Offshore remote sensing of the ocean by stereo vision systems

Guillermo Gallego[1], Ping-Chang Shih[2], Alvise Benetazzo[3], Anthony Yezzi[2], Francesco Fedele[2]

(1) Univ. Politécnica de Madrid (Spain), (2) Georgia Institute of Technology (USA), (3) CNR – ISMAR Venice (Italy)

Summary. We develop a remote sensing imaging system for the stereoscopic measurement of ocean waves via variational methods. This technique is non-invasive and enables a better understanding of the space-time dynamics of ocean waves over an area rather than at selected point locations of traditional monitoring methods (buoys, etc.).
The wave surface is obtained as the minimizer of an energy functional that combines image observations and space-time smoothness priors. Two energy functionals are considered ("elevation" and "disparity"), yielding similar results. Multigrid methods are used to numerically solve the partial differential equations (PDEs) derived from the optimality conditions of the functional. Experiments were carried out to measure and analyze ocean waves from real data collected at two offshore platforms in the Black Sea (Crimean Peninsula) and the Northern Adriatic Sea (Venice coast, Italy).

1. Variational Stereo Methods

1.1 Ocean surface represented as an **elevation map** $S(u,v) = (u, v, Z(u,v))$
Energy functional to be minimized:

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

- **Data fidelity**: measure photo-consistency of the video for a candidate surface.

$$E_{\text{data}} = \sum_{i=1}^{N_c} E_i \qquad \text{with} \qquad E_i(Z,f) = \int_T \int_{\Omega_i} \tfrac{1}{2}\big(I_i(\mathbf{x}_i) - f(\mathbf{x}_i)\big)^2 d\mathbf{x}_i\, dt,$$

- **Regularizers**: enforce spatial and temporal smoothness of the solution.

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

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

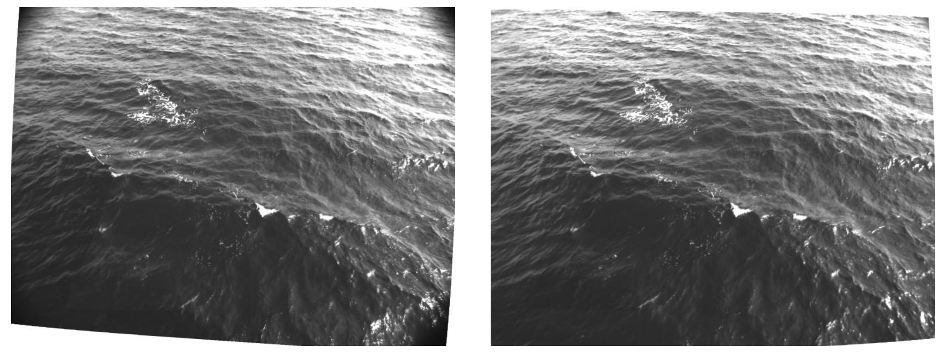
Minimization approach:
- Obtain Euler-Lagrange eqs (Necessary optimality) → set gradient descent PDEs
- Discretize and solve PDEs using 3-D multigrid methods.

Non-linear term (data-fidelity) :

$$g(Z,f) = \underbrace{\nabla f}_{\text{Radiance derivative}} \cdot \sum_{i=1}^{N_c} \underbrace{|\mathtt{M}^i|}_{\text{Focal length}} \underbrace{\tilde{Z}_i^{-3}}_{\text{Distance to surface}} \underbrace{(I_i - f)}_{\text{Photometric error}} \underbrace{(u - C_i^1, v - C_i^2)}_{\text{Optical ray and surface normal}},$$

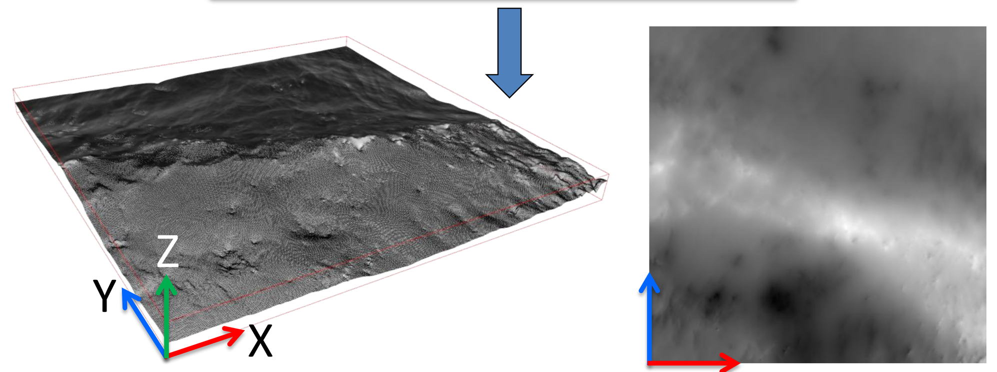
Advantages of variational methods:
- ✓ Enforce continuity of the wave surface in space and time (no holes).
- ✓ Improve robustness: less sensitive to image matching problems.
- ✓ Provide dense surface reconstructions.
- ✓ Allow controllability/priors on the unknowns.
- ✓ Can incorporate global properties of wave heights (statistics, etc.).
- ✓ Imply less post-processing than traditional methods.

