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MEASUREMENT OF DIRECTIONAL WAVE SPECTRA USING A WAVE ACQUISITION STEREO SYSTEM: A PILOT EXPERIMENT

The capabilities of a Wave Acquisition Stereo System (WASS) are tested for the measurement of wave spectra. A first experiment with relatively low resolution cameras (2 megapixels) at 12 m height above the sea was conducted on the Marine Hydrophysical Institute platform in the Black Sea in October 2010. The acquisition of a few hours of data allowed testing the performance of the system in moderate wave conditions. The stereo video data is processed using an epipolar method into maps of the sea surface elevation every 0.1s. The retrieved sea surface appears consistent for scales larger than 1 m, and suffers from various processing and discretization errors for the shorter scales. Although the field of view is only about 40 by 40 meters, the analysis of the direction of longer waves can be performed thanks to the linearity of these waves using classical array analysis techniques.

KEYWORDS: *wind waves, stereo-video processing, wind wave spectra.*

The detailed estimation of the wave spectrum is still a subject of debates and technological developments, especially for waves with periods shorter than 2.5 s. Indeed, routine wave measurements today only provide very limited information on the directional distribution of wave energy (e.g. [1]) and do not cover short waves. These details are important for many applications, from the analysis of remote sensing data to the understanding of both underwater and seismic noises (e.g. [2]). Up to date, typical systems for directional wave measurements are arrays of pressure or capacitance wave gauges that can provide a useful metrological verification of other systems (e.g. [3]).

Recently, the French and Chinese space agency have joined forces to launch the China-France Ocean Satellite (CFOSAT) that will carry the first real aperture wave radar into orbit, allowing the mapping of directional spectra down to wavelengths of 80m. Thus, it is very important to be able to validate the directional properties of CFOSAT wave measurements. However, to date there are very few measuring systems capable of providing accurate estimate of directional spectra, in particular the dependency on the wave frequency of both the mean direction and spectral spread. To our knowledge only the 4-laser array on Ekofisk platform in the North Sea has the capability of providing directional spectra at a resolution better than that from buoy measurements.

We have thus decided to test the accuracy of a Wave Acquisition Stereo System (WASS) [4 – 6] in estimating directional spectra, in order to assess if such system can be exploited for both the calibration and validation phase of CFOSAT. WASS is also uniquely suited to investigate the geometry of the sea surface at multiple scales for a better understanding of CFOSAT measurements. This first trial at sea is not quite set up in the configuration that would be used for CFOSAT. However, it already provides an initial assessment of the quality of stereo recostructed measurements.

Equipment and data processing. e used relatively low resolution cameras (2 megapixels) mounted 12 meters above the mean sea level on the research platform of the Marine Hydrophysical Institute, located in Katsiveli, at the southern tip of the Crimean peninsula, between Sevastopol and Yalta, as shown in fig.1, *a*. Geometry of view with the two cameras, separated by 2 meters, is shown in fig.1, *b*. The system was oriented to the east-south-east, with moderate sun reflections in the morning, and was operated at an acquisition frequency of 10 Hz producing pairs of images, as shown in fig.1, *c – d*. The internal and external camera parameters and geometry of the stereo pair were calibrated using standard procedures [4]. String resistant wave gauge recordings were running simultaneously providing information about the gravity wave spectrum.

The images were then processed using several variations of the epipolar method in order to map the real world coordinates *X*, *Y* and *Z* from the two pairs of pixel positions (i_1, j_1) and (i_2, j_2) of matched points. En example of extracted sea surface is presented in fig. 1*e*. As a result, time series $z(t)$ was obtained for any point (x, y) in the pentagonal field of view depicted in fig.1, *b*. Frequency spectra for sea surface elevations were then estimated by processing $z(t)$ and averaging over field of view. In the area of spectral peak, these spectra corresponded to the spectra estimated using wave staff (see fig.1, *f*).

Preliminary results. *Problems in estimating high frequency spectra.* We did not smooth the resolved $Z(X,Y)$ mapping (also called the 'disparity map') because we wanted to test the ability of the WASS system to resolve the smallest possible scales of the sea surface. Clearly the 3D reconstruction without smoothing produces artificial short-scale roughness as shown in fig.2, *a*; this is likely related to pixel discretization (see for details e.g. [7]). Observe that smoothing the disparity map filters out physical short scales as shown in fig.2, *b – c*.

