Offshore remote sensing of the ocean by stereo vision systems

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Outline

- Prior vision-based systems for wave measurement
- Variational stereo methods.
- Extensions
  - Enforce wave height models
  - Space-time processing
  - Refinement of camera parameters
- Conclusions

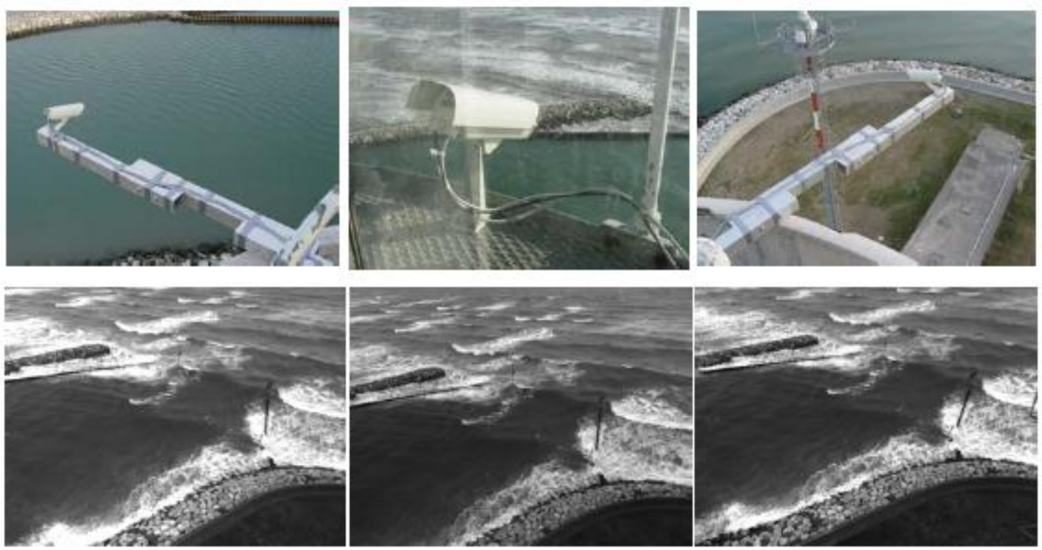
Motivation

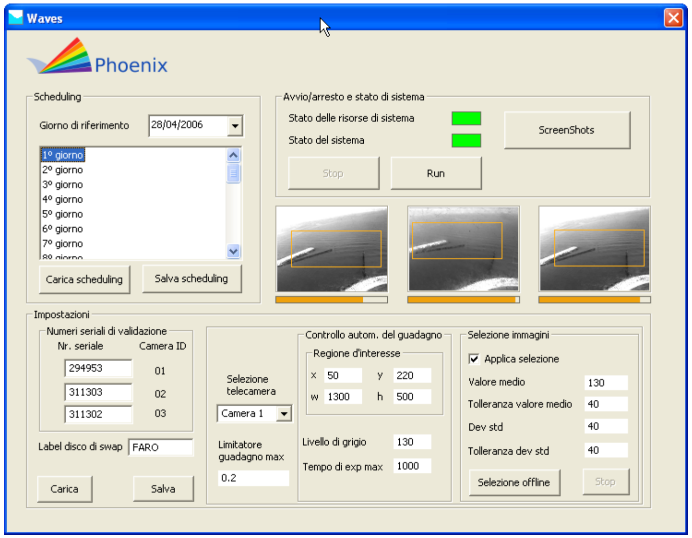
- Topic: measurements of ocean waves using vision systems.
- Applications:
  - Monitoring of sea states
  - Improvement in the design of platforms
  - Study of turbulence and wave mechanics
  - Validation of physical models of the ocean
- Interdisciplinary work: ocean eng. and computer vision

Literature review. WASS (Benetazzo, 2006)

Goal: to study and predict ocean wave patterns from image sensors

- Image acquisition
(Bi/Trinocular synchronized and calibrated digital cameras)



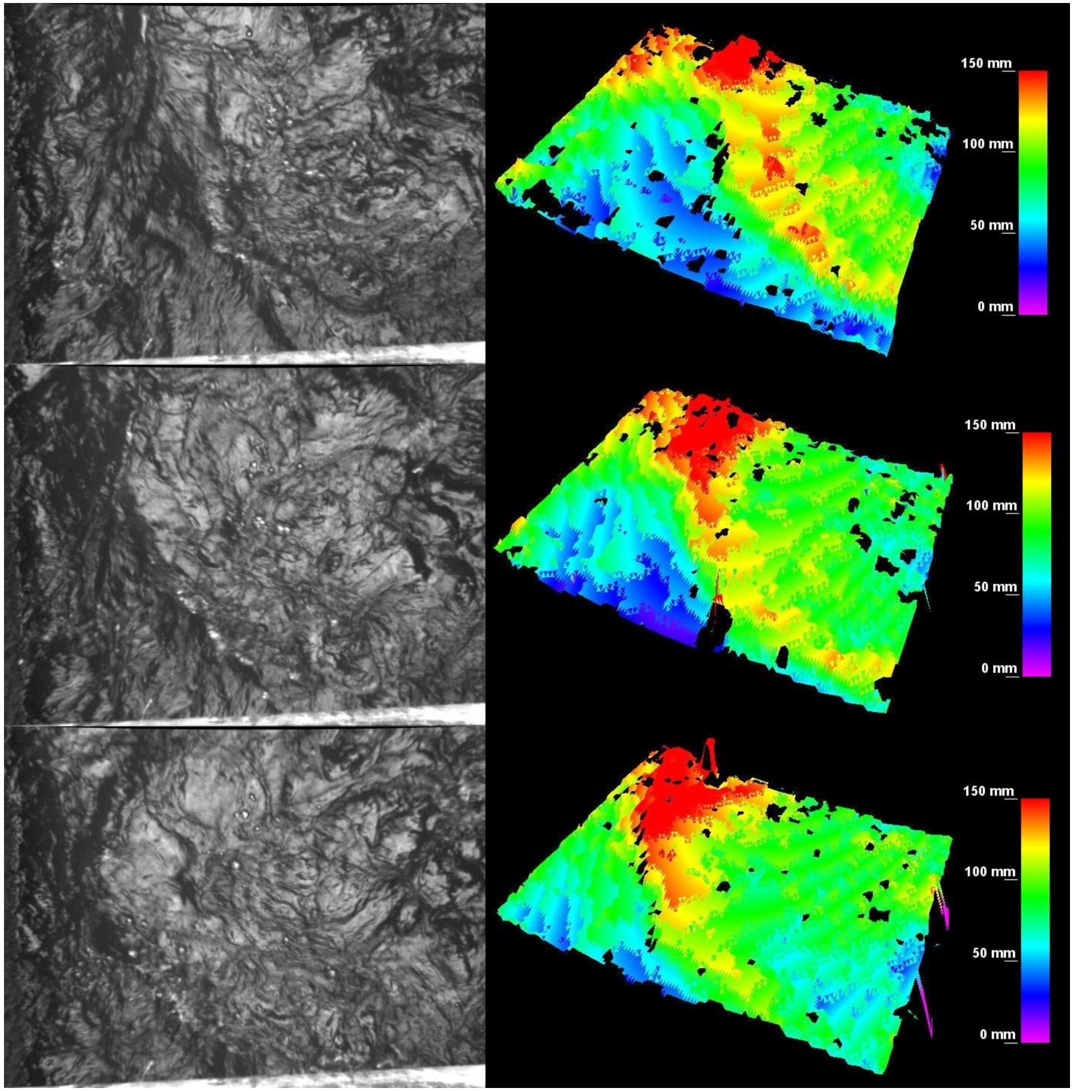


- Image processing
Reconstruct the surface of the water (epipolar stereo method)

Benetazzo, A. "Measurements of short water waves using stereo matched image sequences". *Coastal Engineering*, 53:1013-1032, 2006.

Literature review. WASS (Benetazzo, 2006)

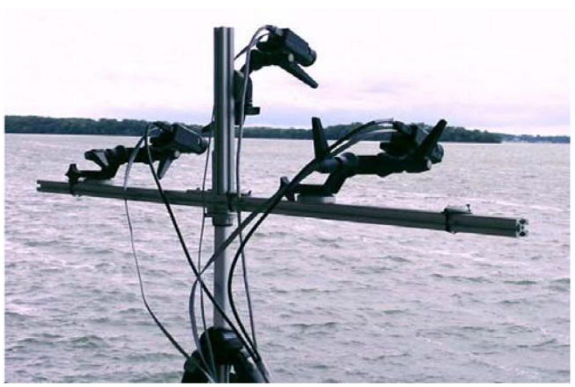
Water surface elevation in *time*:
from 2D image sequences to 3D map sequences

