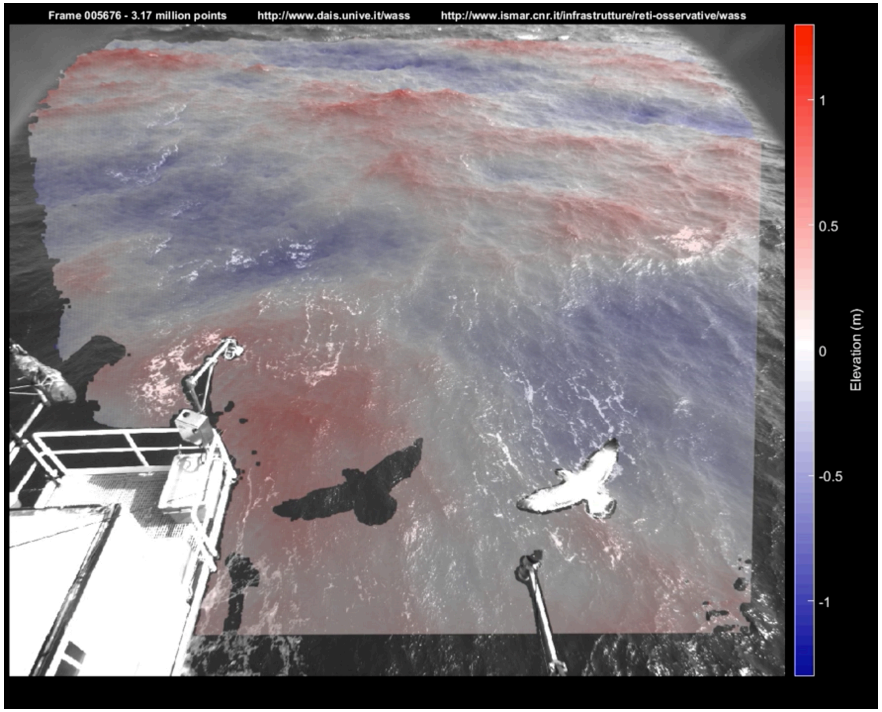
Characterizing the signature of a spatio-temporal wave field
(in situ stereo imaging observations)

Alvise Benetazzo (ISMAR-CNR, Italy), **Filippo Bergamasco** (UNIVE, Italy), F. Barbariol, A. Torsello, L. Cavaleri, and many users

CNR ISMAR ISTITUTO DI SCIENZE MARINE

Università Ca'Foscari Venezia



OVERVIEW (from meeting keywords)

➔Providing (some) sea truths for satellite and model data

- Significant wave height
- Directional spectrum shape
- Mean square slope
- Wave-ice interaction
- Wave-wave interaction
- Wave-current interaction
- Rogue waves

OVERVIEW

STEREO 3D IMAGING FOR SEA WAVES

- Features, present and future

APPLICATIONS

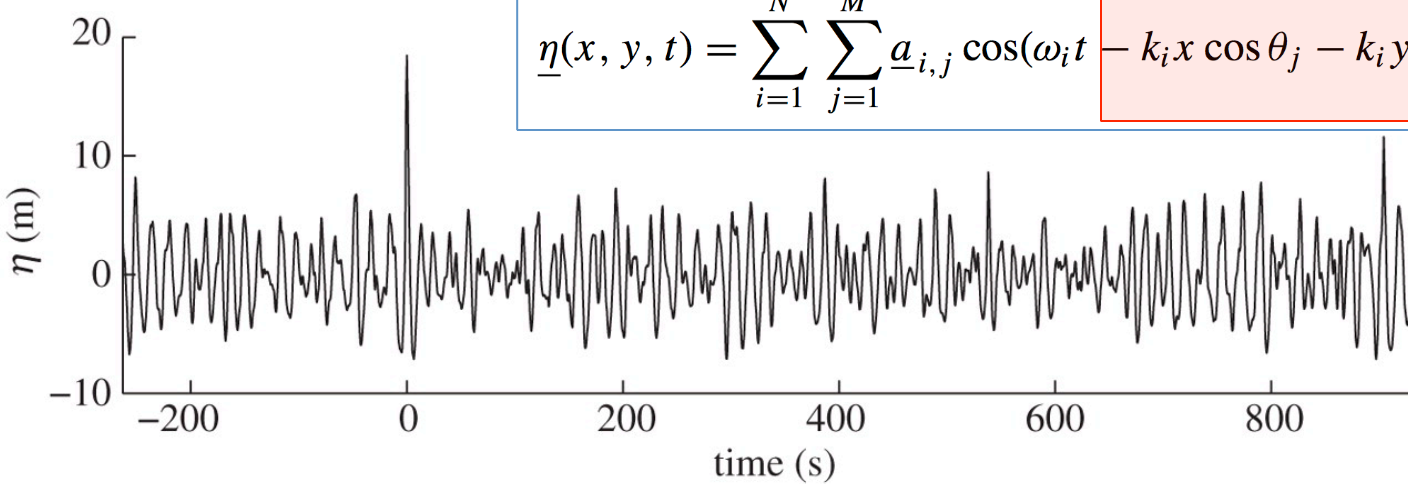
- Characterization of the spatio-temporal wave field

Why are we interested in *in situ* 3D observation for wave studies?

Spectral and statistical properties of wind waves are historically inferred from buoys or wave gauges installed at fixed locations at sea

> They can acquire elevation time-series at a single point only: $\eta(t)$

$$\underline{\eta}(x, y, t) = \sum_{i=1}^{N} \sum_{j=1}^{M} \underline{a}_{i,j} \cos(\omega_i t - k_i x \cos\theta_j - k_i y \sin\theta_j + \underline{\alpha}_{i,j})$$



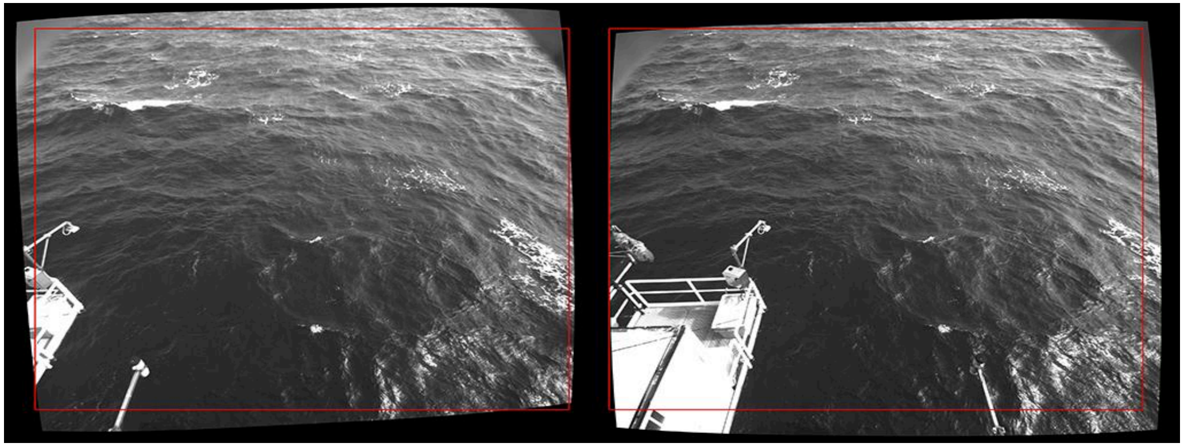
➔ A single time series can not describe accurately the complete space-time wave dynamics and the directional distribution