Vision acquisition system at offshore platforms: Adriatic and Black Seas



Multi-view videos

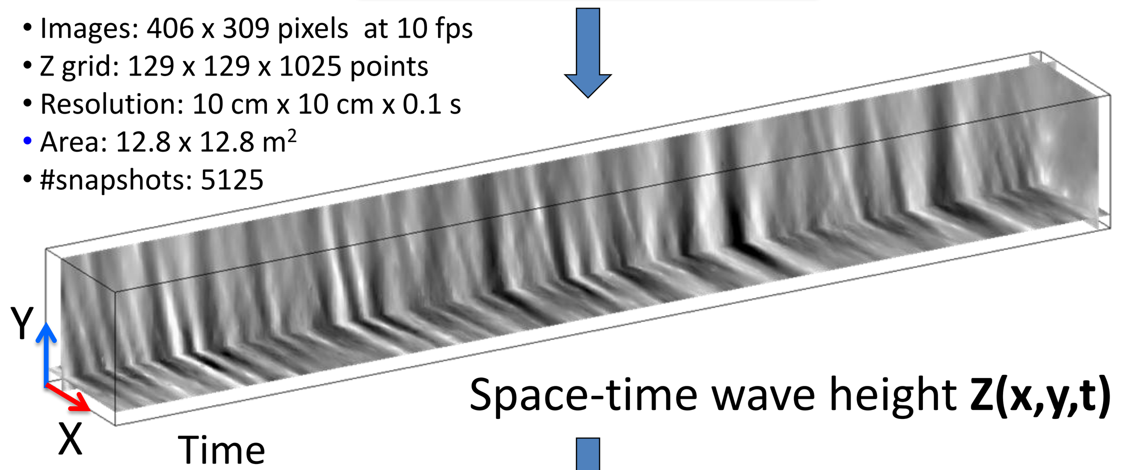
Variational stereo, Multigrid methods



Estimated wave height (**Z**), surface model

Temporal processing

- Images: 406 x 309 pixels at 10 fps
- Z grid: 129 x 129 x 1025 points
- Resolution: 10 cm x 10 cm x 0.1 s
- Area: 12.8 x 12.8 m^2
- #snapshots: 5125