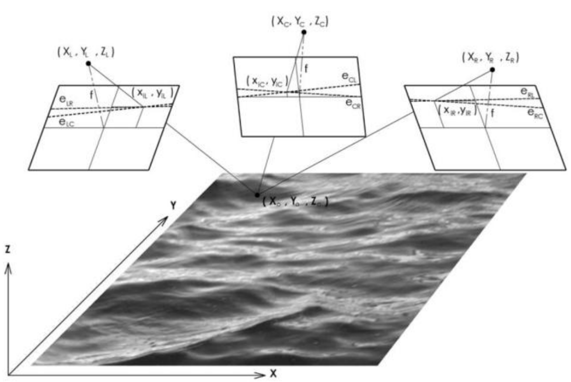


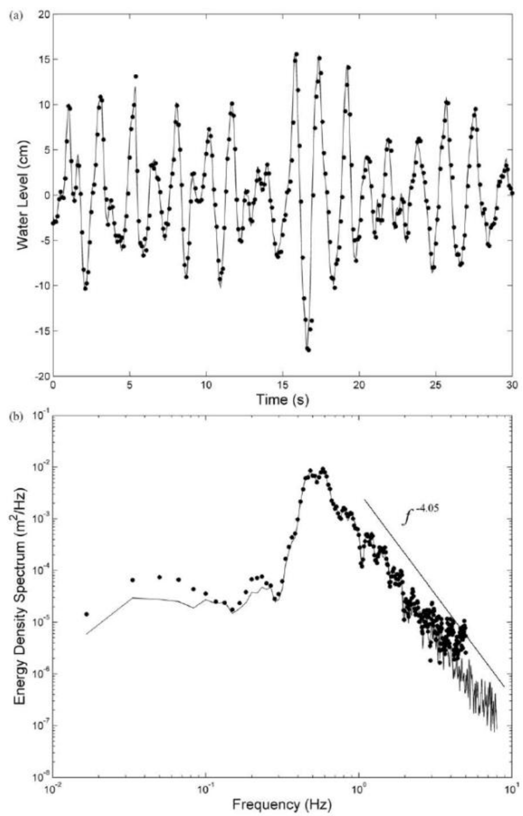
- $Z_0 \sim 1.70$ m, b = 0.22 m
- Matched Area : 0.94 x 0.78 m^2
- $e_{rx} = e_{ry} = 0.15$ cm, $e_{rz} = 0.69$ cm
- 90 % of points matched
- 480 x 640 pixel camera
- F = 6.3 mm, ss=1/200 s

Literature review. ATSIS

- Automatic Trinocular Stereo Imaging System (ATSIS) (Wanek and Wu, 2006).
- Measurement and analysis of ocean wave fields in 4D (MacHutchon and Liu, 2007, 2009).
- Virtual wave gauges for measuring surface wave characteristics (Bechle and Wu, 2011).







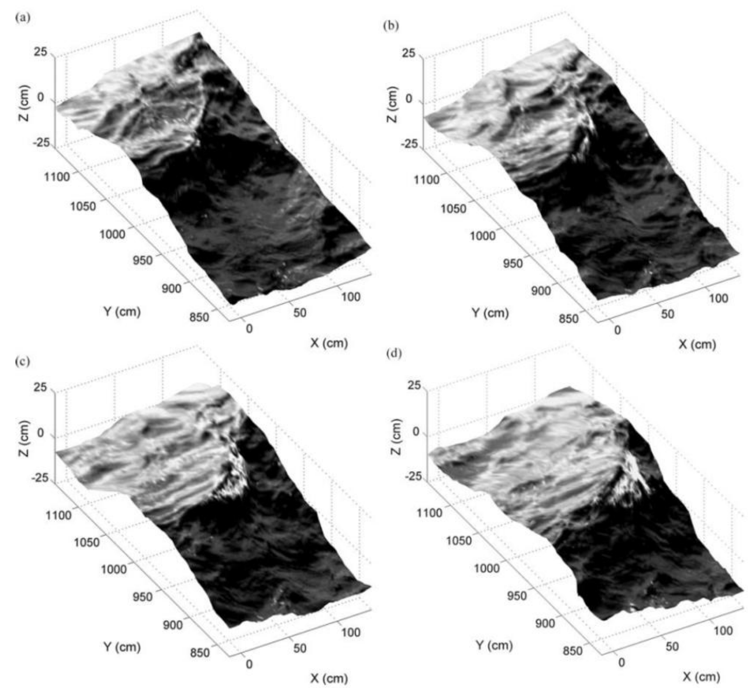
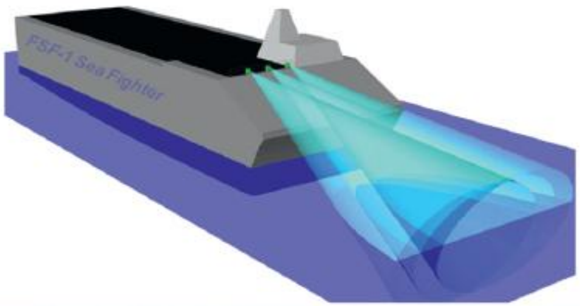


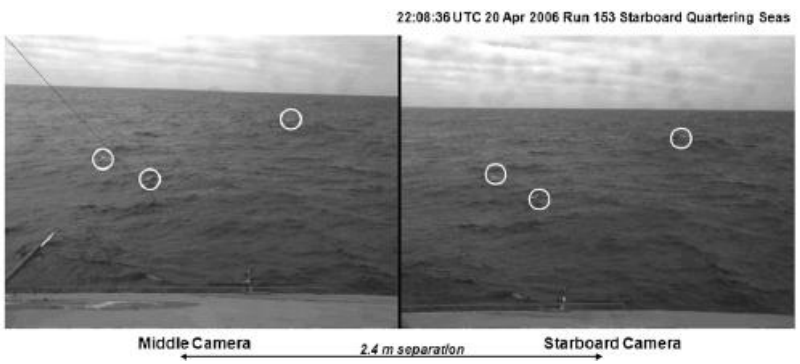
Fig. 9. A temporal evolution of a three dimensional wave breaking event at (a) $t=0.0$ s, (b) $t=0.1$ s, (c) $t=0.2$ s, (d) $t=0.3$ s, (e) $t=0.4$ s, and (f) $t=0.5$ s.

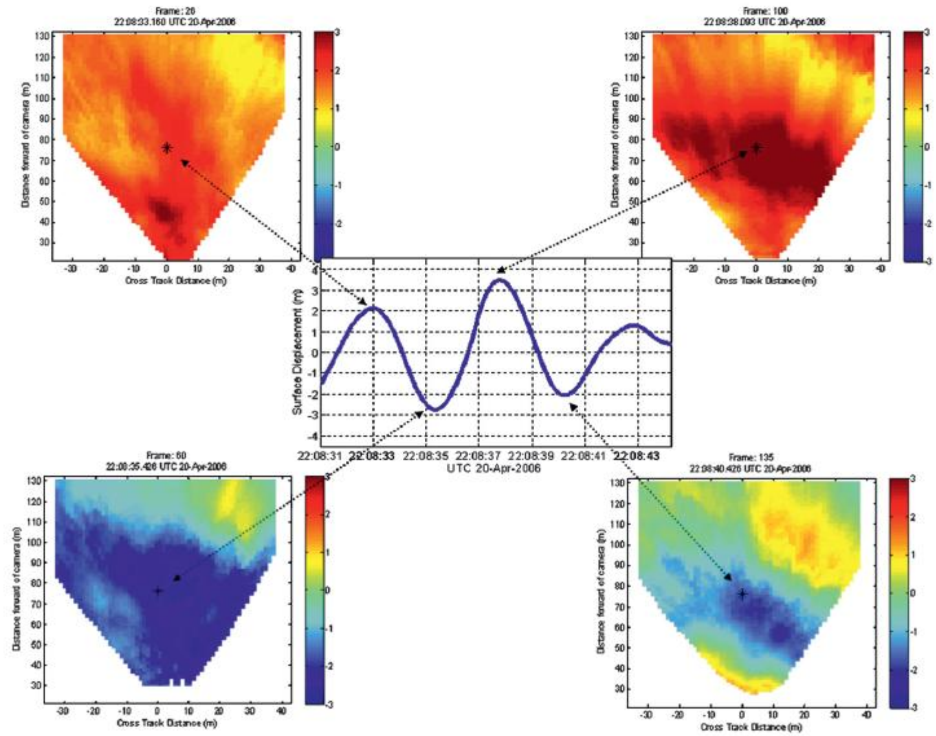
Literature review. Stereo systems

- Three-Dimensional Imaging of the High Sea-State Wave Field encompassing ship slamming events

  (Brandt et al 2010).

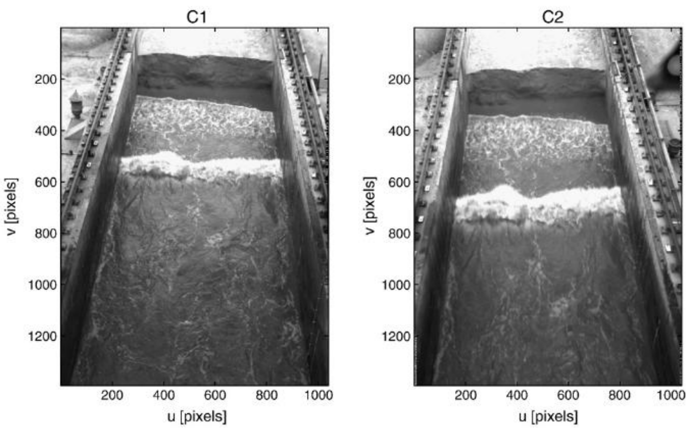






Literature review. Stereo systems

- Remote sensing of surf zone waves using stereo imaging
  (S. de Vries et al, 2011)



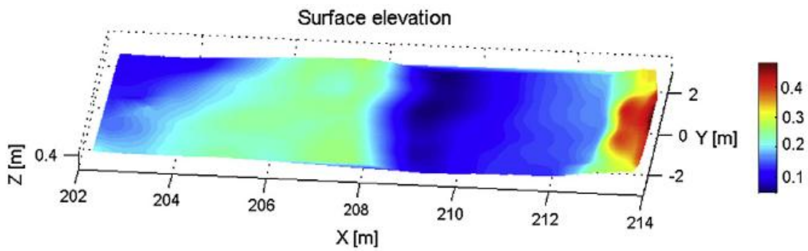


Fig. 12. Perspective view of the sample reconstruction of water surface elevation. Color contours denote elevation in meters.