Stereo wave imaging

This gap can be filled by vision-based 3D measurement systems

INPUT

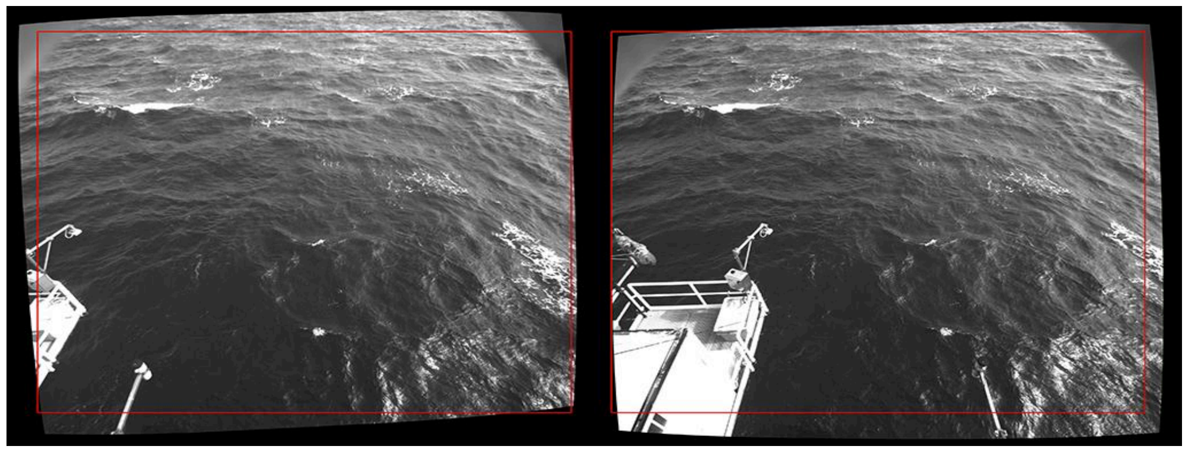
Stereo images ➔



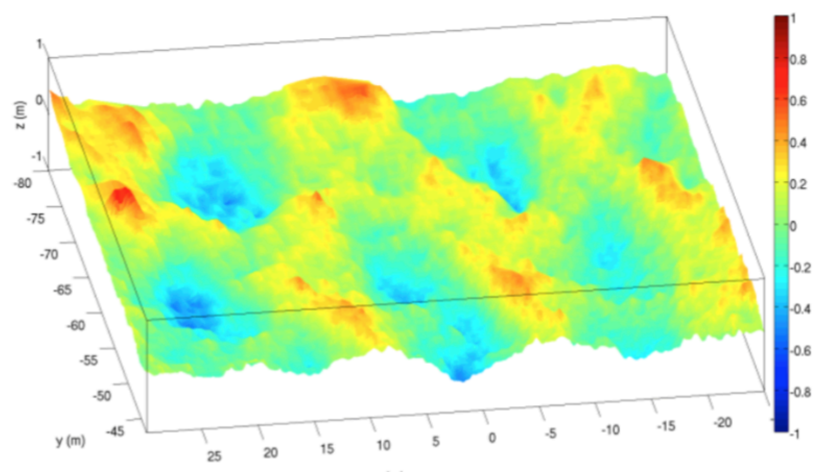
Stereo wave imaging

This gap can be filled by vision-based 3D measurement systems

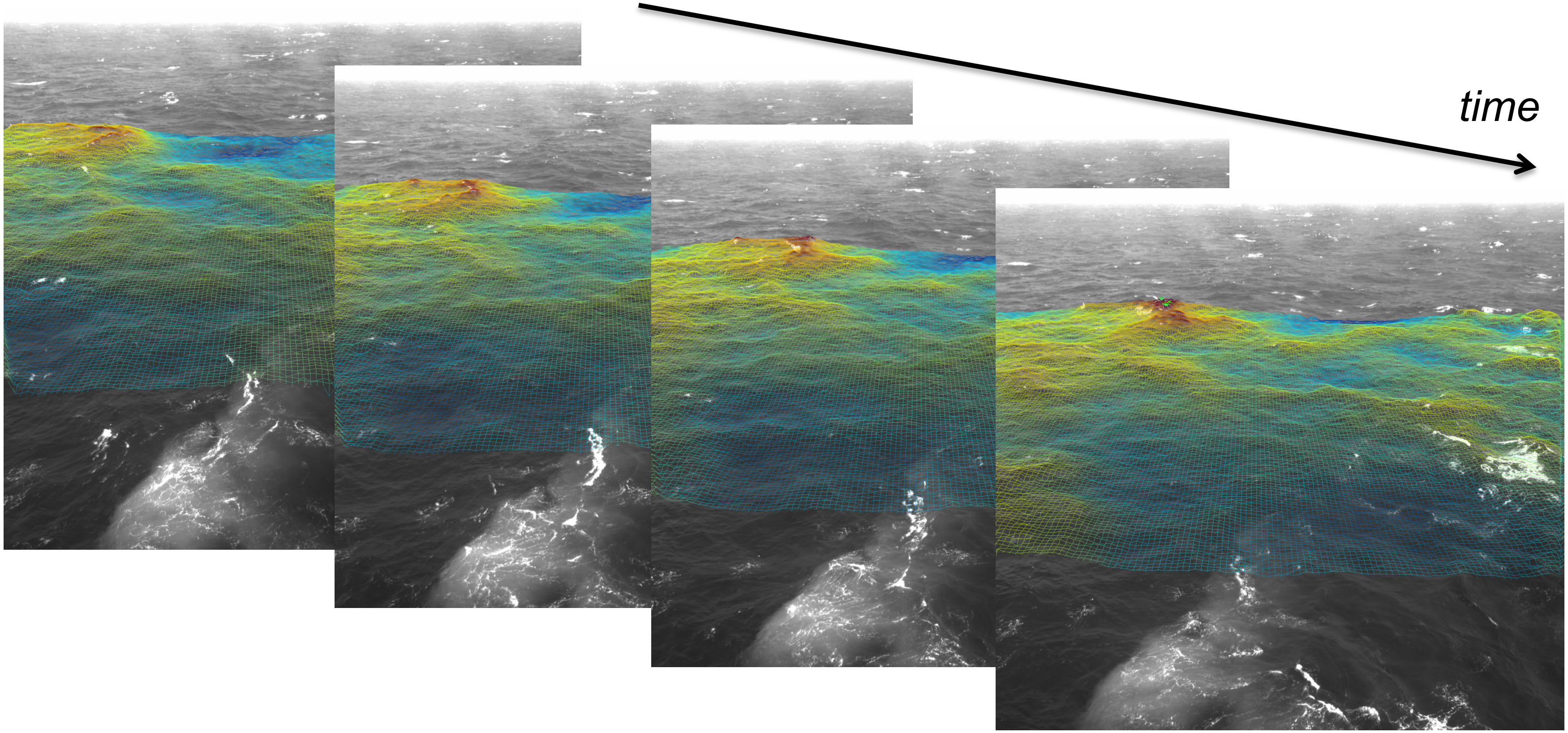
INPUT
Stereo images →



OUTPUT $\eta(x, y)$ →



3D stereo measurement in time



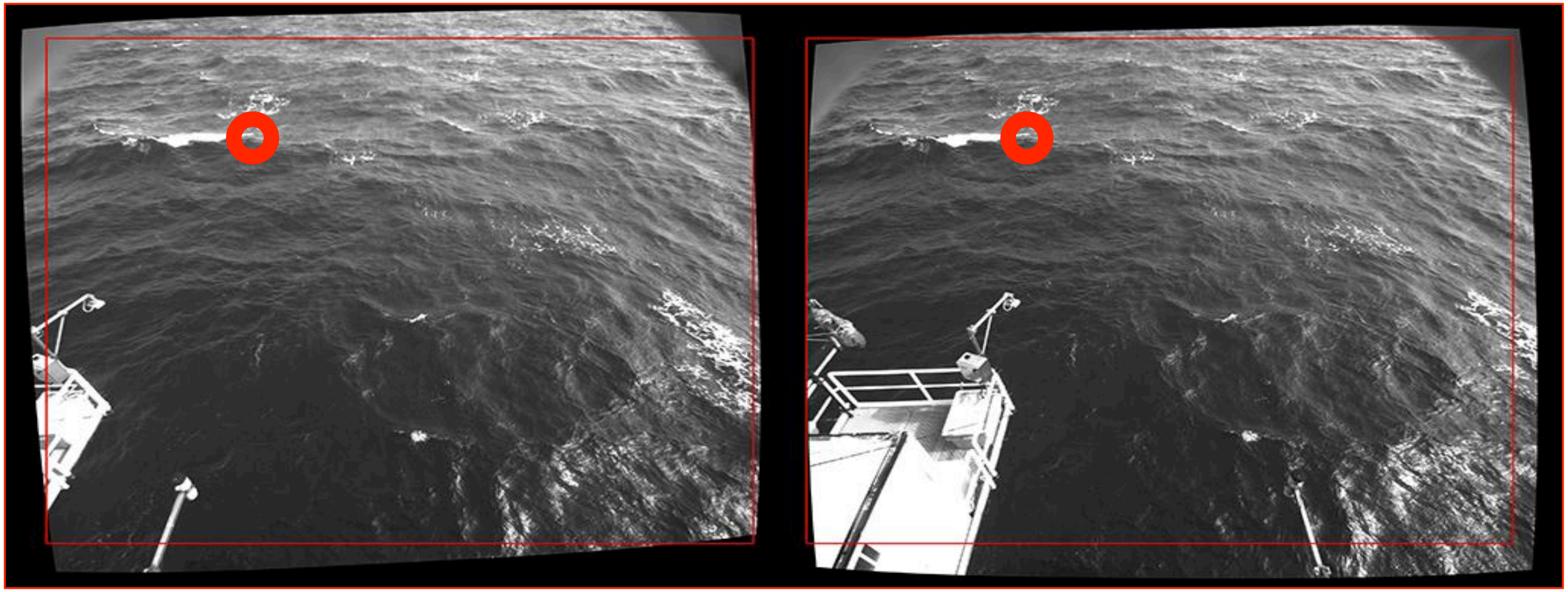
We are able to measure the space-time evolution of the wave field in an area ~200 m x 200 m over time (10-15 Hz)

Acqua Alta oceanographic tower (Venice, Italy)

Stereo-vision: principle of operation

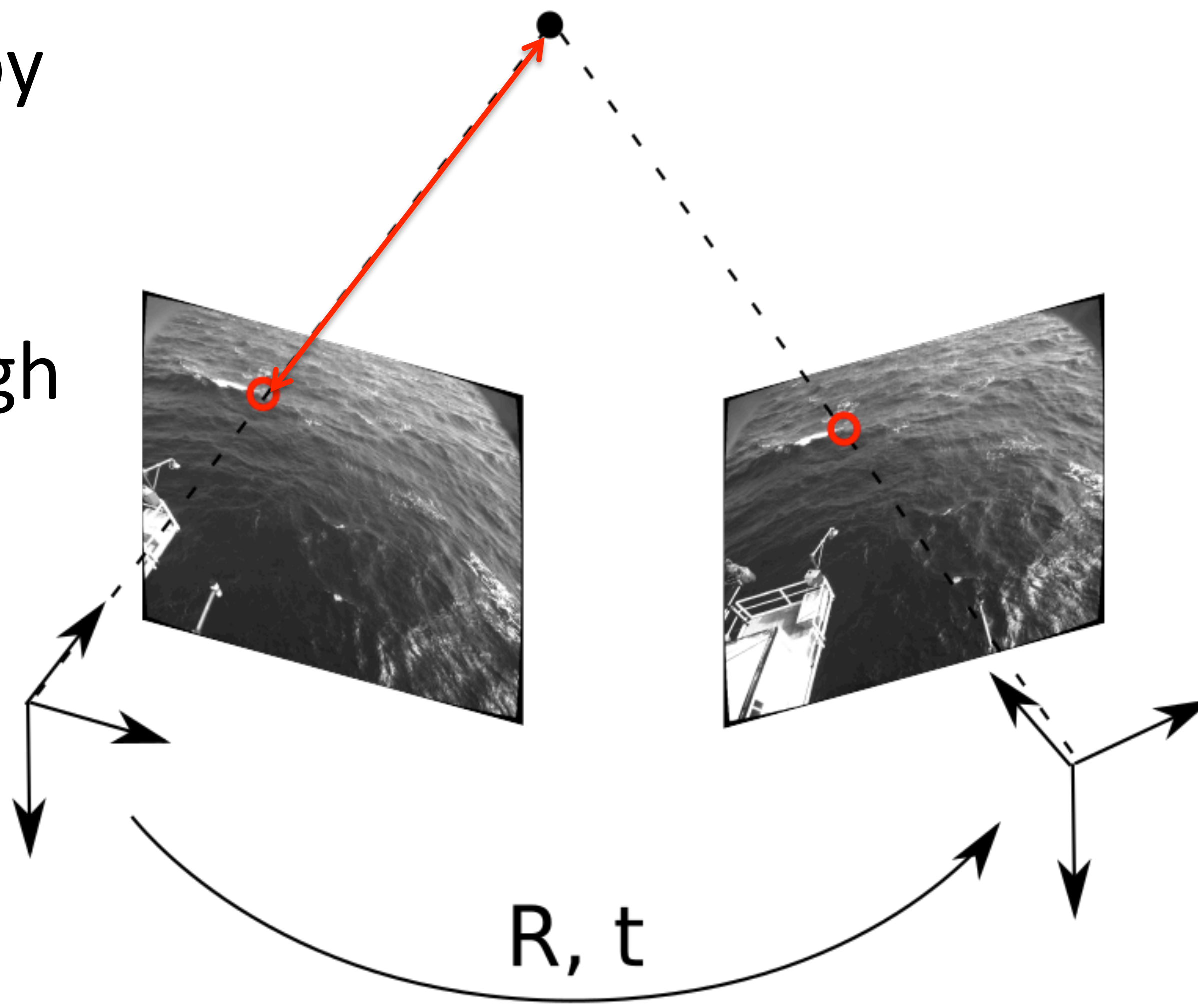
Let's assume we are able to:

1. Identify **corresponding points** in two images



Stereo-vision: principle of operation

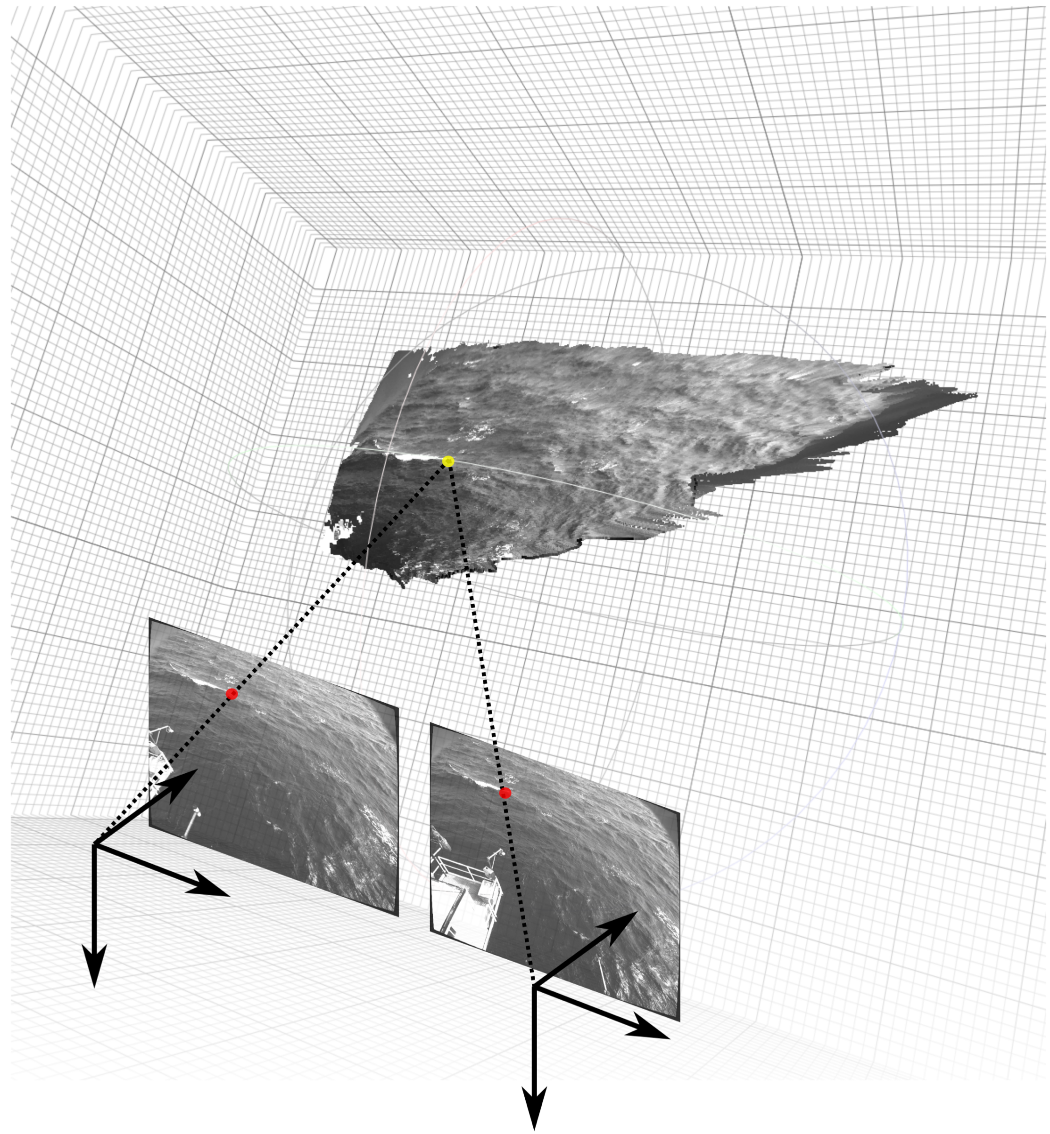
Depth of each point can be estimated by intersecting (**triangulating**) 3D rays passing through the corresponding points and the optical centers



Stereo-vision: principle of operation

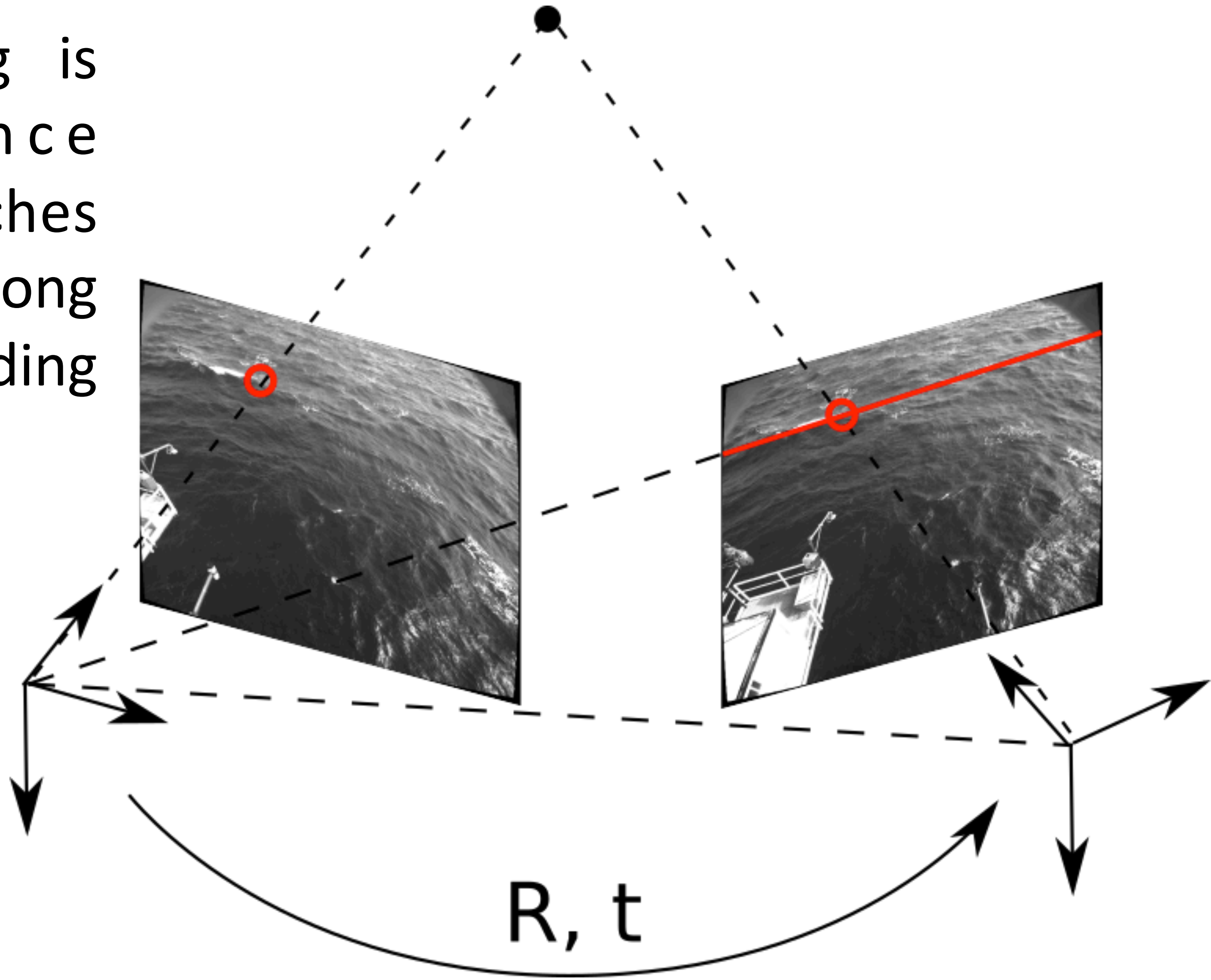
Problems

1. How to **match** points efficiently (robust and fast)?
2. How to accurately **calibrate** the system?
   – Intrinsic
   – Extrinsic (R, $\boldsymbol{t}$)



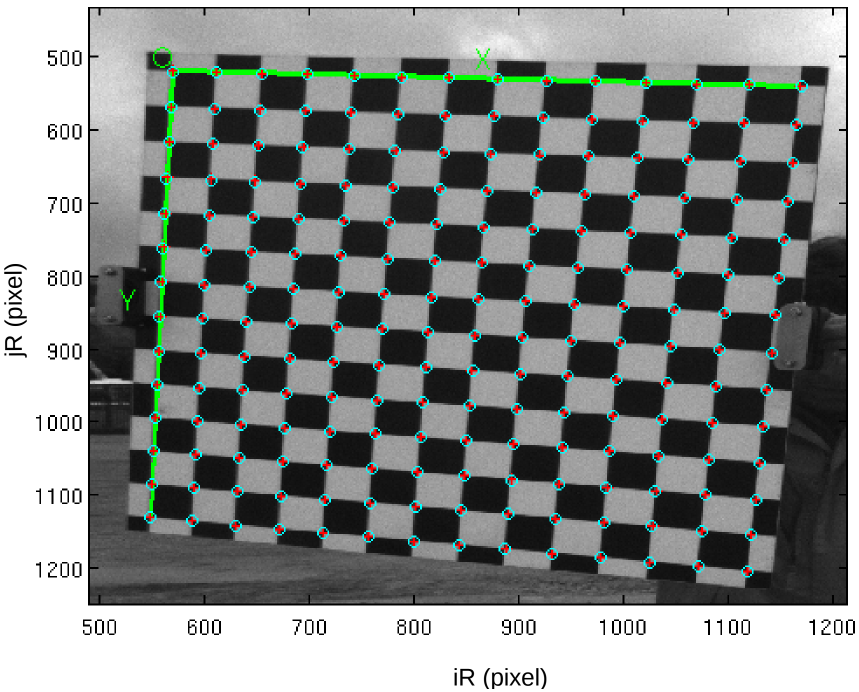
Matching corresponding points

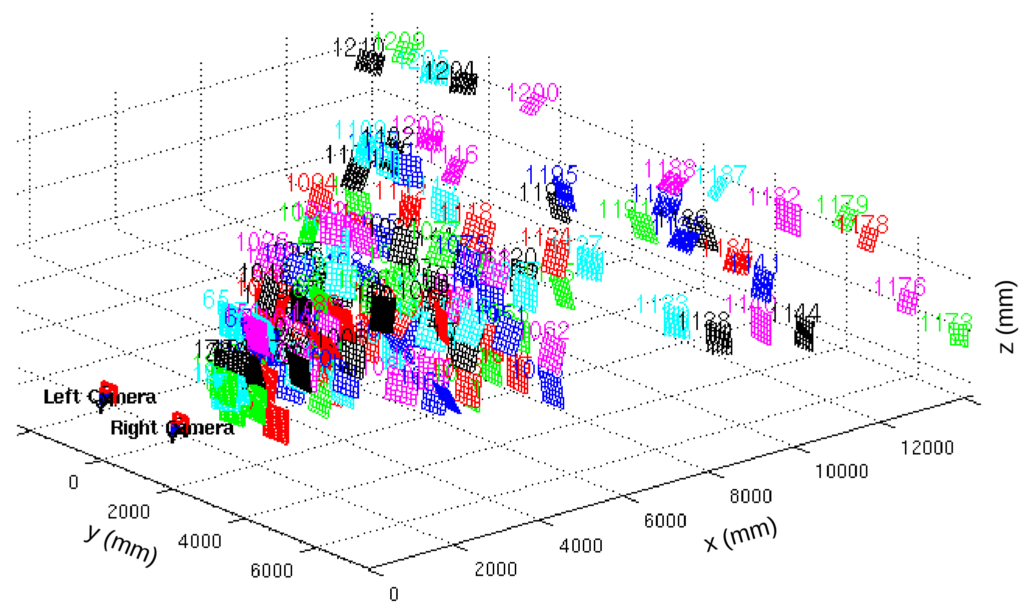
Stereo-matching is **efficient** since potential matches can be found along each corresponding **epipolar lines**



Camera (intrinsic) calibration

- A **known object** (usually a planar chessboard) is imaged by the stereo rig in multiple poses to recover its **geometrical** properties.





Previous experiences

[1] Chase, J.L *et al.* The directional spectrum of a wind generated sea as determined from data obtained by the Stereo Wave Observation Project *Department of Meteorology and Oceanography and Engineering Statistics Group* **03**, 267 (1957).

[2] Sugimori, Y., A study of the application of the holographic method to the determination of the directional spectrum of ocean waves. *Deep-Sea Research and Oceanographic* **22**, (1975).

[3] Holthuijsen, L. H., Observations of the directional distribution of ocean-wave energy in fetch-limited conditions. *Journal of Physical Oceanography* **13**, 191–207 (1983).

[4] Shemdin, O. H., Tran, H. M., & Wu, S. C. Directional measurement of short ocean waves with stereophotography. *Journal of Geophysical Research: Oceans* **93**, 13891–13901 (1988).

[5] Banner, M. L., Jones, I. & Trinders, J. c. Wavenumber spectra of short gravity waves. *Journal of Fluid Mechanics* **198**, 321–344 (1989).