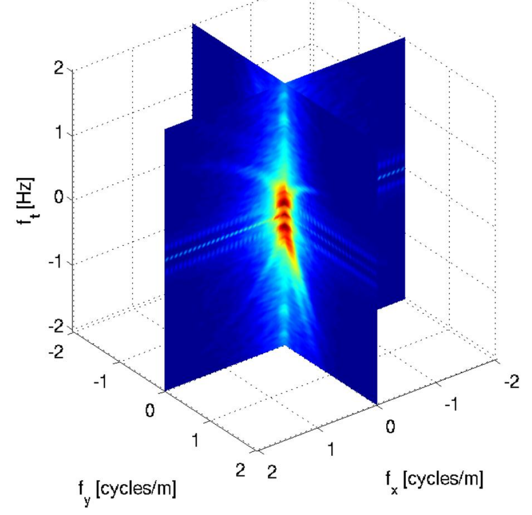
Space-time wave height **Z(x,y,t)**

Data Analysis

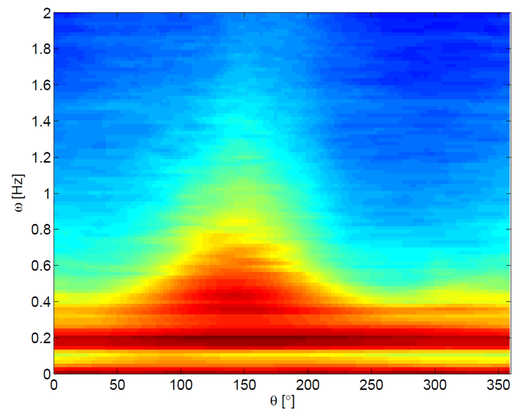
2. Data Analysis

Spectra

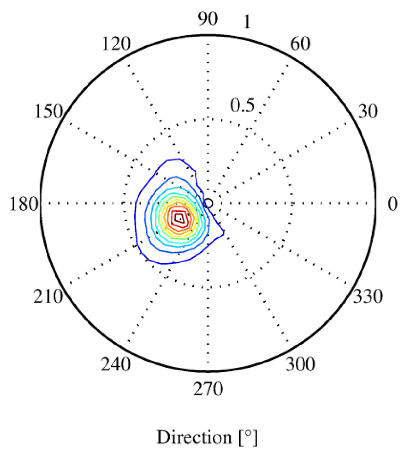
Distribution of energy in frequency domain.



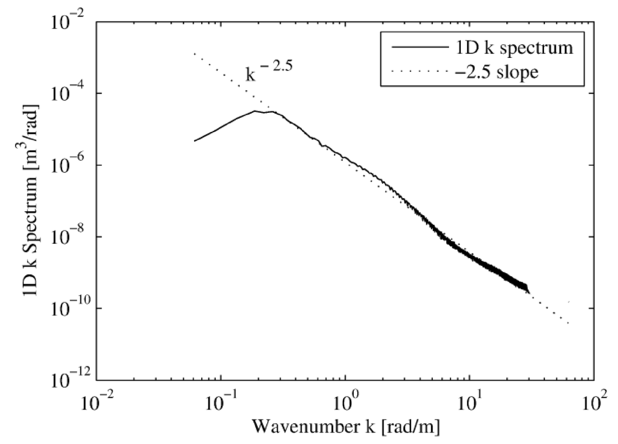
Estimated 3D power spectrum.



Directional spectrum F(ω, θ)



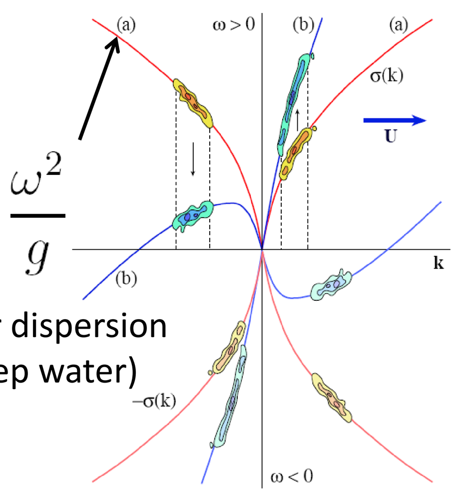
Directional spectrum.

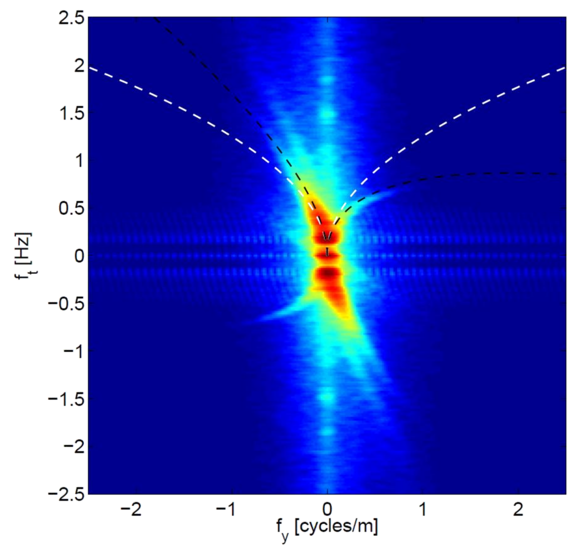


Omni-directional spectrum.
in wavenumber k (rad/m)

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

Linear dispersion (in deep water)





Estimate surface currents causing Doppler shift of dispersion.