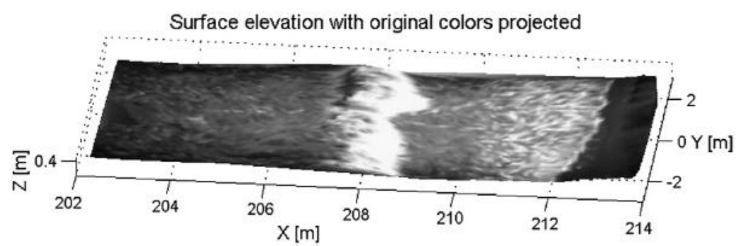
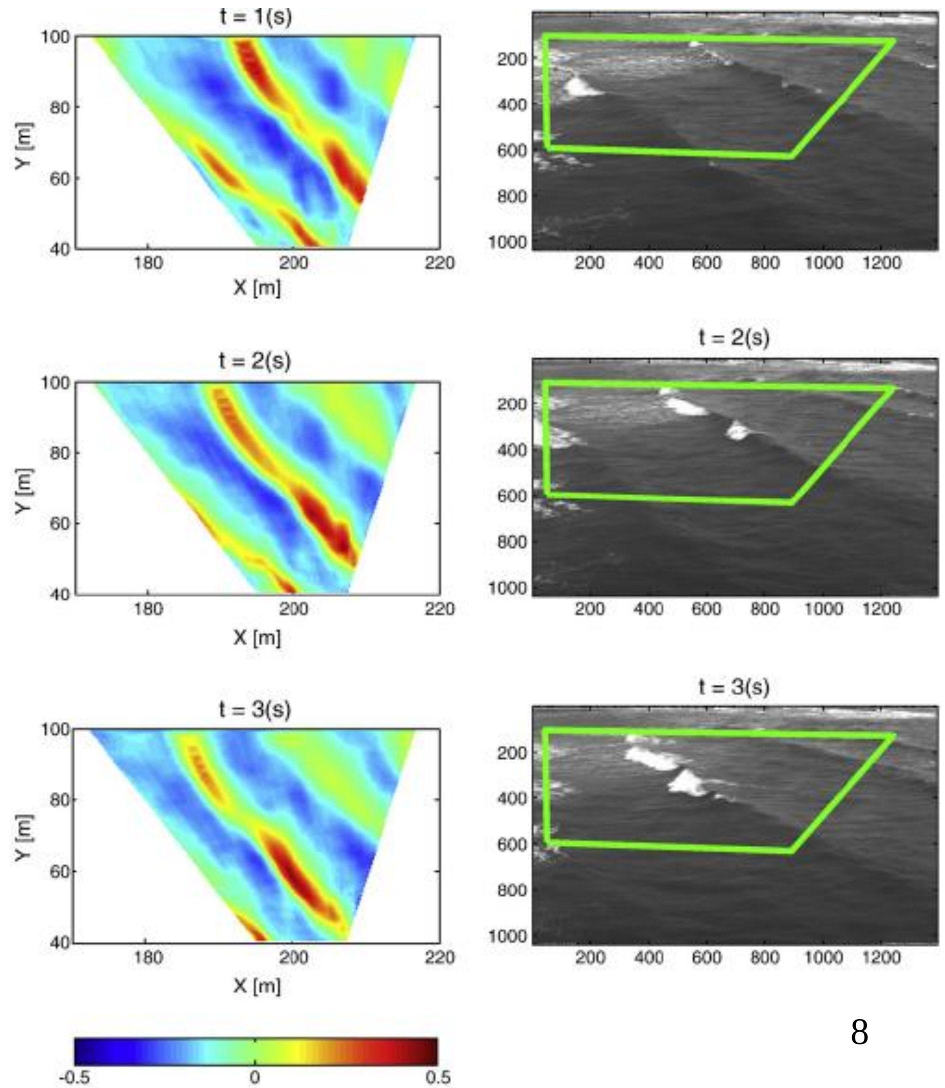


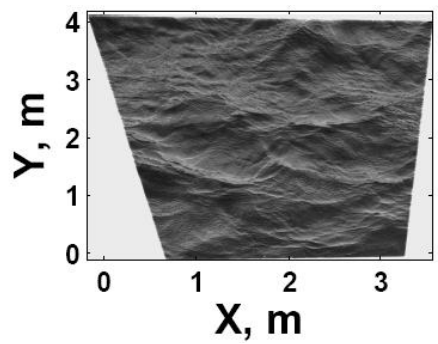
Fig. 13. Perspective view of original camera image mapped onto the three-dimensional water surface elevation.

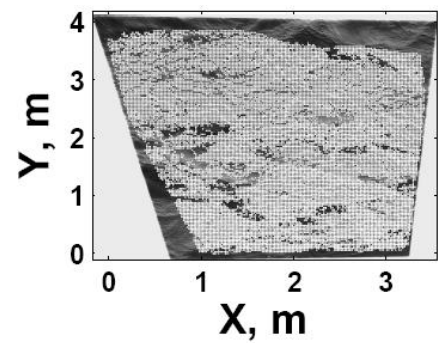


Literature review. Stereo systems

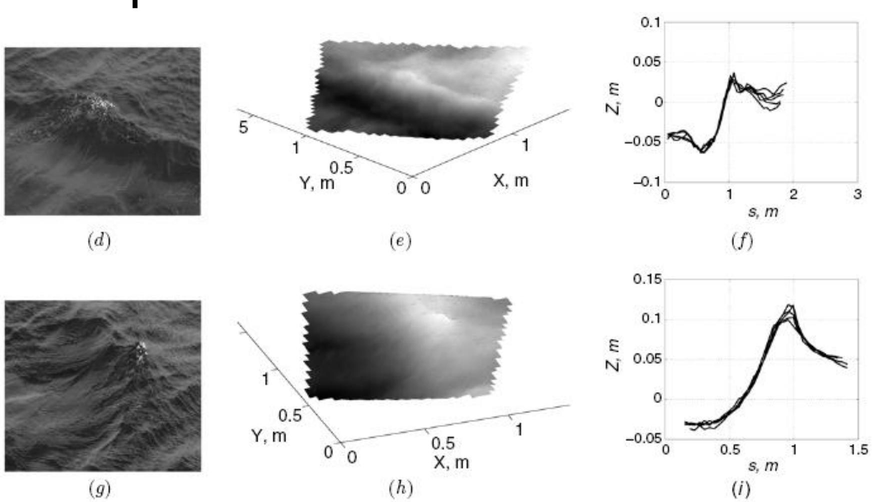
- Extraction of short wind wave spectra from stereo images
  (Kosnic and Dulov, 2011).
- Statistical characterization of short wind waves
  (Mironov, Kosnik, Dulov, Hauser, Guérin, 2012).

Problem: gaps (holes) in reconstructed surface

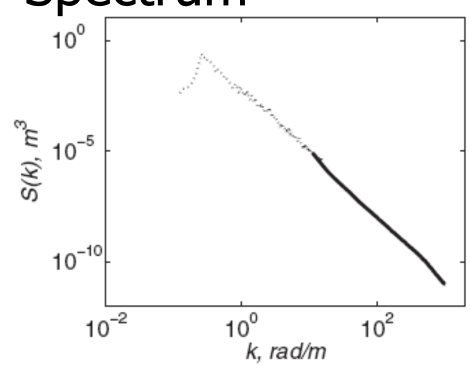




Sample reconstructions:



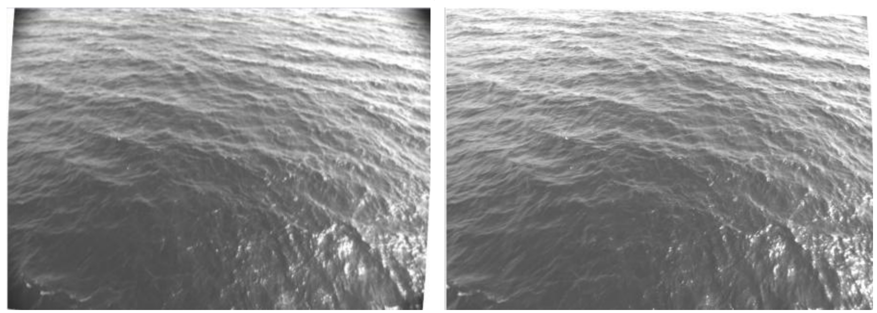
Spectrum



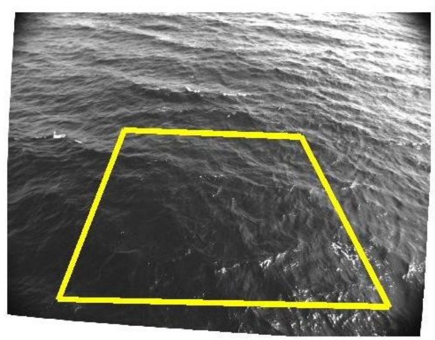
Wave measurement (stereo reconstruction) overview

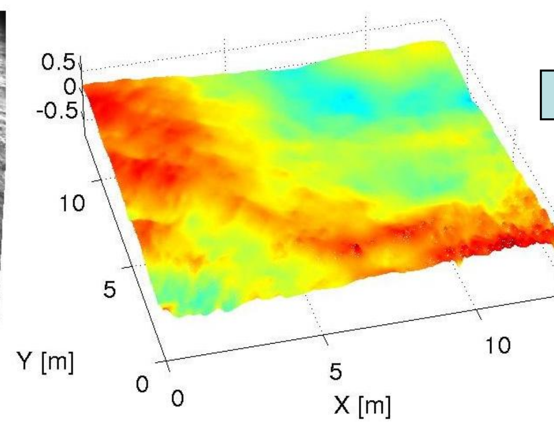
Platform: camera setup.
Acquisition system (storing, synchronization, calibration, etc.)