… lack of Computer Vision techniques and Computing power…

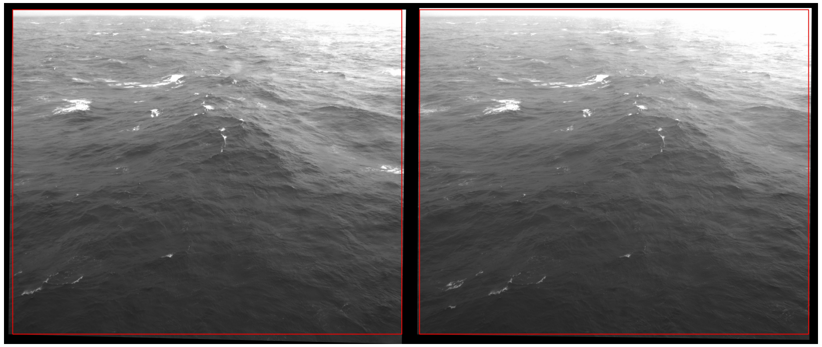
The WASS pipeline

In the past years, we proposed state-of-the-art methods in this field, contributing to the diffusion of the topic among the oceanographic community

1. Stereo camera ***extrinsic calibration*** (R, $\boldsymbol{t}$) from sea images
2. Point cloud ***filtering*** and mean sea-plane ***alignment***
3. Reconstruction ***errors*** varying the geometrical configuration of the stereo system
4. Reconstruction from ***moving*** vessels

WASS (Wave Acquisition Stereo System)

INPUT



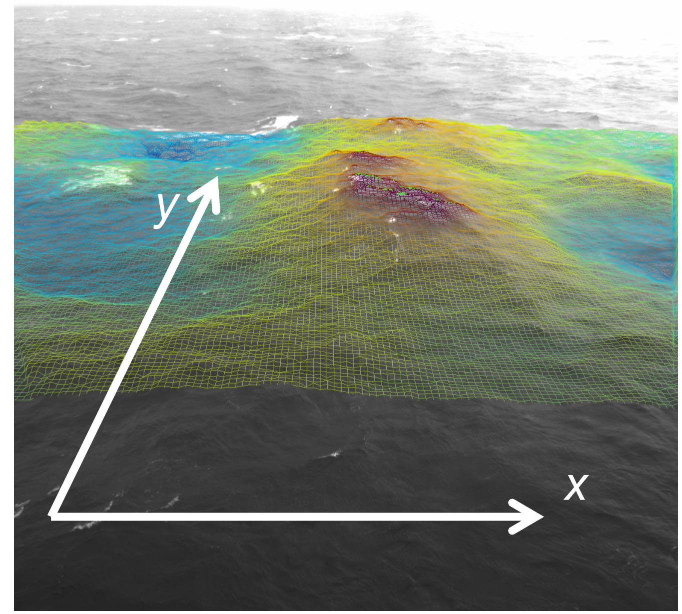
① Stereo frames (synch. < 1 ms)

② Camera intrinsic parameters

- Focal length
- Principal point
- Lens distortion coefficients

(calibrated in the lab)

WASS computes



① Stereo extrinsic parameters (R, $\boldsymbol{t}$)

② Mean-sea-plane coefficients

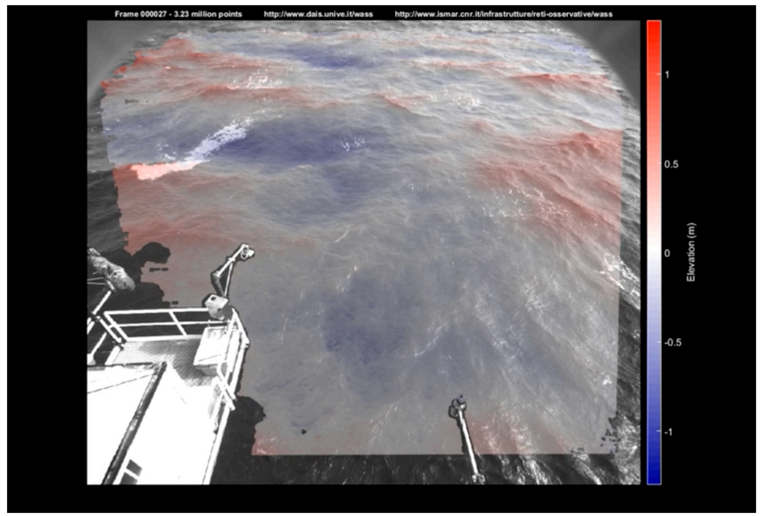
③ 3D wave field $\eta(x, y)$ for each stereo pair

http://www.dais.unive.it/wass

(Bergamasco et al., 2017. C&G)

Welcome to the WASS project

WASS (Waves Acquisition Stereo System) is an optimized stereo processing pipeline for sea waves 3D reconstruction.



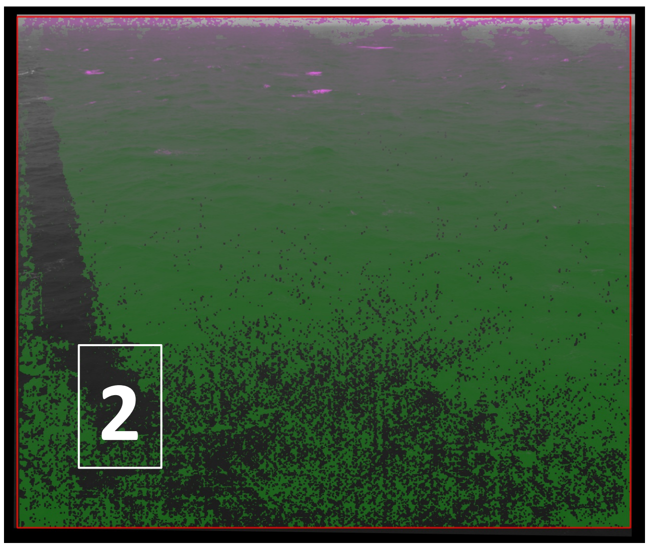
WASS was developed by [Filippo Bergamasco](http://www.dsi.unive.it/~bergamasco/) as a joint-collaboration between [Università Ca'Foscari di Venezia](http://www.unive.it) and [CNR ISMAR](http://www.ismar.cnr.it). It is a result of more than 3 years of active research with [Alvise Benetazzo](http://www.ismar.cnr.it/people/benetazzo-alvise) (CNR-ISMAR) in the field of vision-based 3D surface reconstruction of sea waves.

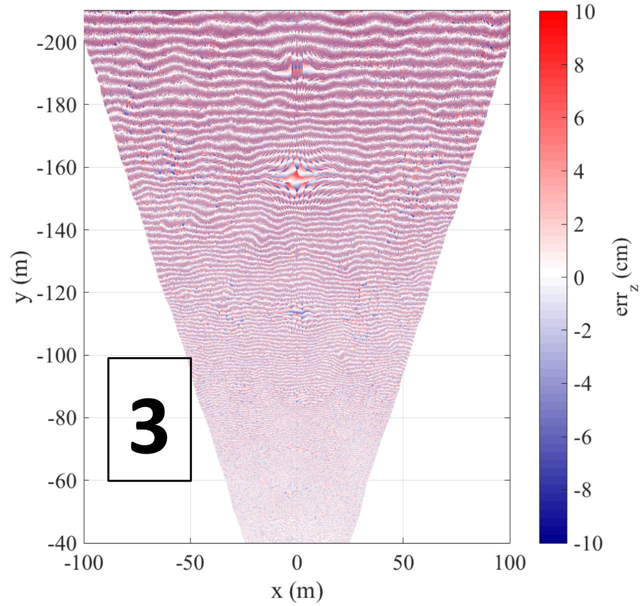
Ca' Foscari University of Venice | CNR Consiglio Nazionale delle Ricerche | ISMAR Istituto di Scienze Marine | Ritmare La ricerca italiana per il mare

The first **open-source** software for sea-waves 3D reconstruction

Kinds of measurement error

1. **Calibration Error:** error in estimating camera parameters
2. **Matching Error**: uncertainty in the determination of the corresponding pixels for each image pair (dark, bright areas)
3. **Quantization Error**: reconstruction is quantized along the image scanlines producing characteristic patterns along the *y*-axis





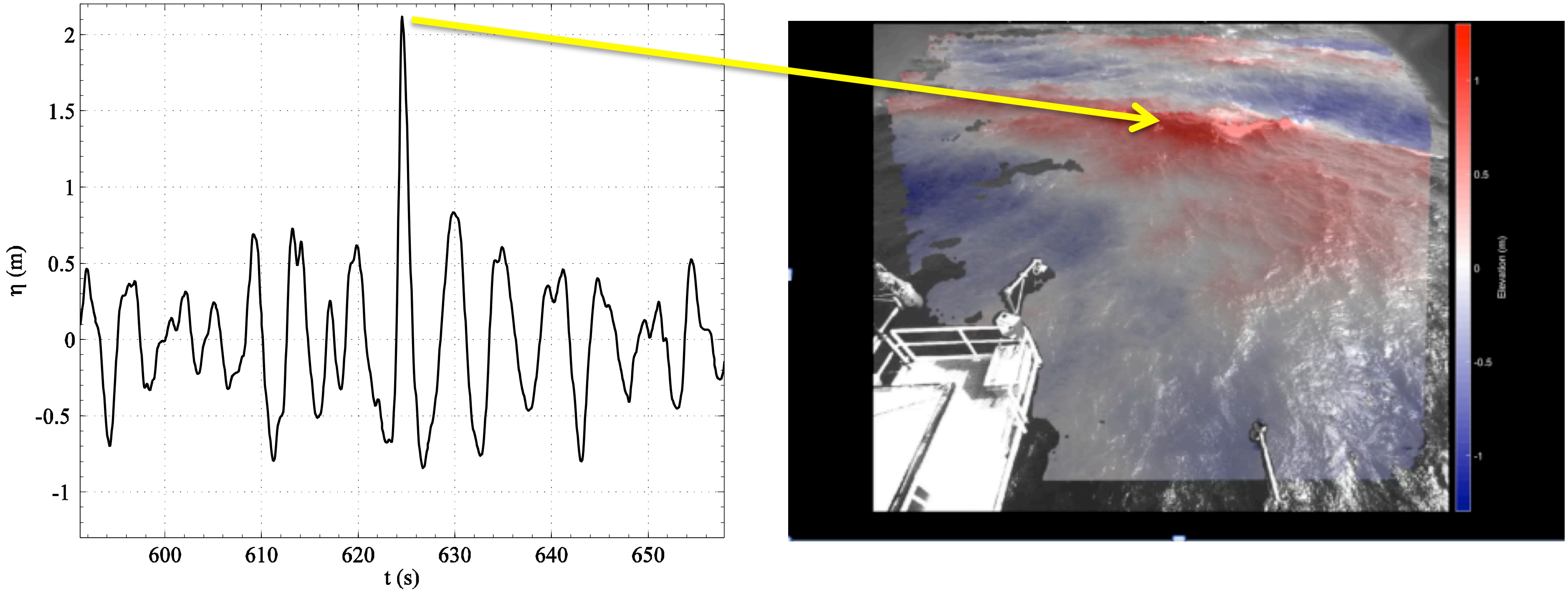
We can simulate and **evaluate** the expected reconstruction accuracy given a stereo setup

Latest Applications

How rogue waves look like in 3D

- Maxima at different locations on the *xy*-space
- Missed by local instruments (e.g., buoys)