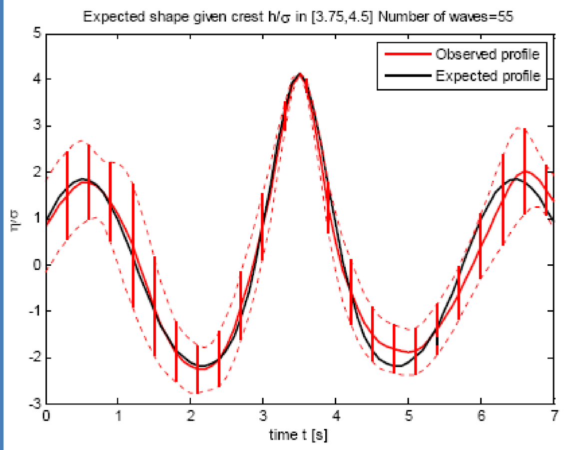
Statistics

Analysis of time series at virtual probes.

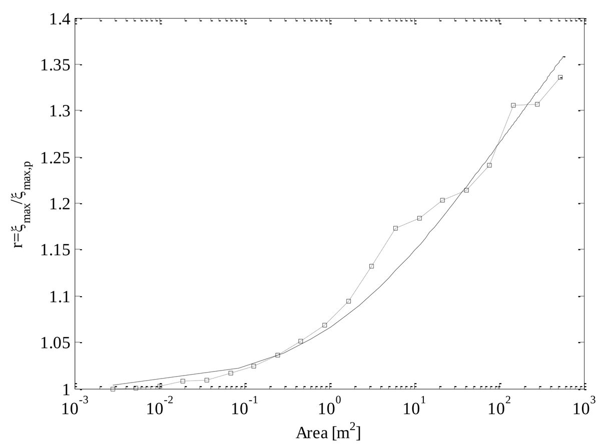
		H_{m0} [m]	$H_{1/3}$ [m]	H_{max} [m]	T_p [s]	T_z [s]	Dir [° N]
Exp 1	CNR	–	0.47	0.68	–	2.91	–
	WASS	0.45	0.41	0.83	4.34	3.09	148.5 ± 3
Exp 2	CNR	1.13	1.09	2.03	4.59	3.51	65.0 ± 3
	WASS	1.15	1.10	2.18	4.83	3.62	59.5 ± 3
Exp 3	CNR	2.23	2.16	3.80	6.37	4.62	69.7 ± 3
	WASS	2.17	2.16	3.95	6.36	4.85	70.1 ± 3

Wave parameters estimated from both *WASS* instruments operational at *Acqua Alta*. *Dir* is the mean wave direction of propagation, measured clockwise from geographic North (wave directions depend upon the platform orientation that is known with an error ~3°). During Experiment 1, H_{mo}, $H_{1/3}$, and *Dir* were not available at *Acqua Alta*.

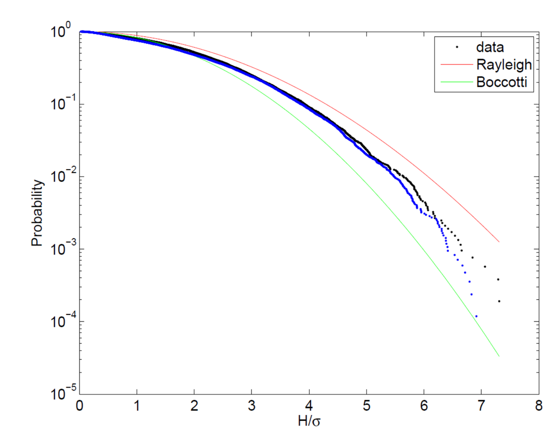
Space-Time Extremes of Oceanic Seas.



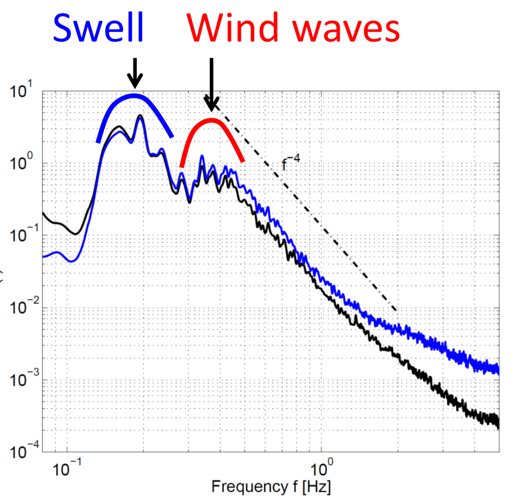
Expected shape of largest waves.



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



Wave height exceedance prob.