Acquired images



3D reconstruction of surface shape





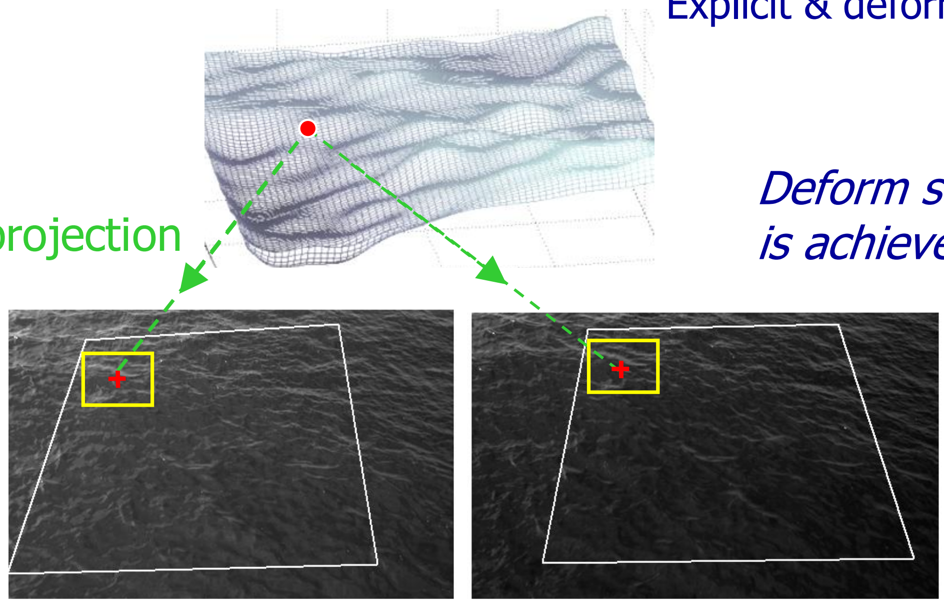
Data analysis (statistics, spectra)

Advantages of variational methods:

- Enforce continuity of the wave surface in space & time: recovered points are not treated independently.
- Improve robustness: less sensitive to matching problems.
- Provide dense surface reconstructions.
- Allow controllability/priors on the unknowns.
- Imply less post-processing than classical methods.

Elevation method (1 snapshot)

Strategy: adjust a 3D model to the 3D world represented
by the data (images) so that an energy functional is minimized.



Elevation method (1 snapshot)

Graph representation: $S(u,v) = \big(u, v, Z(u,v)\big)$

Design a **cost functional** to be minimized:

- Joint estimation of height Z(u,v) or the waves and its radiance f(u,v)

Cost: $E(S,f) = E_{\text{data}}(S,f) + \alpha E_{\text{geom}}(S) + \beta E_{\text{rad}}(f), \qquad \alpha, \beta > 0.$

Data fidelity term: $E_{\text{data}} = \sum_{i=1}^{N_c} E_i$ **where** $E_i = \int_{\Omega_i} \phi_i \, \mathrm{d}\mathbf{x}_i, \quad \phi_i = \frac{1}{2}\big(I_i(\mathbf{x}_i) - f(\mathbf{x}_i)\big)^2.$

Regularizers: penalize the norm of the gradients of the height and the radiance

Cost as a function of height and radiance

$E(Z,f) = \int_U L(Z, Z_u, Z_v, f, f_u, f_v, u, v)\, \mathrm{d}\mathbf{u}.$ ⟹ **Euler-Lagrange equations**

Elevation method (1 snapshot)

Necessary optimality conditions:
System of coupled PDEs in height Z and radiance f of the surface.

$$
\left.\begin{aligned}
g(Z,f) - \alpha \Delta Z &= 0 && \text{in } U,\\
b(Z,f) + \alpha \frac{\partial Z}{\partial \boldsymbol{\nu}} &= 0 && \text{on } \partial U,\\
-\sum_{i=1}^{N_c} (I_i - f)\,\mathrm{J}_i(Z) - \beta \Delta f &= 0 && \text{in } U,\\
\beta \frac{\partial f}{\partial \boldsymbol{\nu}} &= 0 && \text{on } \partial U,
\end{aligned}\right\}
$$

Non-linear term (due to data-fidelity cost):

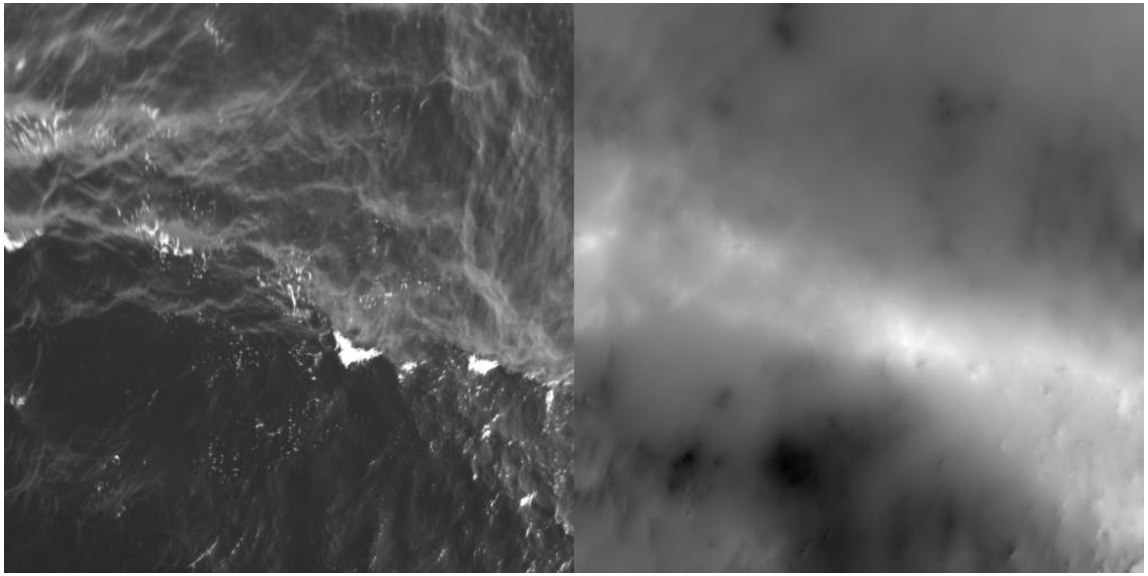
$$
g(Z,f) = \nabla f \cdot \sum_{i=1}^{N_c} |\mathrm{M}^i| \tilde{Z}_i^{-3} (I_i - f)(u - C_i^1, v - C_i^2),
$$

Focal length: $|\mathrm{M}^i|$
Depth of point: $\tilde{Z}_i^{-3}$
Optical ray and Unit Normal: $(u - C_i^1, v - C_i^2)$
Radiance deriv: ∇f
Photometric error: $(I_i - f)$

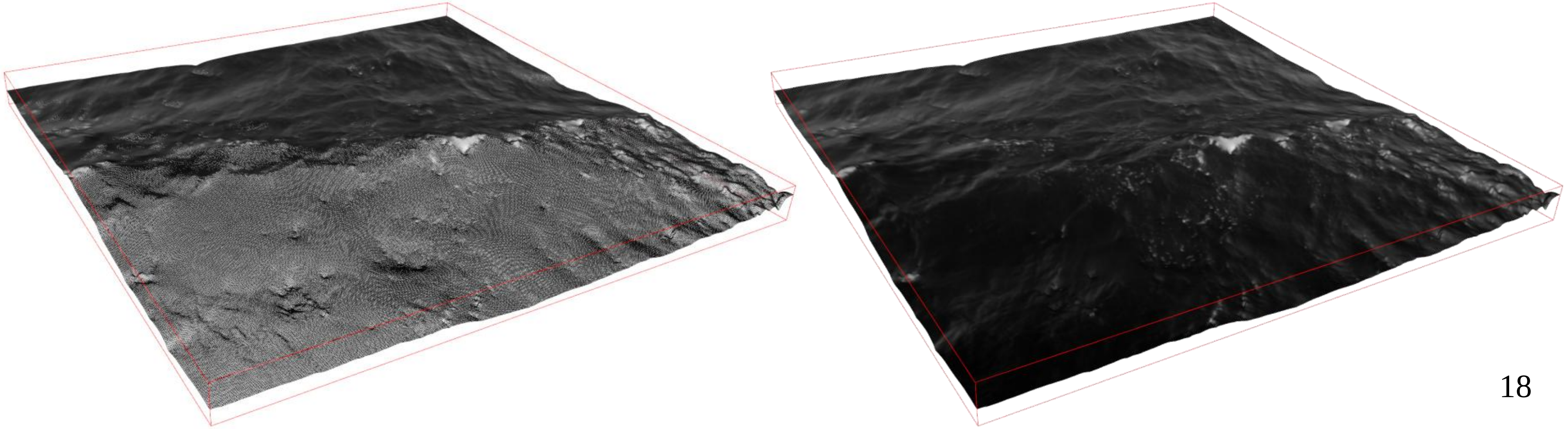
Multigrid solver: standard method for non-linear elliptic boundary value problems like this one.
Steepest descent method for the system of non-linear PDEs.