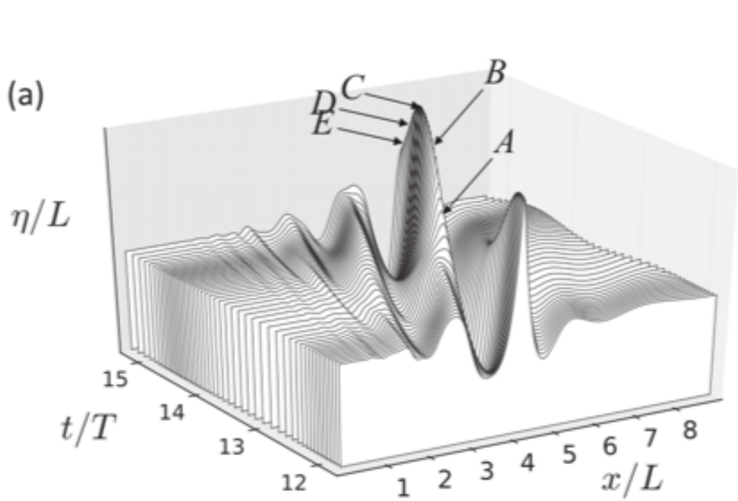
Rogue waves in Space and Time



- ➔ Individual, rogue wave is isolated in time (…it seems to appear out of nowhere…) but coherent in space-time
- ➔ Likelihood and shape of rogue waves

(Benetazzo et al., 2015; Benetazzo et al., 2017)

Crest speed of high waves



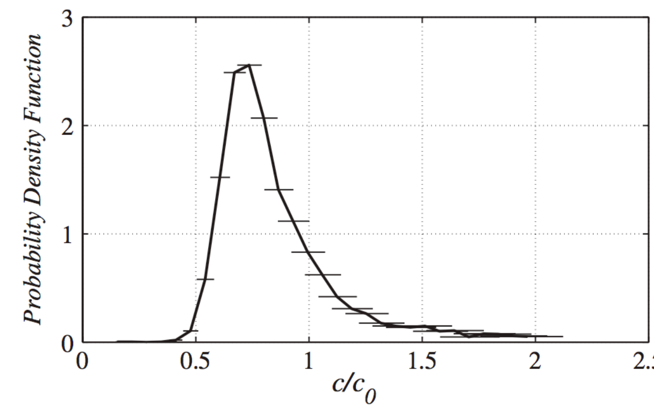


FIG. 3. Probability density function of normalized crest speed c/c_0 for all crests transitioning through a maximum local crest steepness, from a 35-minute WASS stereo-video sequence from an ocean tower. Note, the tall peak at $c/c_0 \sim 0.75$. Local standard error bounds are indicated.

PRL **112,** 114502 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

Linking Reduced Breaking Crest Speeds to Unsteady Nonlinear Water Wave Group Behavior

M. L. Banner,[1,*] X. Barthelemy,[1,2] F. Fedele,[3] M. Allis,[2] A. Benetazzo,[4] F. Dias,[5] and W. L. Peirson[2]

[1]*School of Mathematics and Statistics, The University of New South Wales, UNSW Sydney, NSW 2052, Australia*

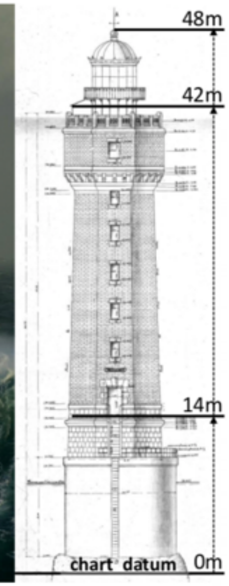
[2]*Water Research Laboratory, School of Civil and Environmental Engineering, The University of New South Wales, Manly Vale, New South Wales 2093, Australia*

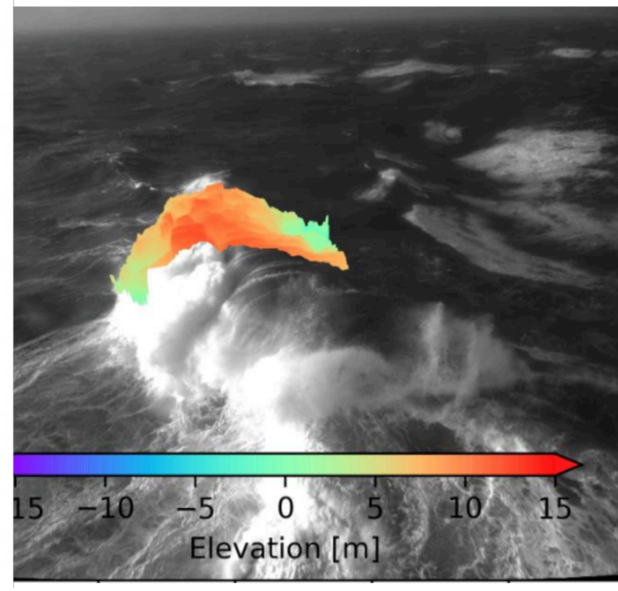
[3]*School of Civil and Environmental Engineering, and School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*

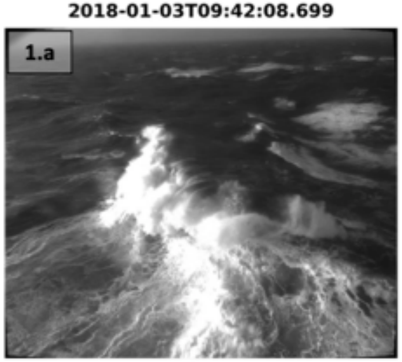
[4]*Institute of Marine Sciences, National Research Council (CNR-ISMAR), Venice 30122, Italy*

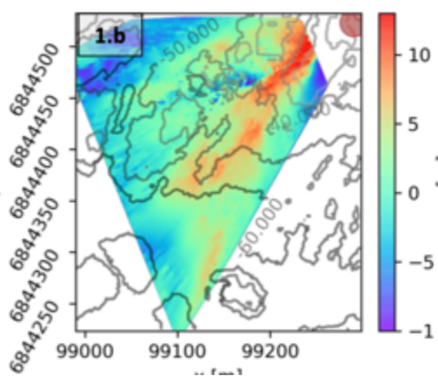
[5]*UCD School of Mathematical Sciences, University College Dublin, Belfield, Dublin 4, Ireland*

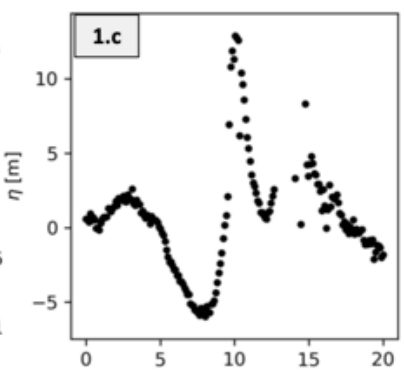
Wave load on marine structures











PHILOSOPHICAL TRANSACTIONS A

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Research

Article submitted to journal

Subject Areas:
heritage structure, extreme waves, lighthouse

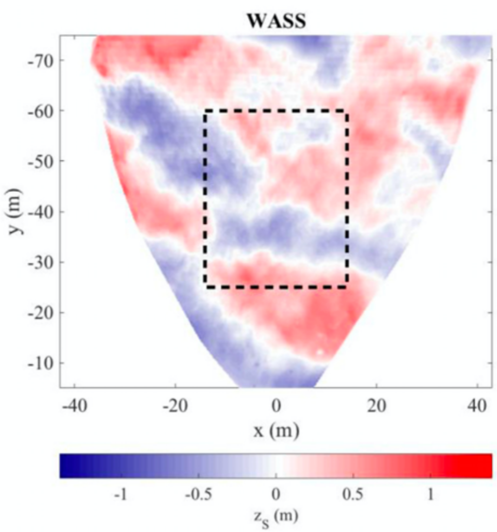
Keywords:
extreme wave, wave breaking, wave loading

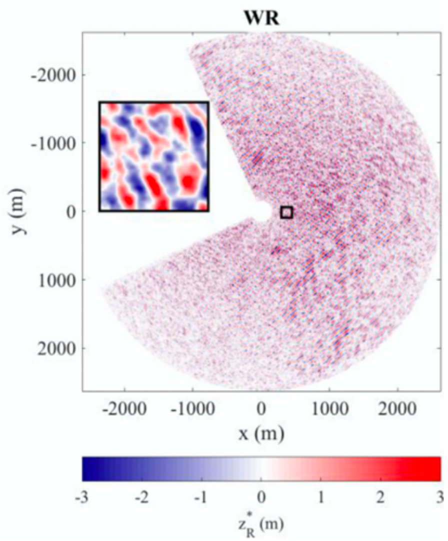
La Jument Lighthouse: a real scale laboratory for the study of giant waves and of their loading on marine structures

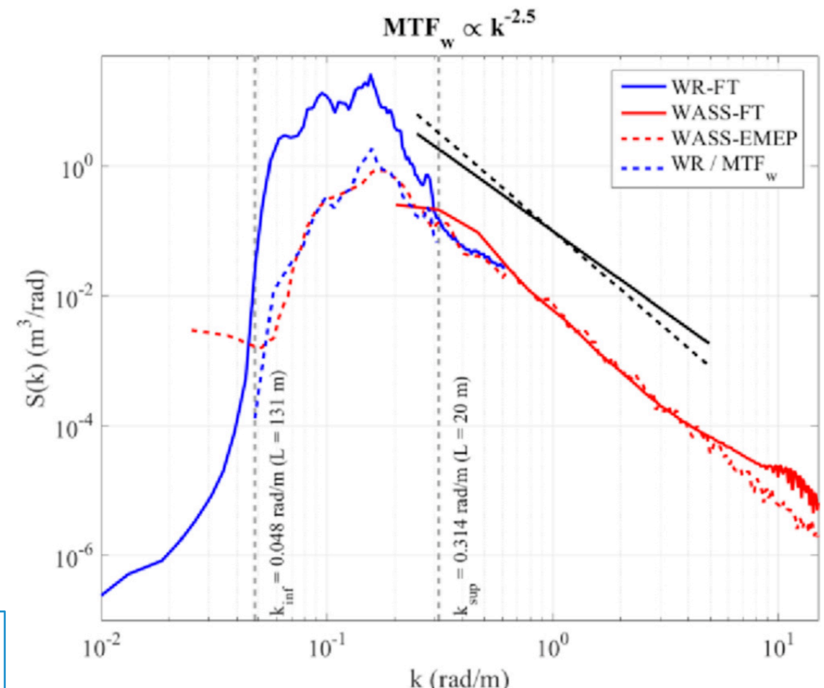
J.-F. Filipot[1], P. Guimaraes[2], F. Leckler[2], J. Hortsmann[3], R. Carrasco[3], E. Leroy[4], N. Fady[4], M. Prevosto[5], V. Roeber[6], A. Benetazzo[7], C. Raoult[2], M. Franzetti[8], A. Varing[1], N. Le Dantec[4]

[1]France Energies Marines, Plouzané, France, [2]Shom, Brest, France, [3]HZG, Geestacht, Germany, [4]Cerema, Plouzané, France, [5]Ifremer, Plouzané, France [7]CNR, Venice, Italy, [8]IUEM-LGO, Plouzané, France

Stereo/x-band radar data fusion







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Ocean Engineering

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Stereo imaging and X-band radar wave data fusion: An assessment

Alvise Benetazzo [a,*], Francesco Serafino [b], Filippo Bergamasco [c], Giovanni Ludeno [d], Fabrice Ardhuin [e], Peter Sutherland [e], Mauro Sclavo [a], Francesco Barbariol [a]