Normalized freq. Spectrum
(disparity, elevation methods)

3. Conclusion and future work

Stereo wave measurement methods:
- have more advantages than classical wave measurements (area vs. point measurements).
- provide dense wave height field estimations and allow to enforce continuity in space & time.
- provide reliable statistics and predictions of ocean waves due to the rich information content of video data.

Current and future research: improve processing power, scalability and computational efficiency.
Improve robustness (camera calibration refinement).

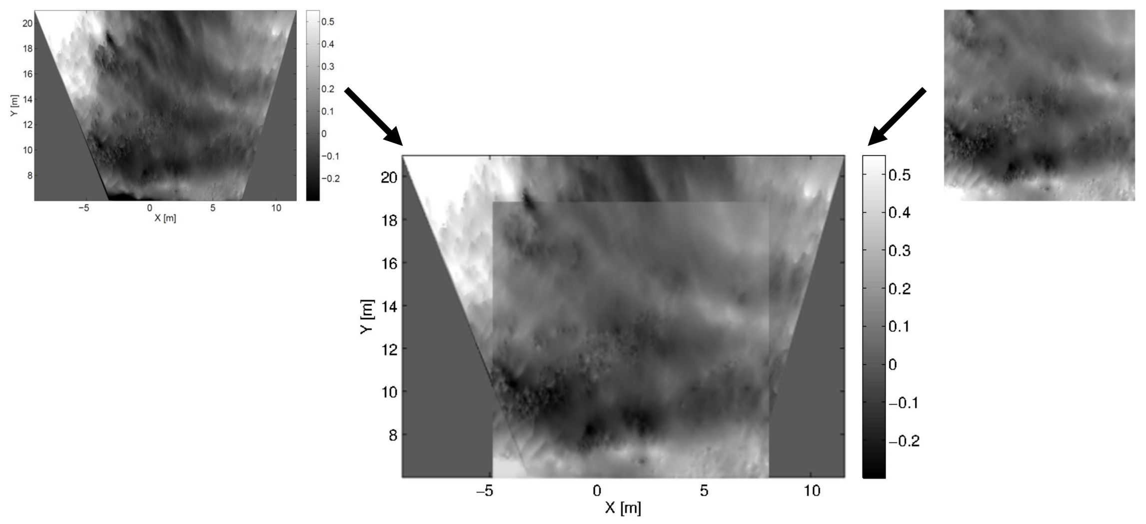
1.2 Another variational stereo method:
- Ocean surface is represented as a **disparity map** λ (depth from the cameras).
- Energy functional with data fidelity and smoothness terms:

$$E'_{\text{data}}(\lambda) = \int_T \int_\Omega \tfrac{1}{2}\big(I_1(\mathbf{x}_1) - I_2(\mathbf{x}_2)\big)^2 d\mathbf{x}_1\, dt,$$

$$E_{\text{smooth}}(\lambda) = \int_T \int_\Omega \tfrac{1}{2}\|\nabla\lambda\|^2 d\mathbf{x}_1\, dt,$$

- Same optimization approach: gradient descent PDE → multigrid methods.
- Then, back-project matched image points and fit a surface through 3D points.

Disparity method vs. Elevation method



References

1) G. Gallego, A. Yezzi, F. Fedele, A. Benetazzo. Two variational stereo methods for space-time measurements of ocean waves. **OMAE** 2013.
2) G. Gallego et. al., Variational stereo imaging of oceanic waves with statistical constraints. **IEEE Trans. Image Processing**, 22(11):4211-4223, 2013.
3) F. Fedele et al., Space-time Measurements of Oceanic Sea States. **Ocean Modelling**, 70:103-115, 2013.
4) A. Benetazzo, F. Fedele, G. Gallego, P.-C. Shih, A. Yezzi, Offshore stereo measurements of gravity waves, **Coastal Engineering**, 64:127-138, 2012.
5) F. Fedele et al., Euler characteristics of oceanic sea states. **Math. & Computers in Simulation** 82(6), 1102–1111, 2012.
6) G. Gallego et al., A variational stereo method for the 3-D reconstruction of ocean waves. **IEEE Trans. Geosci. Remote Sens.** 49(11):4445-57 2011.
7) F. Fedele, A. Benetazzo, G.Z. Forristall. Space-time waves and spectra in the Northern Adriatic Sea via a Wave Acquisition System. **OMAE** 2011.
8) A. Benetazzo. Measurements of short water waves using stereo matched image sequences. **Coastal Engineering** 53, 1013–1032, 2006.
9) http://www.gti.ssr.upm.es/~ggb/