Elevation method (1 snapshot)

Radiance **f** Height **Z**

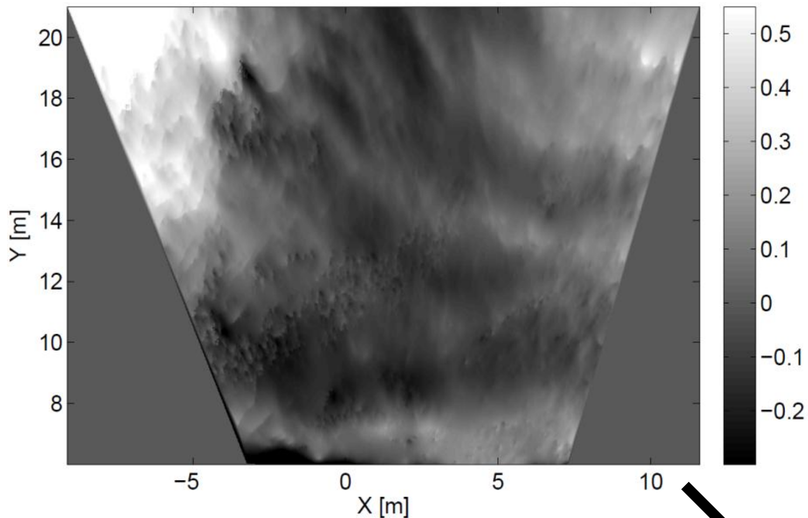


Reconstructed surface & texture (height Z and radiance f)

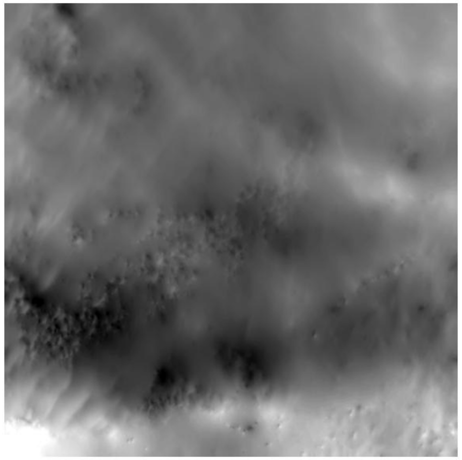


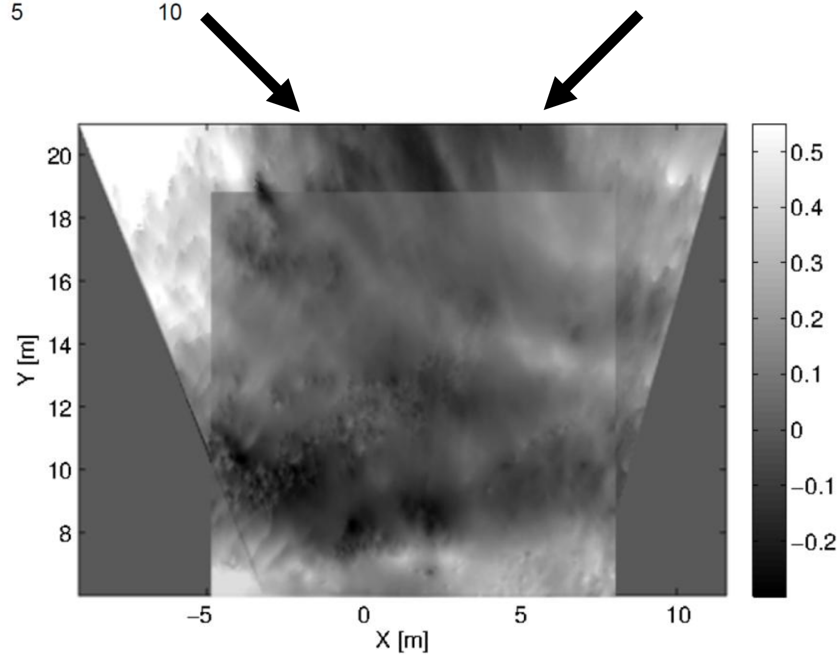
Comparison of estimated wave heights

Disparity method



Elevation method





Things we can do & things we are working on

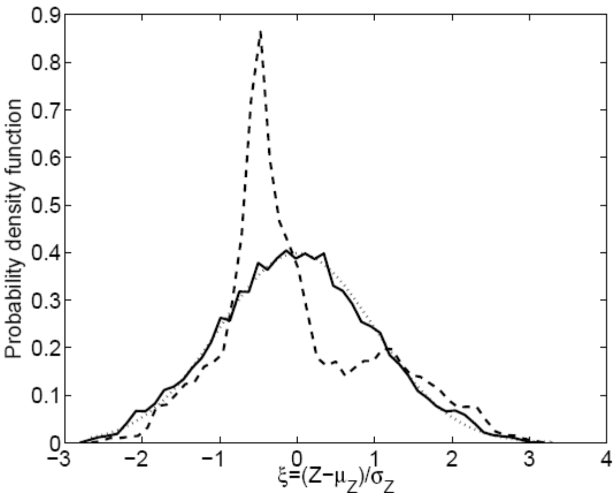
- Enforce wave statistics during estimation.
- Simultaneous snapshot reconstruction.
- Better wave analysis.
- Refinement of (varying) camera parameters.
- Scalable and efficient estimation of wave heights:
  multiresolution + hardware parallelization.

Enforce wave statistics during estimation

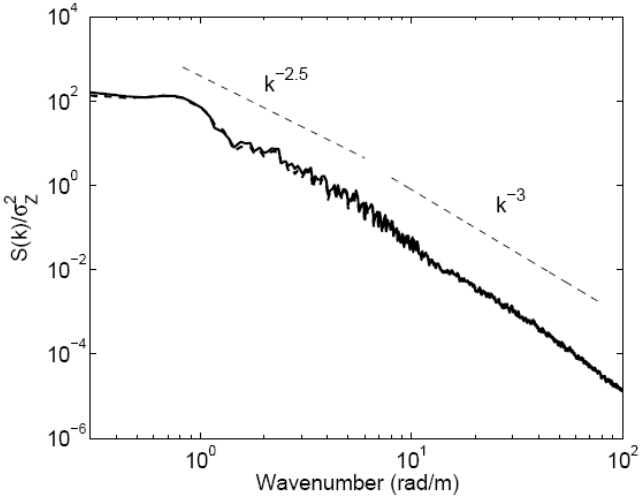
Add a cost penalty to measure statistical wave height distribution error:

$$E_{\text{stat}} := \int_{-\infty}^{\infty} w(z)\tfrac{1}{2}\left(G(z) - \text{cdf}^Z(z)\right)^2 dz$$

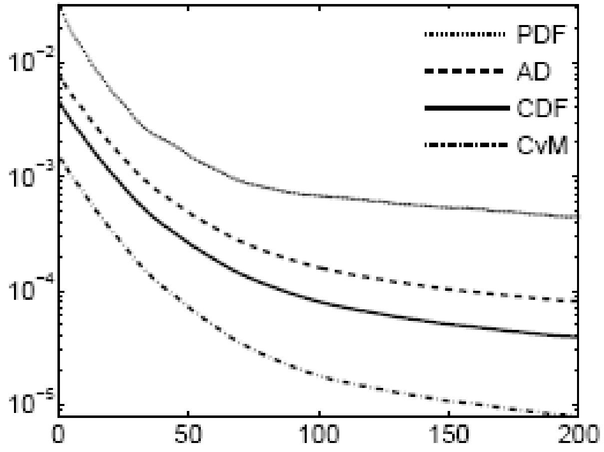
PDFs



Omnidir spectrum



Cost evolution



Simultaneous snapshot reconstr. Time coherence

Data fidelity: measure photo-consistency througout the video for a candidate surface.
Regularizers: enforce spatial and temporal smoothness of the solution (disparity or height & radiance).

$$E_i(Z,f) = \boxed{\int_T} \int_{\Omega_i} \phi_i \, d\mathbf{x}_i \, dt,$$

$$E_{\text{geom}}(Z) = \boxed{\int_T} \int_U \tfrac{1}{2} \|\nabla Z\|^2 \, d\mathbf{u} \, dt,$$

$$E_{\text{rad}}(f) = \boxed{\int_T} \int_U \tfrac{1}{2} \|\nabla f\|^2 \, d\mathbf{u} \, dt,$$

Minimization approach:
- Obtain modified Euler-Lagrange eqs → set gradient descent eqs.
- Discretize and solve using 3-D multigrid methods.

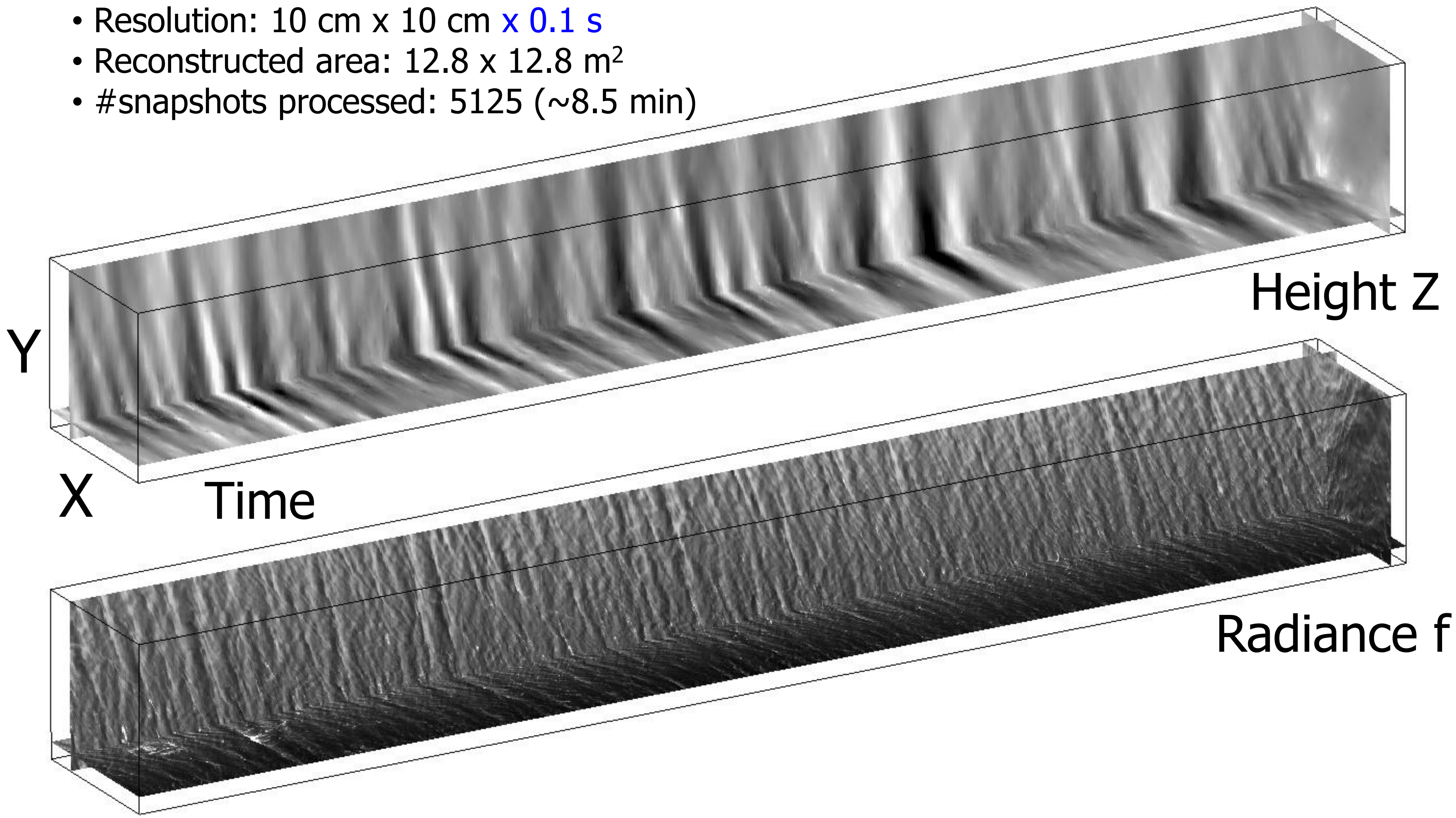
Elevation method. Estimated wave height volume