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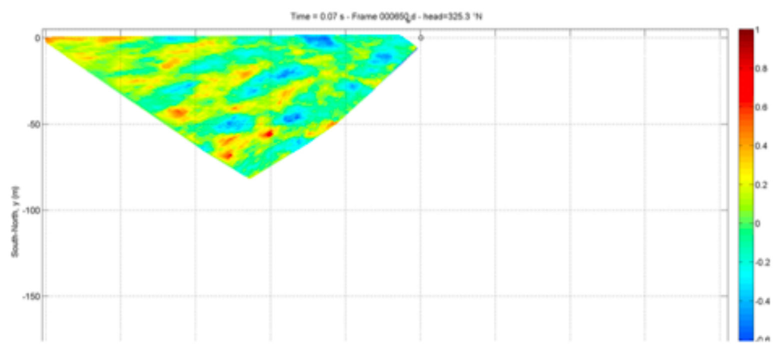
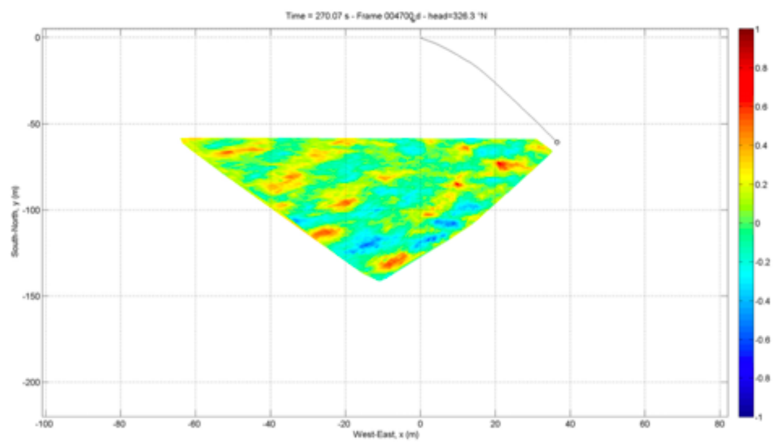
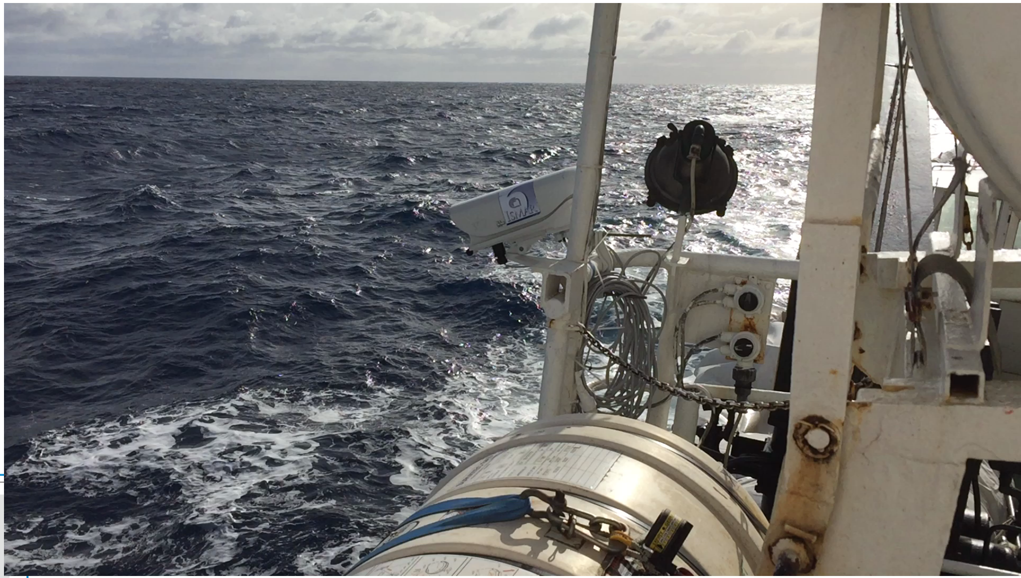
[c] *DAIS – Università Ca' Foscari, Venice, Italy*
[d] *Institute for Electromagnetic Sensing of the Environment, Italian National Research Council (IREA-CNR), Naples, Italy*
[e] *Laboratoire d'Océanographie Physique et Spatiale (LOPS), Univ. Brest, CNRS, Ifremer, IRD, Brest, France*

From a moving ship





➔ **Coupling with an IMU for the 6-DOF motion**



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Stereo wave imaging from moving vessels: Practical use and applications

Alvise Benetazzo [a,*], Francesco Barbariol [a], Filippo Bergamasco [b], Andrea Torsello [b], Sandro Carniel [a], Mauro Sclavo [a]

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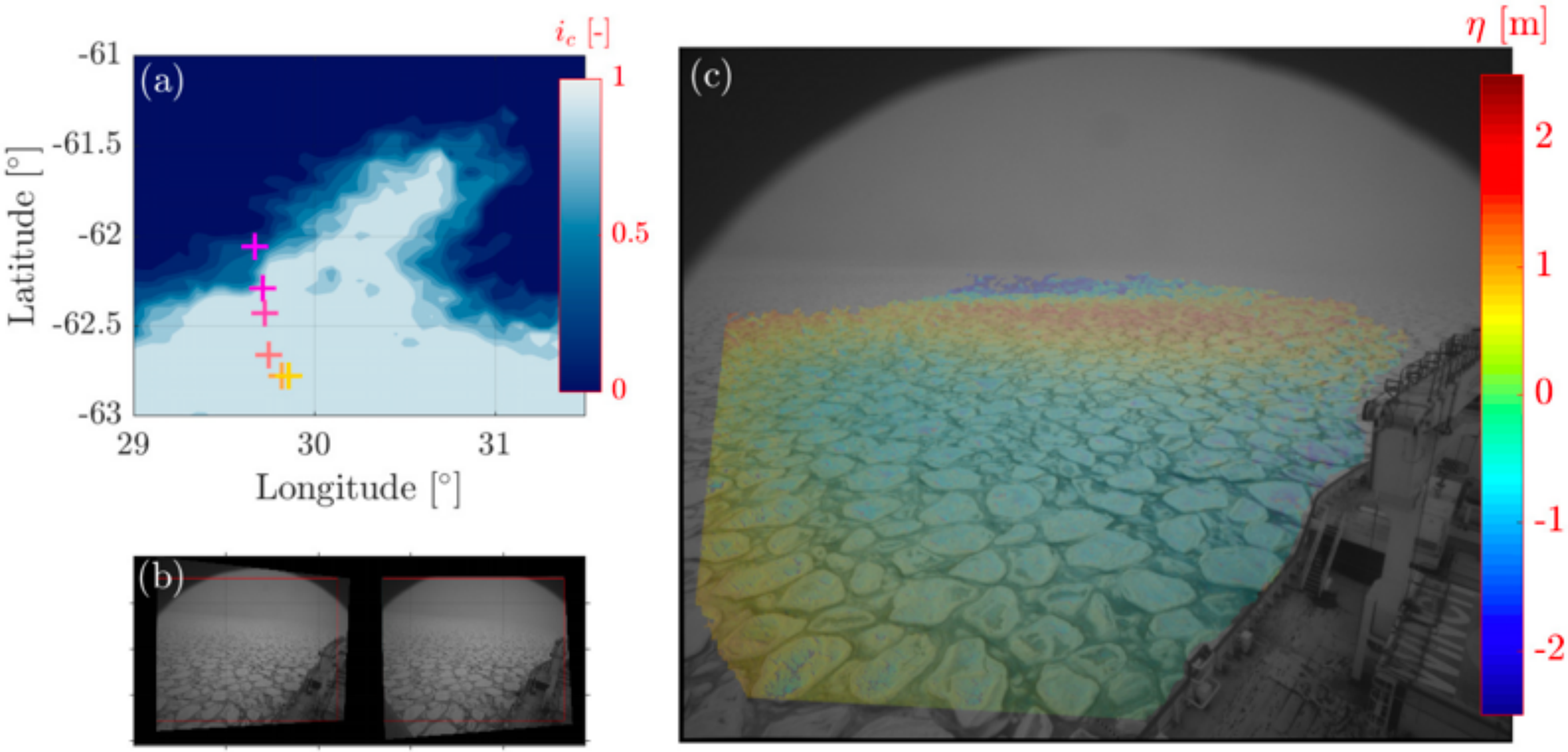
Sharp-Crested Breaking Surface Waves Observed from a Ship-Based Stereo Video System

MICHAEL S. SCHWENDEMAN AND JIM THOMSON

Applied Physics Laboratory, University of Washington, Seattle, Washington

(Manuscript received 9 August 2016, in final form 24 January 2017)

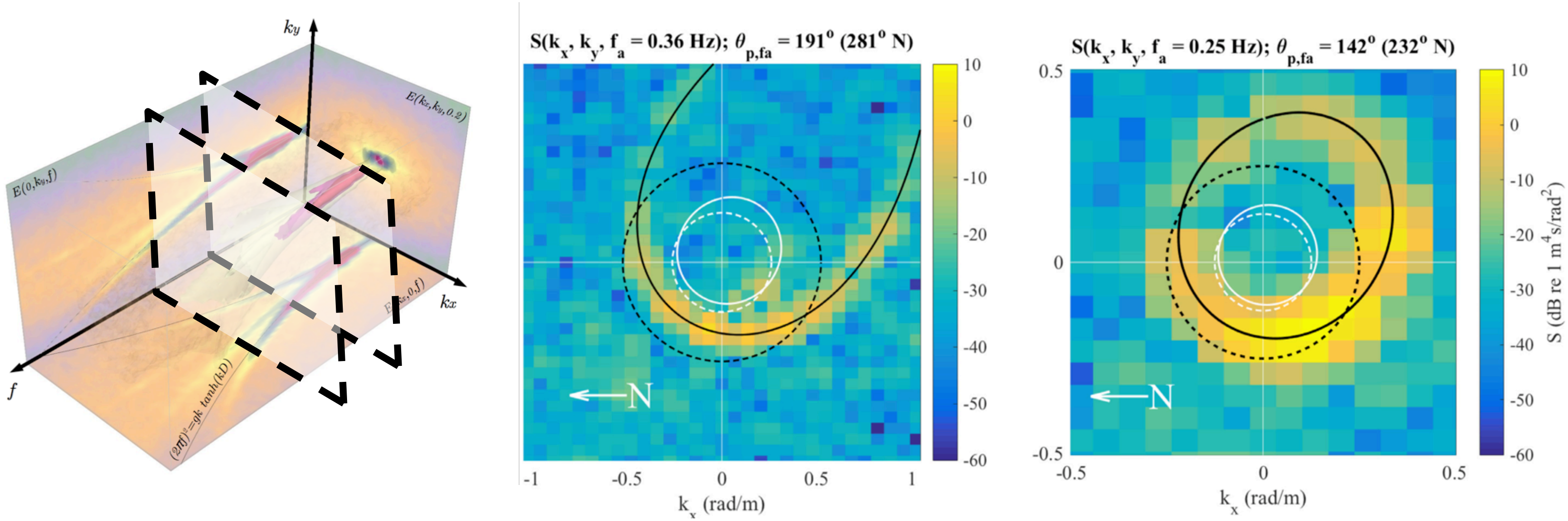
Wave dissipation in the MIZ



→Wave fields (from 3D) and sea-ice concentration (from images)

(Alberello et al., 2021)

