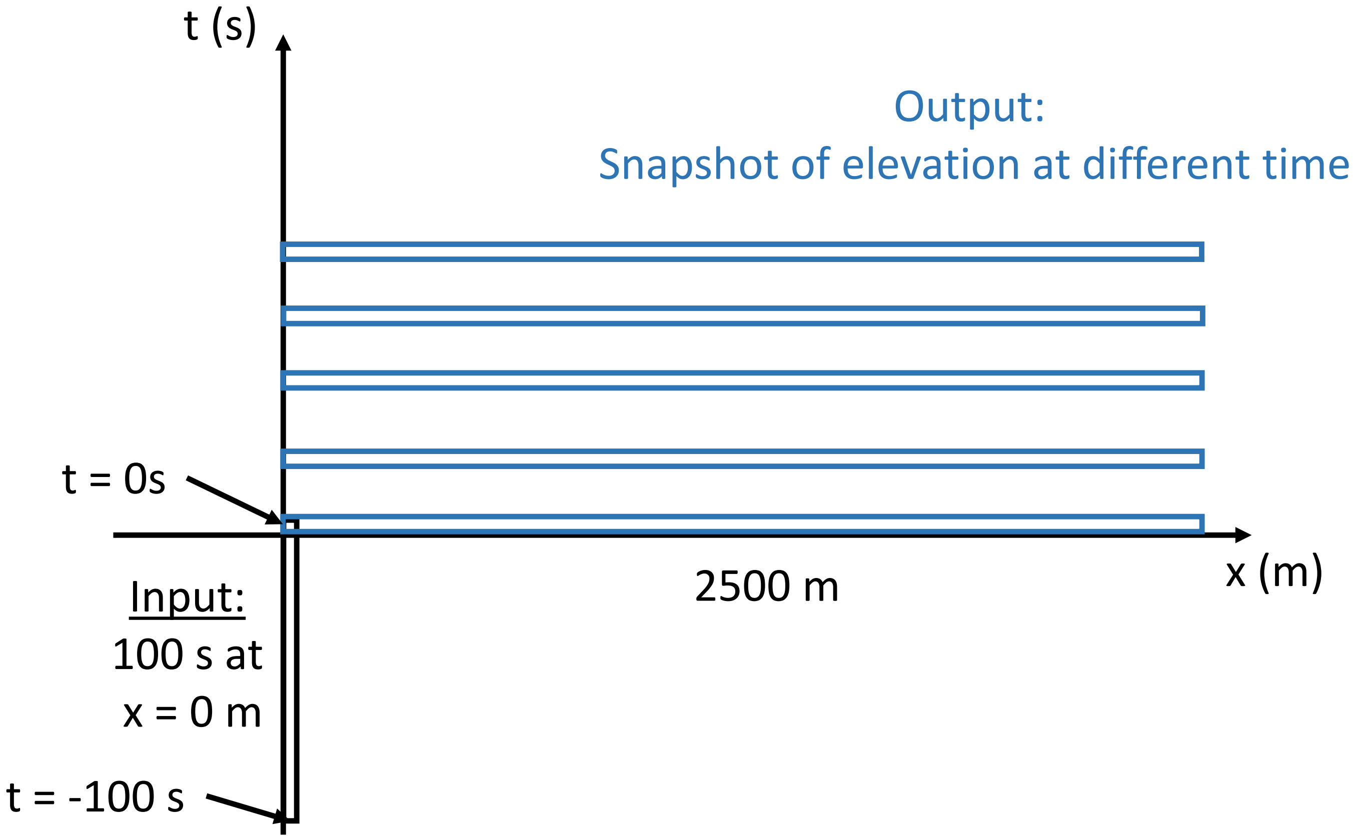
- Predict wave field in prediction region
- Input:
  - 15 x 77 grid points
  - Elevation measured from t = -25 s to 0 s
- Output:
  - Wave field predicted from t = 0 s to 180 s, at 5 s interval



Unidirectional Waves

- Input
  - Elevation at x = 0 m, collected from t = <u>-100 s</u> to <u>0 s</u>

- Output
  - Snapshot of elevation (x = 0 – 2500 m) at different time



Outline

- Models for real-time prediction
  - Linear Wave Theory (LWT)
  - Artificial Neural Network (ANN)
- Quantification of prediction error
- Application on
  - Unidirectional waves
  - Directional waves
- Future Work

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Models for real-time prediction

- Linear Wave Theory (LWT)
- Artificial Neural Network (ANN)

Linear Wave Theory (LWT)

- Given measurements of wave field in space, 2D FFT is conducted to extract the information of each wave number

- Each wave component is propagated independently in time by multiplying
- Linear dispersion relation is assumed

$$\eta(\vec{x},t) = \mathrm{Re}\left[\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} A_{mn}\exp(i\vec{k}_{x,m}\cdot\vec{x} - i\omega_n t + \phi_n)\right]$$