Input stereo video (2 cameras) at Crimean Platform:

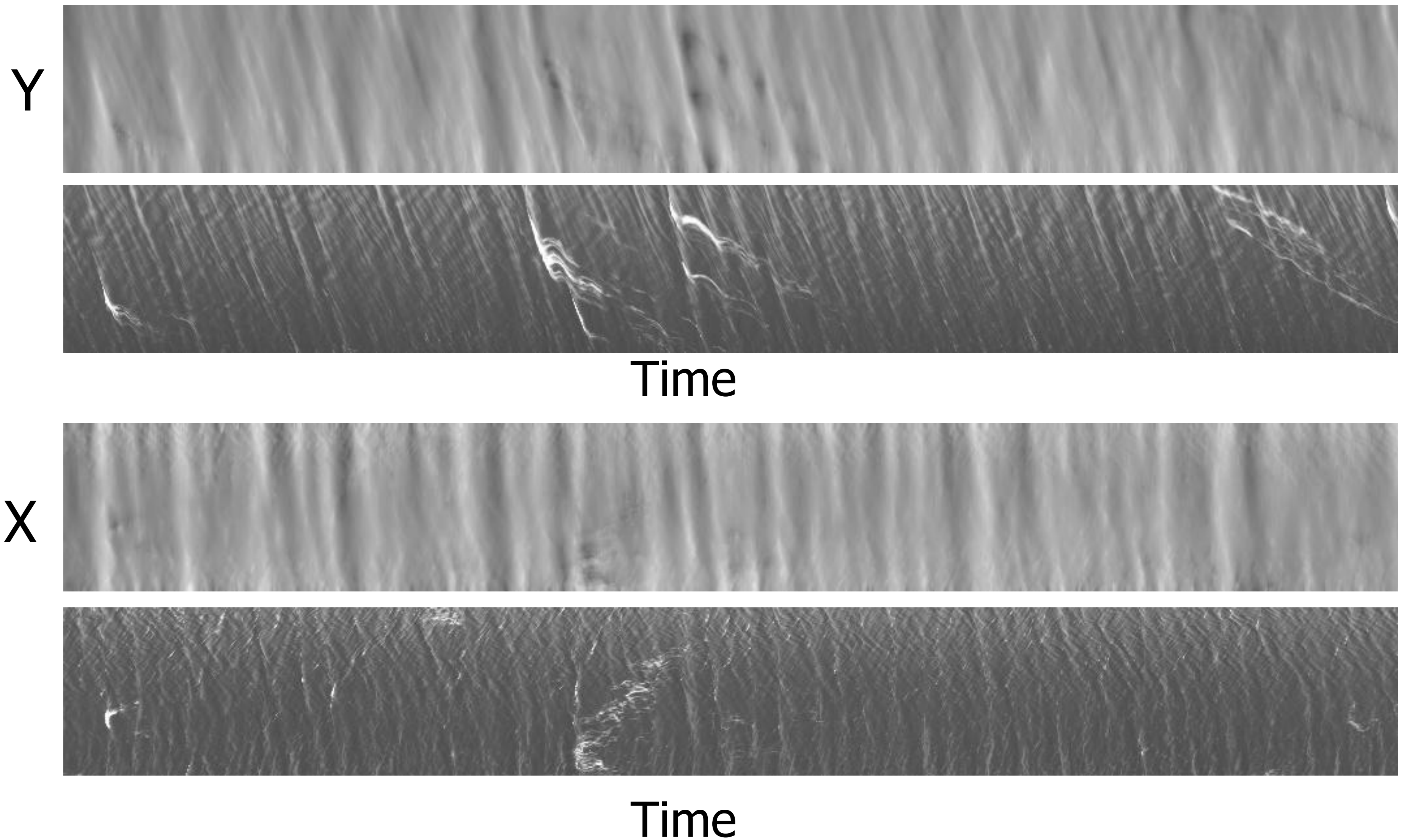
- Input (subsampled) images: 406 x 309 pixels at 10 Hz frame rate.

Reconstruction:

- Computational grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Reconstructed area: 12.8 x 12.8 m^2
- #snapshots processed: 5125 (~8.5 min)

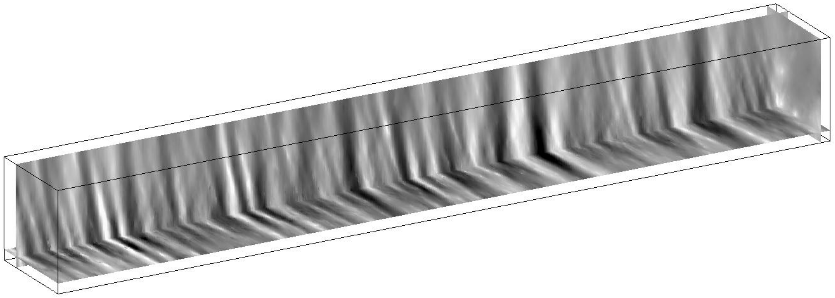


Elevation method. Estimated wave height volume

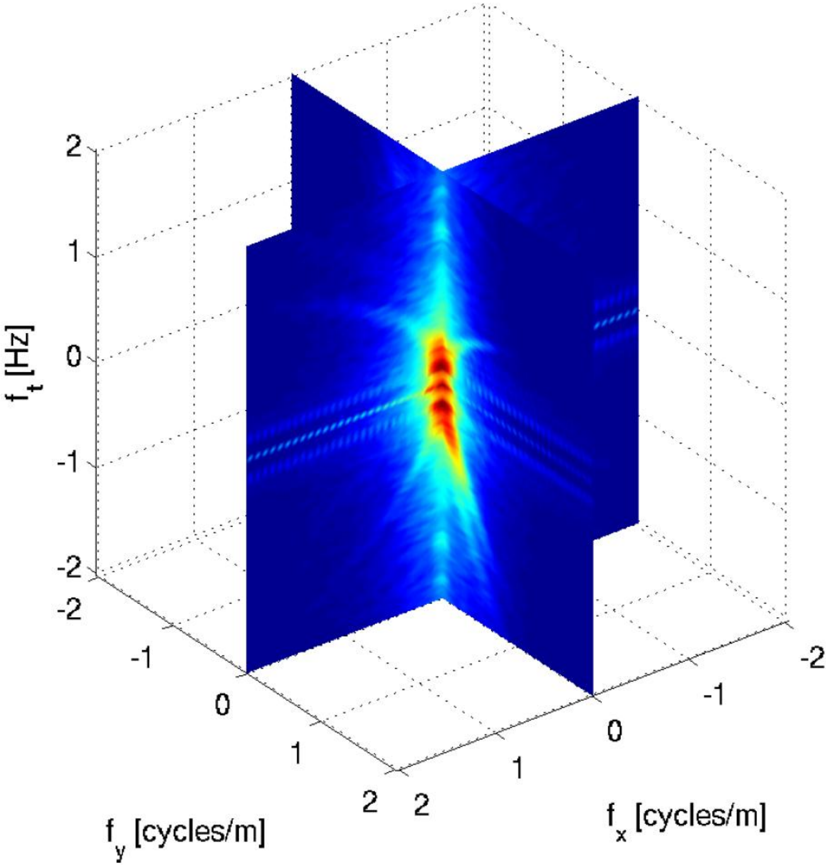


Estimated 3-D (power) spectrum

Wave height volume Z(x,y,t)



Fourier



Crimea sequence. Input: 129x129x4100.