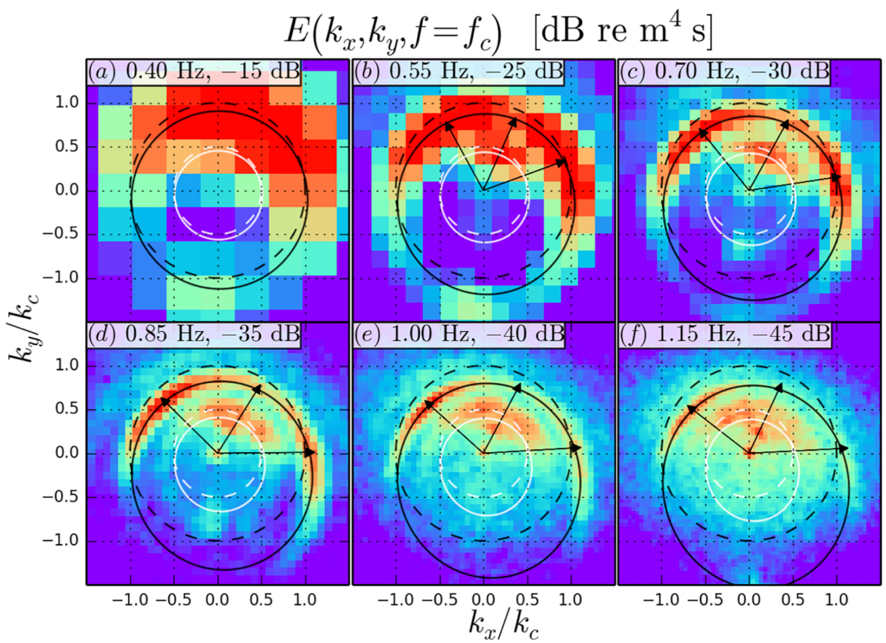
Wavenumber-Frequency 3D spectrum

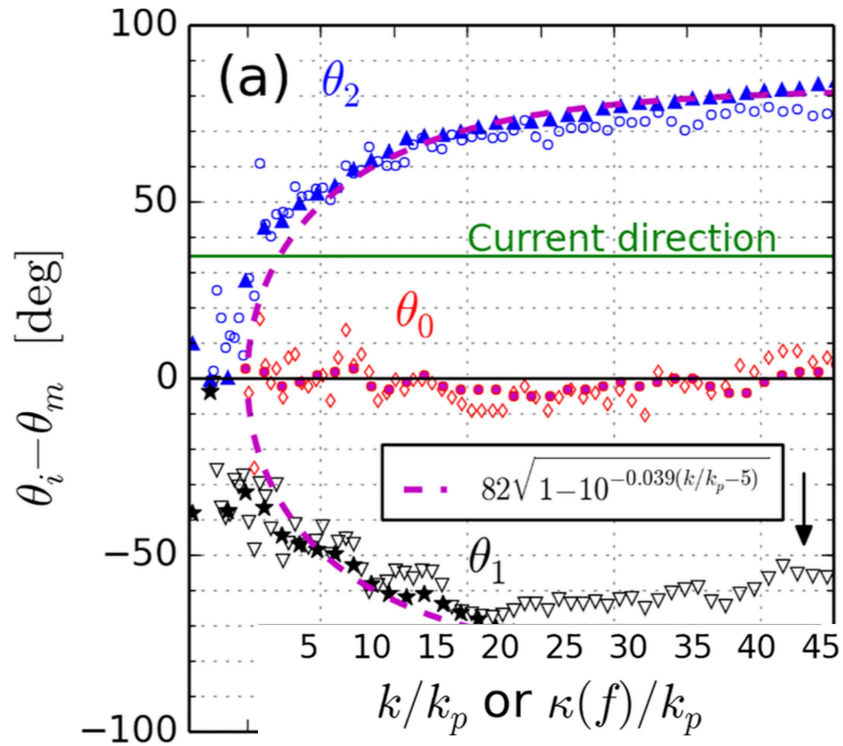


- Oceanic near-surface current (via Doppler shift)
- Energy of linear / nonlinear modes
- Directionality of short waves

(Benetazzo et al., 2018; OM)

Bi-modal distribution of short-wave energy





Ocean Sci., 14, 41–52, 2018
https://doi.org/10.5194/os-14-41-2018

Ocean Science

Note on the directional properties of meter-scale gravity waves

Charles Peureux[1], Alvise Benetazzo[2], and Fabrice Ardhuin[1]

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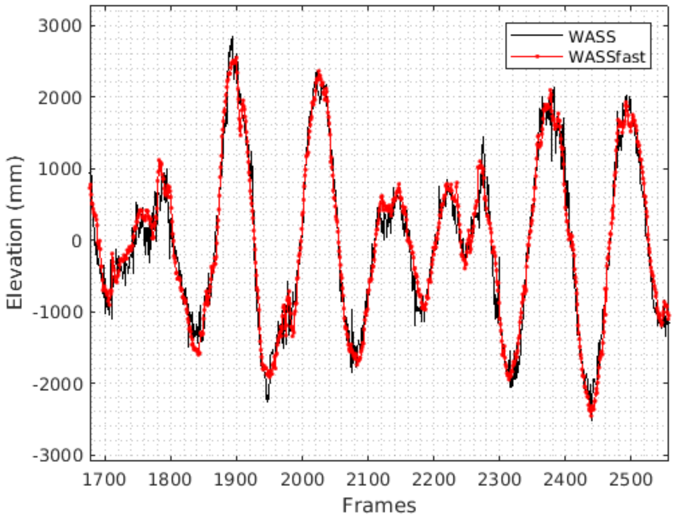
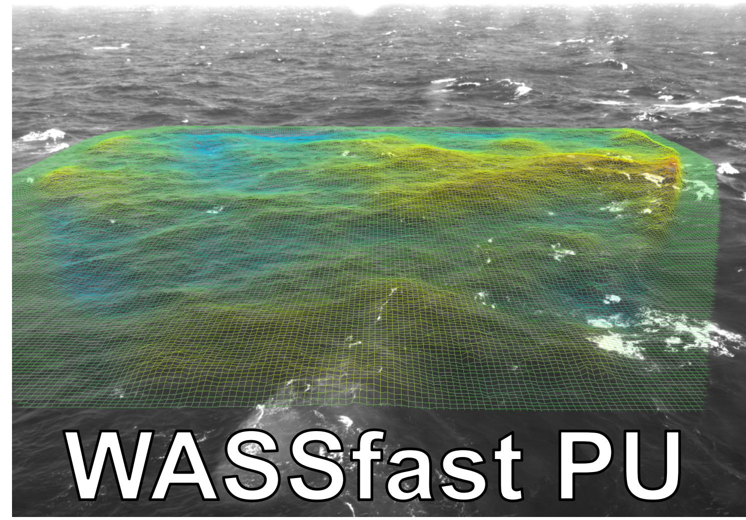
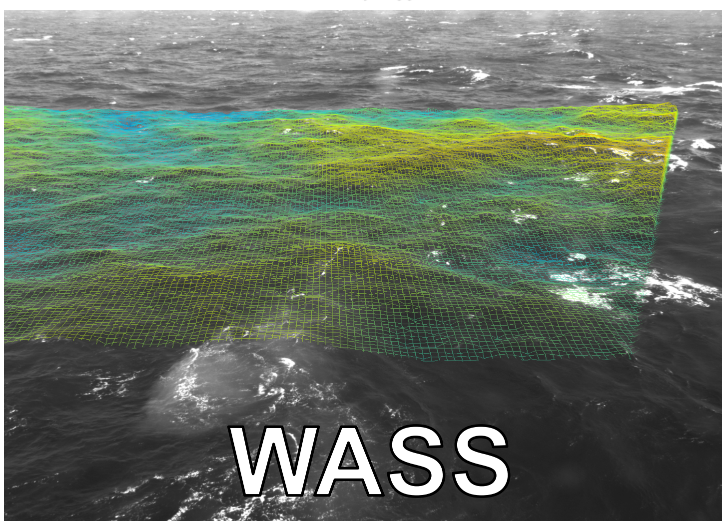
[2]Institute of Marine Sciences, Italian National Research Council, Venice, Italy

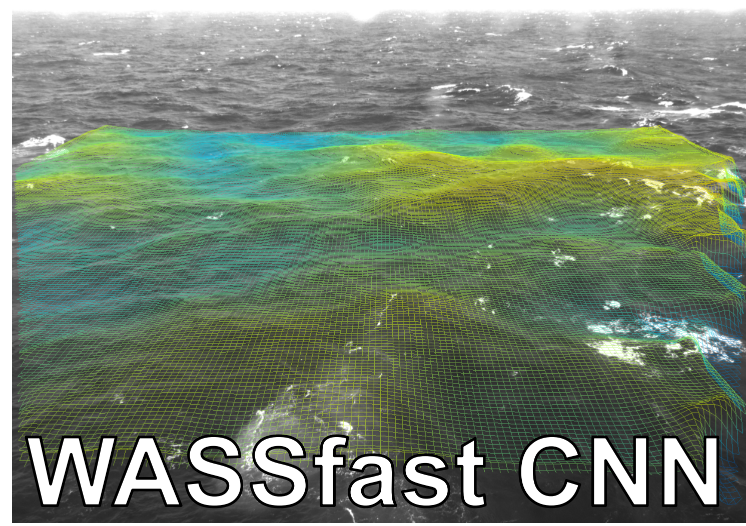
Present research: WASSfast

WASS computes a 3D wave field from stereo pair in ~1 min (half of the time is spent for *gridding* from the point cloud)



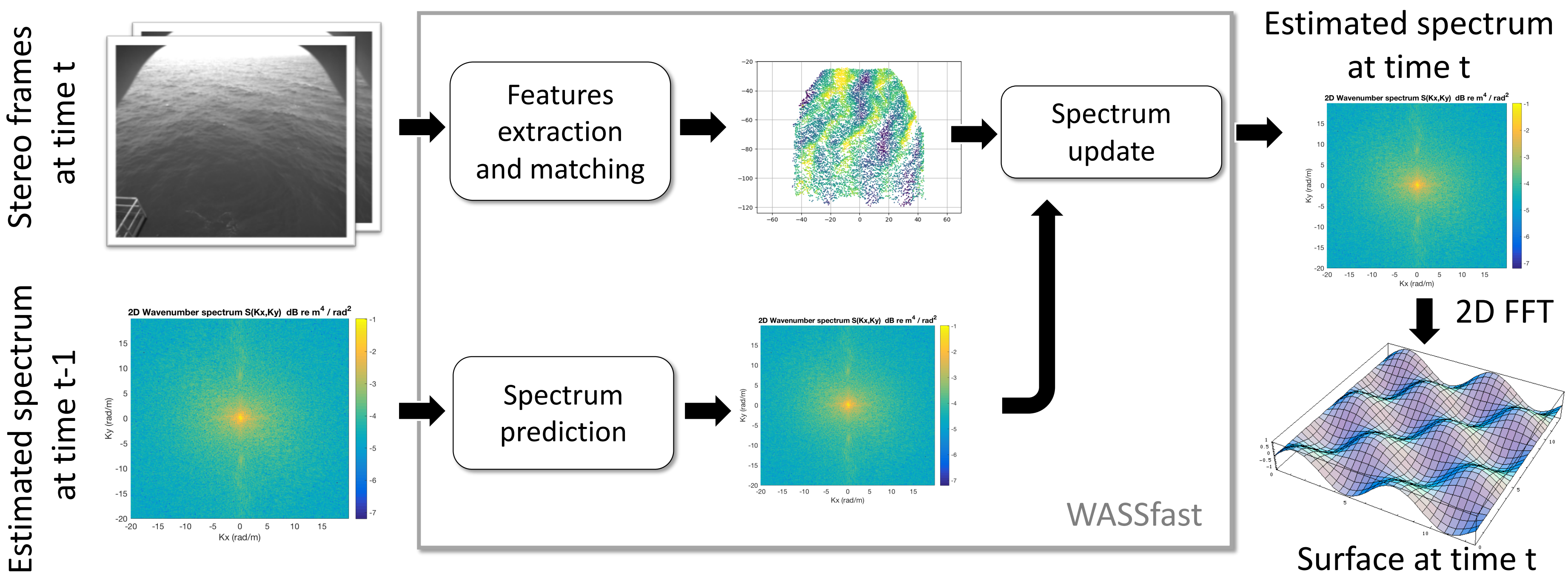


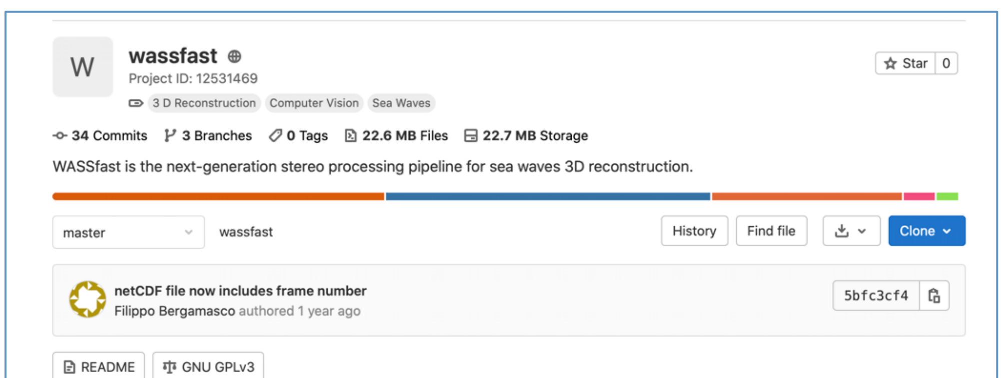




(Bergamasco et al., 2021; C&G)