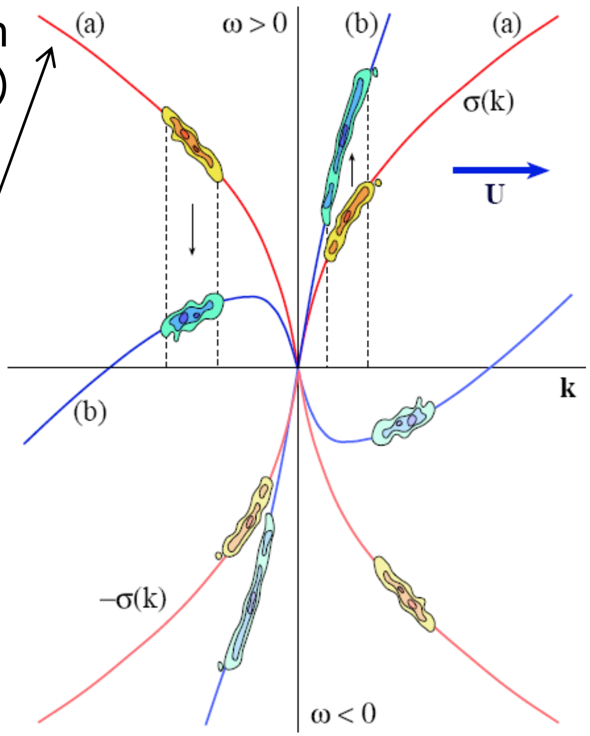
Output: 512x512x512

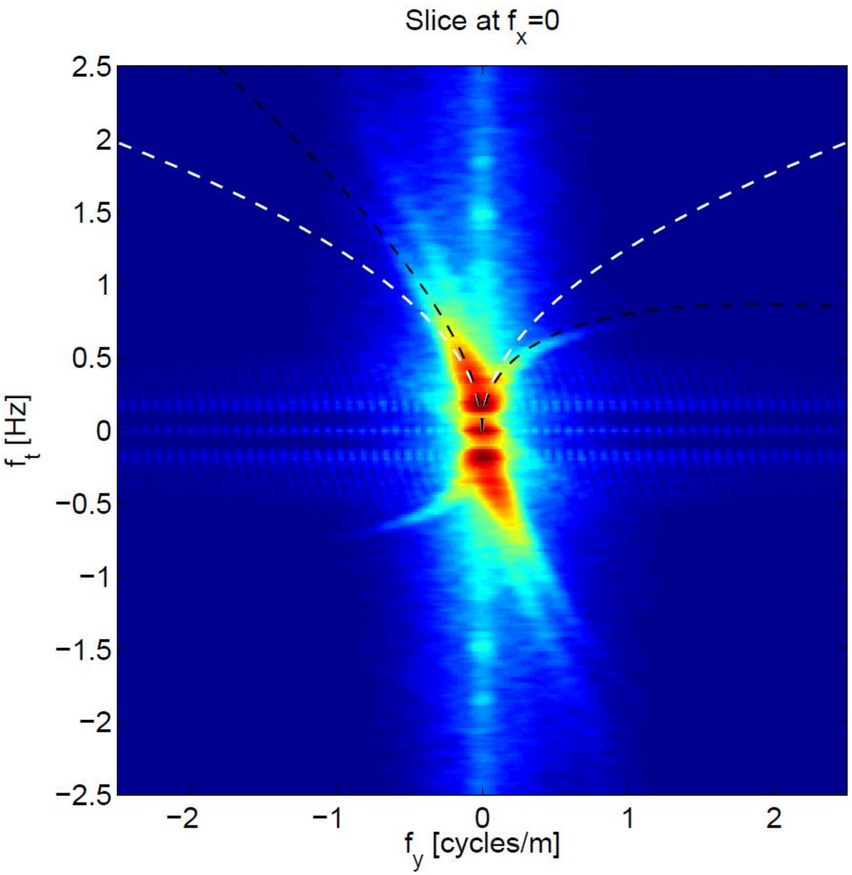
3-D spectrum. Estimation of wave currents

Taking into account the effect of surface currents:

Linear dispersion (in deep water)