WASSfast


Stereo frames
at time t
Features
extraction
and matching
Spectrum
update
Estimated spectrum
at time t
2D Wavenumber spectrum S(Kx,Ky) dB re m^4 / rad^2
Kx (rad/m)
Ky (rad/m)
2D FFT
Estimated spectrum
at time t-1
Spectrum
prediction
WASSfast
Surface at time t


W
wassfast
Project ID: 12531469
3 D Reconstruction
Computer Vision
Sea Waves
Star 0
34 Commits
3 Branches
0 Tags
22.6 MB Files
22.7 MB Storage
WASSfast is the next-generation stereo processing pipeline for sea waves 3D reconstruction.
master
wassfast
History
Find file
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netCDF file now includes frame number
Filippo Bergamasco authored 1 year ago
5bfc3cf4
README
GNU GPLv3

WASSfast: spectrum update

Two alternative approaches

1. **PU:** A constrained minimization procedure working in the Fourier wavenumber domain
   - Slower, more accurate
2. **CNN:** A learning-based Convolutional Neural Network to perform "depth completion" based on physical priors
   - Extremely fast, slightly less accurate in the high frequencies, still under heavy testing…

WASS vs. WASSfast

- Reconstructs a dense point cloud (approx. 3E6 points per stereo pair on a 5mpix camera)
- Frames are processed in parallel and no temporal relation is considered
- Gridding is a separate step implemented as a general scattered surface interpolation
- Highly accurate, well tested
- Approx. 30 sec per stereo frame processing time

- Reconstructs a sparse point cloud for each frame (10K on average)
- Frames are processed sequentially, the dispersion relation is used to optimize a time-evolving 3D surface
- Gridding is interleaved with point reconstruction
- Less accurate, designed for real-time processing
- Up to from 0.5 fps (PU) to 5 fps (CNN) on modern GPUs

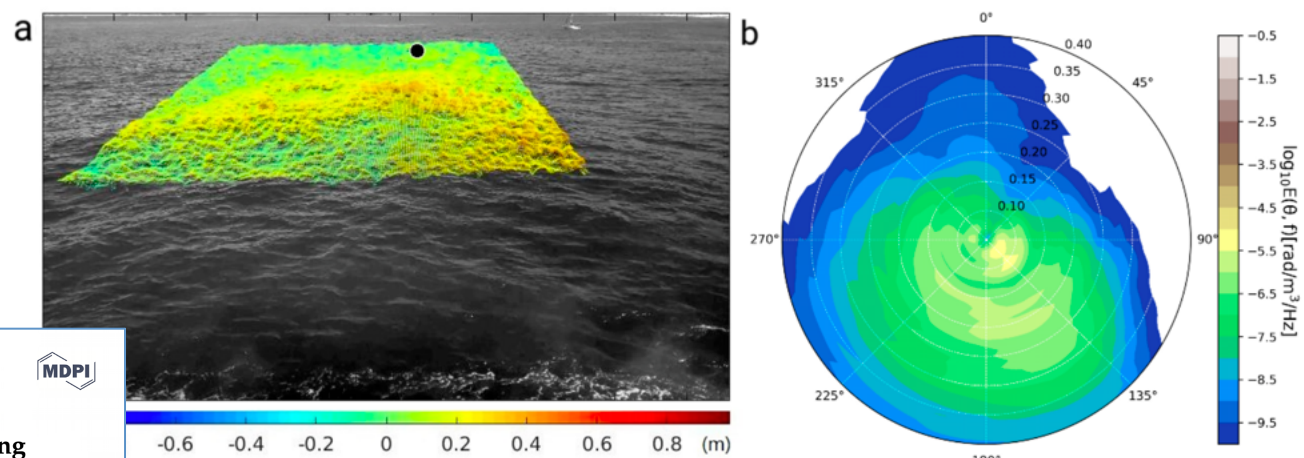
Low-cost WASS with smartphones / GoPro®

Appendix A

The following two codes were written in *Python* and *praat* programming language respectively and were applied to synchronize video data acquired by the smartphones as described in the Section 3.1—*Frame synchronization*.

wass_sync.py

```
'''
author: matheus vieira
needs: Python 2 or 3 / ffmpeg software / Praat software
- set video path (pathname)
- video files (cam0.mp4, cam1.mp4)    inside video path
- path called 'cam0'                  inside video path
- path called 'cam1'                  inside video path
- crosscorrelate.praat file           inside video path
'''
```



Journal of *Marine Science and Engineering*

MDPI

Article

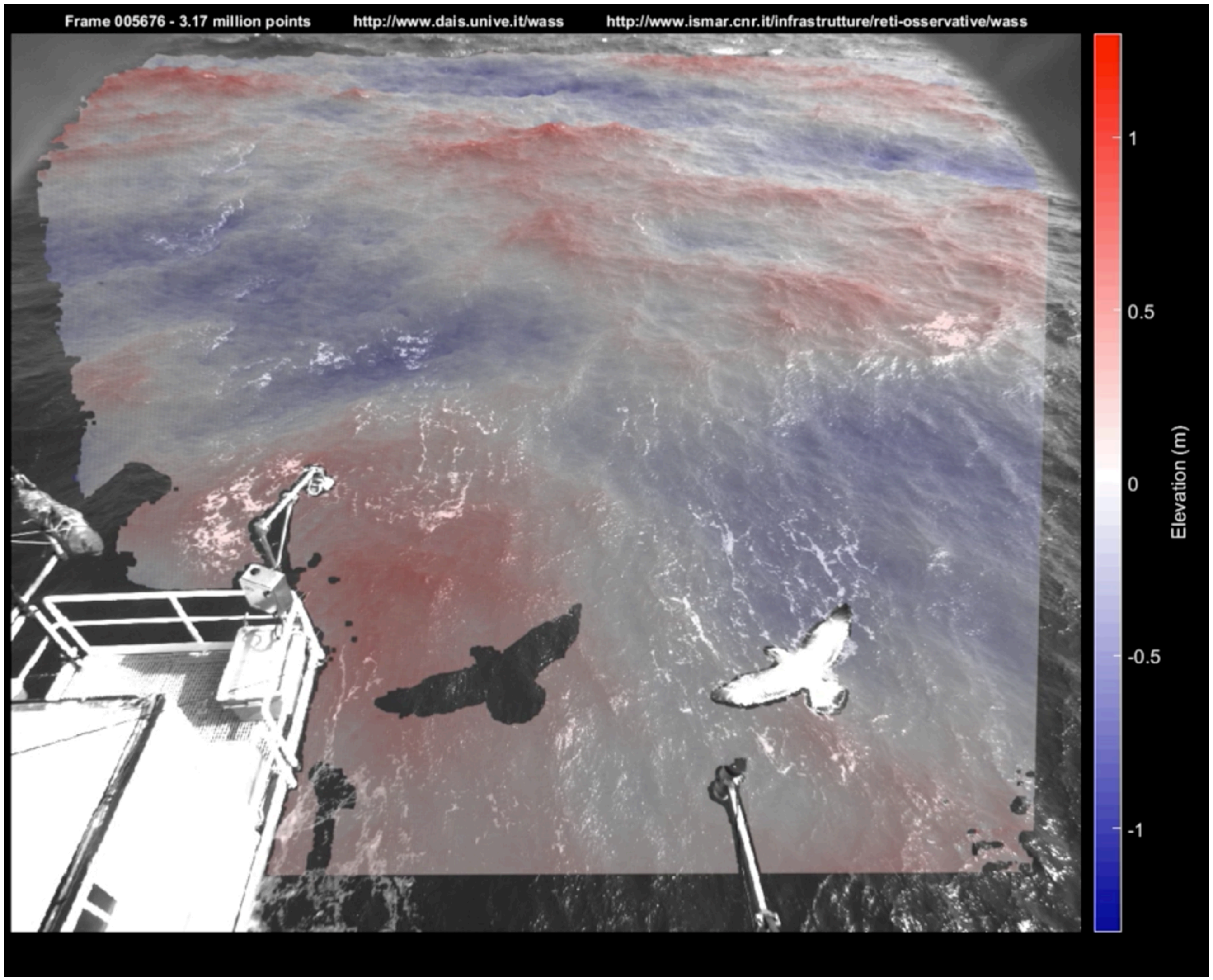
A Low-Cost Stereo Video System for Measuring Directional Wind Waves

Matheus Vieira [1,*,†], Pedro Veras Guimarães [2], Nelson Violante-Carvalho [1], Alvise Benetazzo [3,‡], Filippo Bergamasco [4,‡] and Henrique Pereira [1]

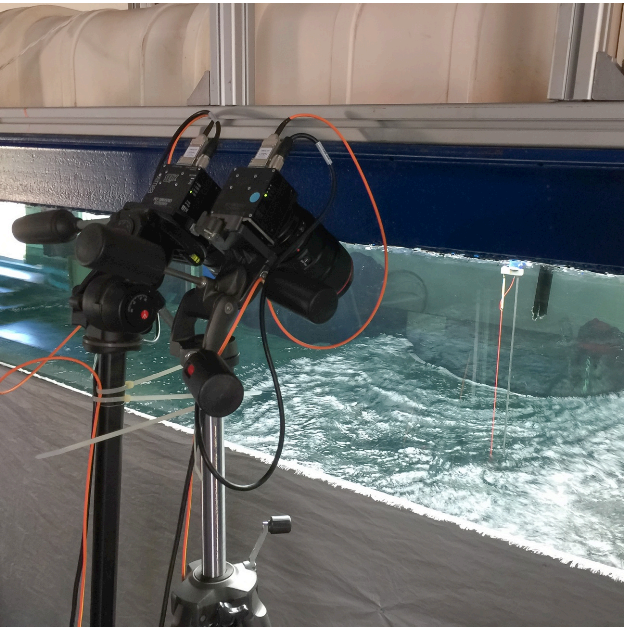
Take home message

- Stereo wave imaging allows to measure the surface wave field in space and time with good accuracy
- No assumptions on the underlying wave mechanics
- Fitting ships of opportunity (code not available yet)
- Limitations
  - Coverage
  - Need of a superstructure (with power supply)
  - Huge amount of data (less with WASSfast)

Many thanks for your attention!



Paddle- and wind-wave tank (Qingdao, P.R. China; FIO)



Paddle- and wind-wave tank (Qingdao, P.R. China; FIO)