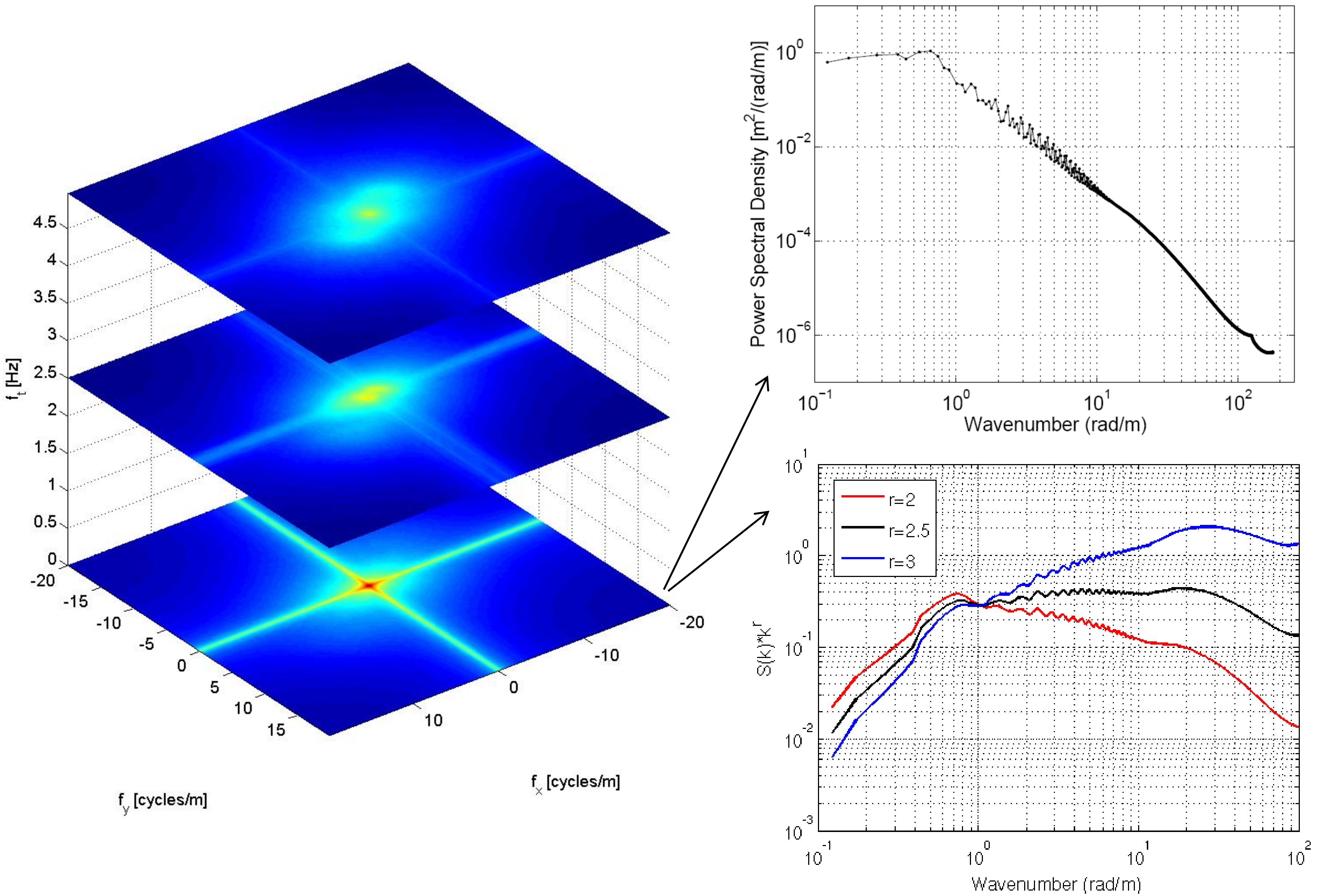
$$k = \frac{\omega^2}{g}$$



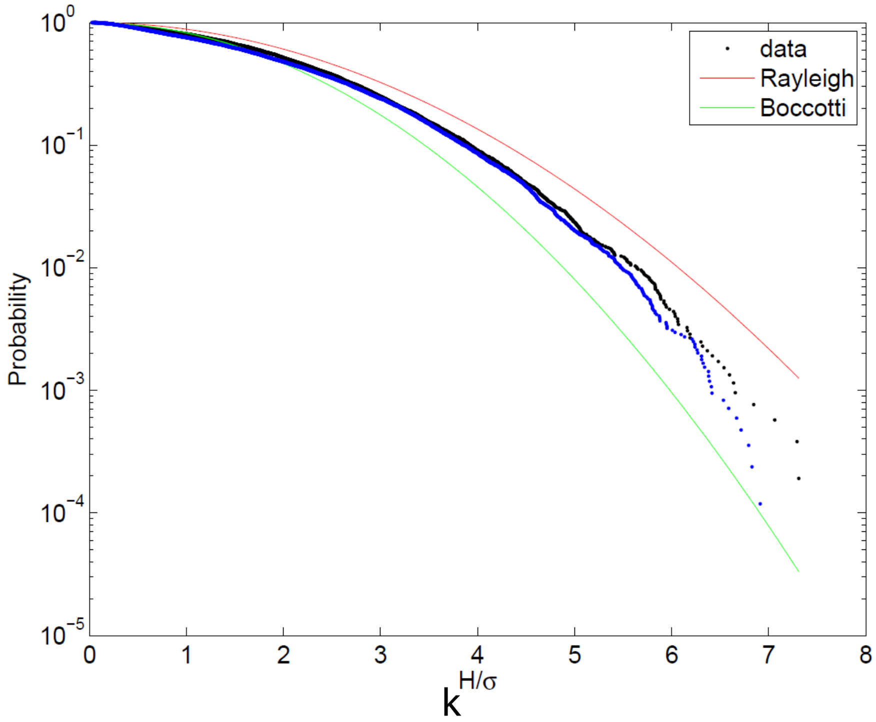


Velocity vector: u = (-0.17,-0.45) m/s

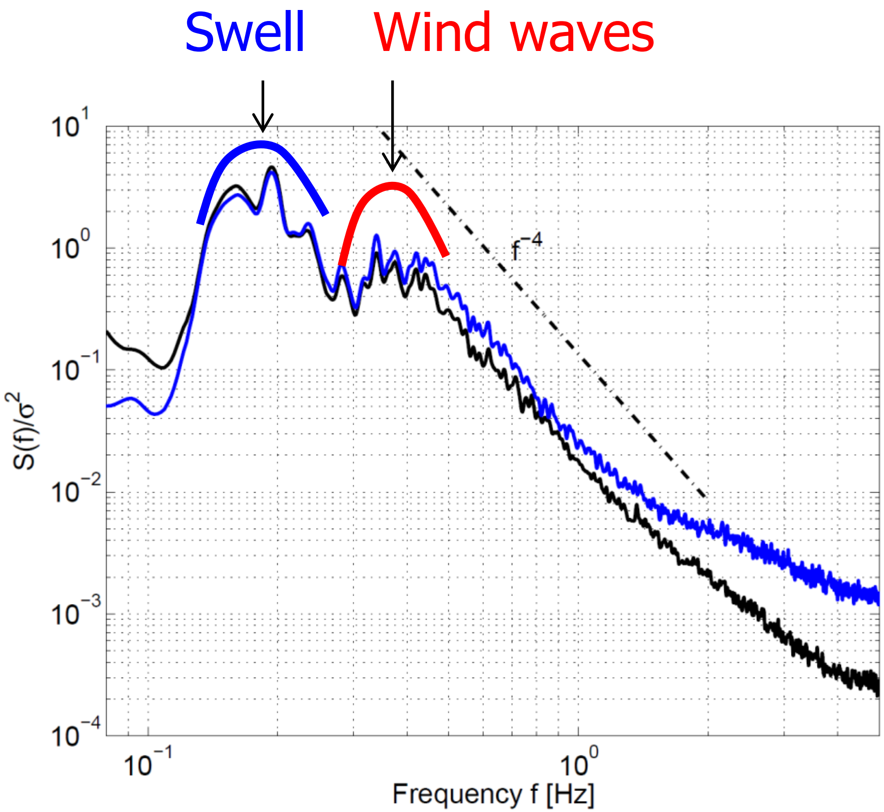
3-D spectrum. Omni-directional spectrum



Analysis of time series at virtual probes.



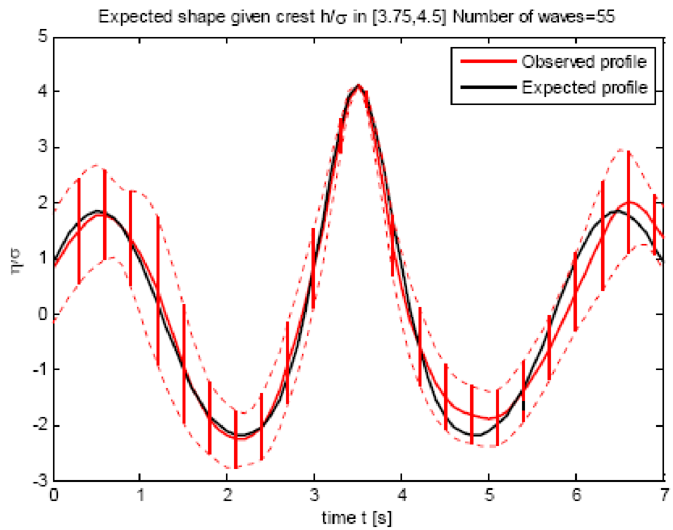
Wave height exceedance probability.
(disparity method)



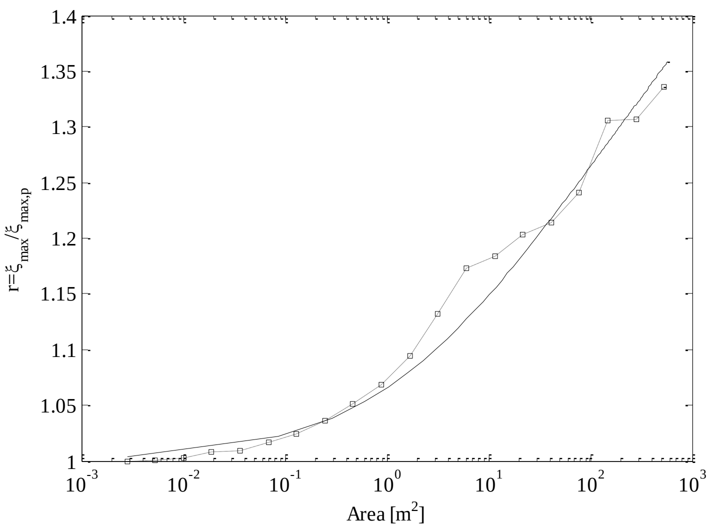
Normalized frequency spectrum.
disparity method & elevation method

More Applications

- Comparison of theoretical models with real data using wave measurements: Hs, Tp, Tm, etc.
- Statistical analysis: space-time extremes of oceanic states (for the design of offshore structures), etc.



Expected shape of largest waves.



Ratio between the expected maximum wave height over an area and that expected at a point.

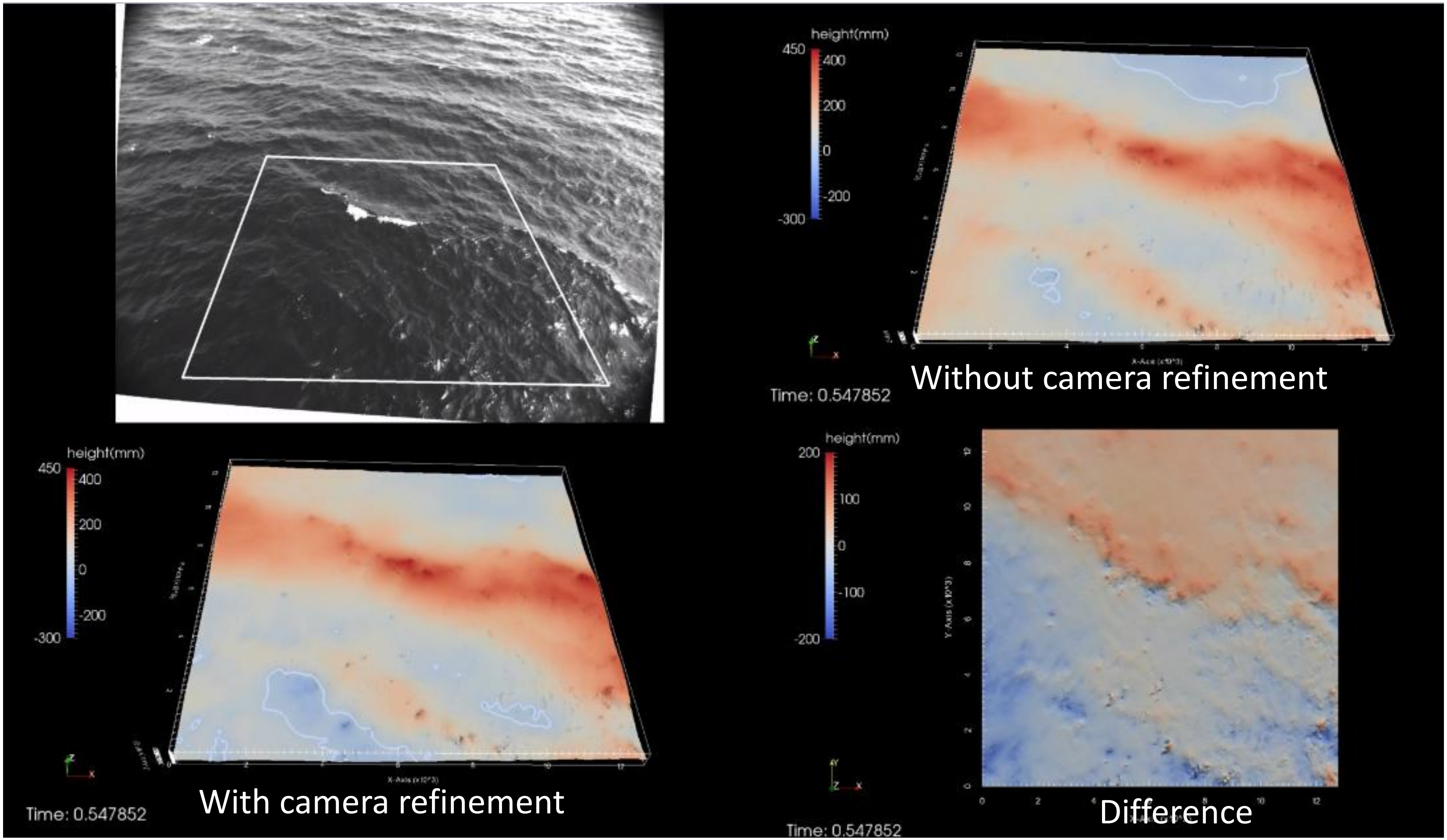
Camera calibration refinement

- Camera parameters:
  - Intrinsic: optical components
  - Extrinsic: relative camera pose

- Sources of noise in camera parameters:
  - Manufacturing deviations
  - Manual operation errors
  - Natural factors such as breeze or vibrations
  - Numerical errors during the camera pre-calibration

- Goal: improve robustness of wave measurements with respect to camera perturbations.

Camera calibration refinement



Conclusions

- Stereo reconstruction methods…
  - have more advantages than classical wave measurements (area vs. point measurements).
  - provide reliable statistics and accurate predictions of ocean waves due to the rich information content of video data.

- Advantages of variational methods for wave measurements:
  - Provide dense wave height field estimations.
  - Allow the enforcement of continuity in space & time.
  - Require less post-processing (few assumptions on data).
  - Allow the incorporation of physics of waves.
  - Allow refinement of camera parameters.

- Disadvantages: computational cost (but feasible).
- Current research: cluster processing – scalability and efficiency.

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THANK YOU FOR YOUR ATTENTION.

ANY QUESTIONS ?

More information:

http://www.gti.ssr.upm.es/~ggb/

http://savannah.gatech.edu/people/ffedele/Research/