Yet, even with this smoothing, some local jumps can be found. These are related to the fact that the epipolar lines, which are used for the search of corresponding points in the image pair, are not exactly horizontal. When the epipolar lines are discretized on the image pixel, they have a few sudden jumps that result in sharp discontinuities of the sea surface elevation. These jumps are always exactly in the same place in the image pixel-coordinate system, but their positions slightly differ in the *XYZ* world system because of the vertical Z coordinate component. As a result the map of the surface mean square slope (fig.3, *a*) exhibits some artificial blurred bands of high values that correspond to quantization effects due to non-horizontal epipolar lines. To overcome this effect, epipolar lines can be forced to be horizontal (i.e. to lie on a single image line) performing auto-calibration procedures on (partially noisy) cameras calibration parameters.

Also in the region nearby (X = 4 m, Y = 18 m), wave slopes are unusually large since we expect the mean square surface slope to be roughly uniform in the field of view. These large slopes may be due to sun glitter effects. To explain this,

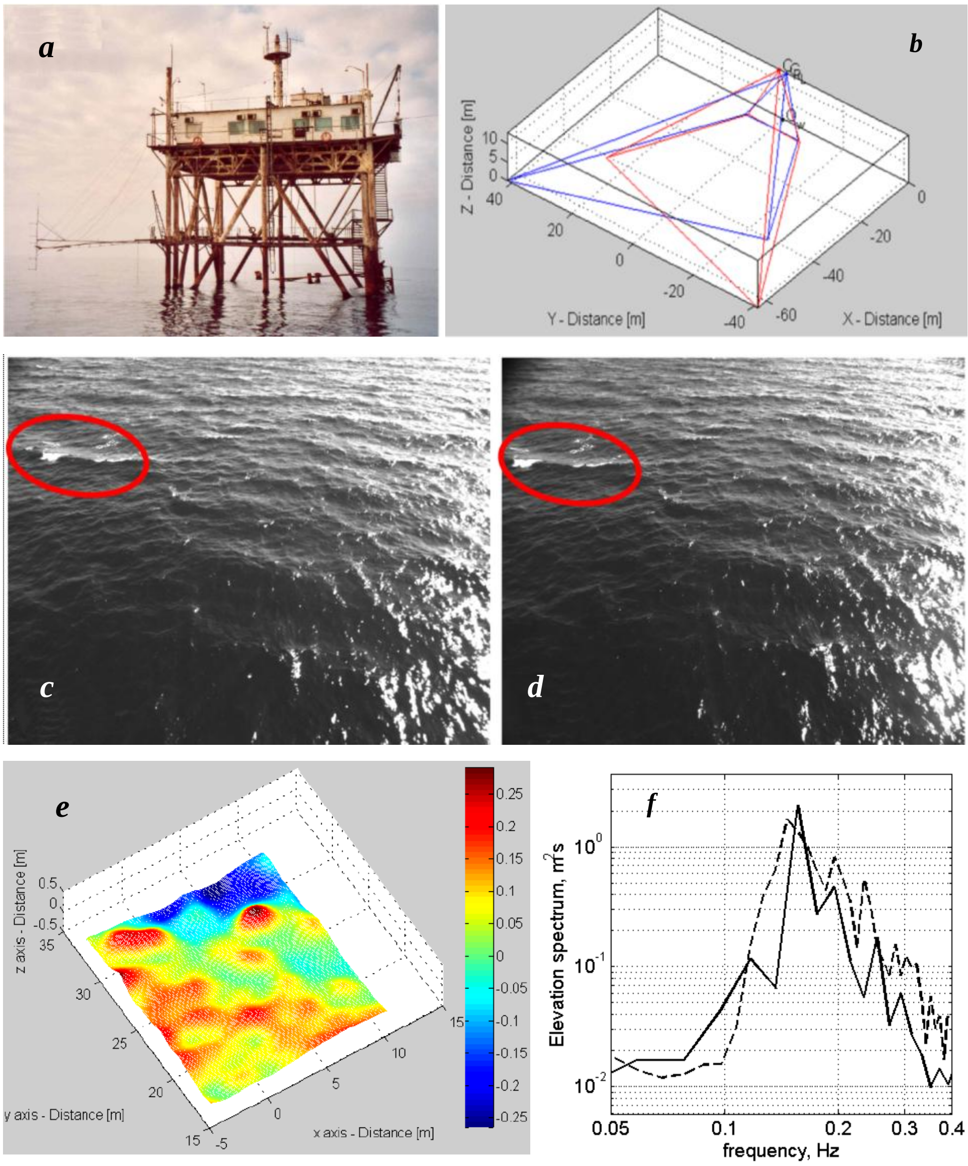
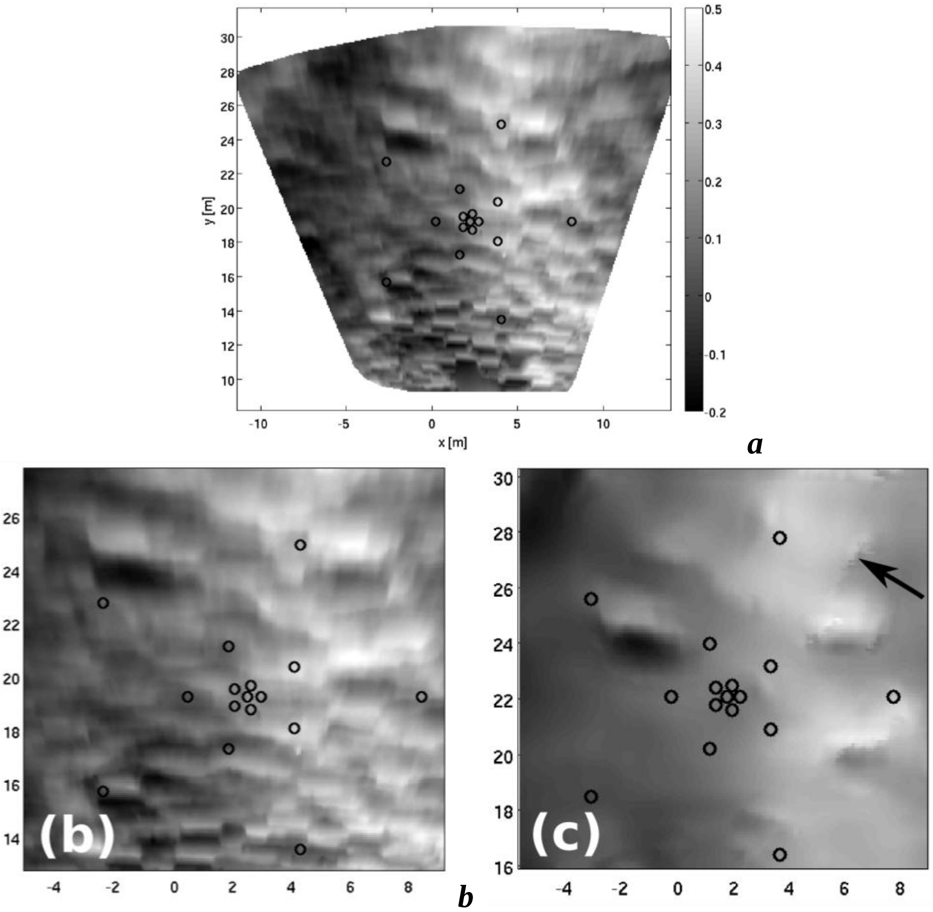


Fig. 1. Experimental set-up and data overview: research platform off Katsiveli, in the Black Sea (*a*); geometry of view with the two cameras, indicated by C_R and C_L (*b*); example of stereo pairs which shows, besides some sun reflection on the right, the foam associated to a whitecap (*c*) and (*d*); fragment of extracted elevation field (*e*); frequency spectra from WASS (solid line) and wave staff (dashed line) (*f*).

note that specular points on the surface will give high correlations of the image pair but in reality the matching points in the two images may likely correspond to different specular points seen by the two cameras, hence producing an error in the 3D reconstruction. This suggests that glitter points should be avoided in the stereo reconstruction, or treated specifically.

Spectral analysis in three dimensions. The stereo-reconstructed three-dimensional wave surface is defined over a trapezoidal-shaped area due to the overlapping fields of view of the two cameras (fig.2, *a*). A square sub-region is considered to apply the FFT algorithm simultaneously in time and space (fig. 2*b*). The Welsh (1969) method [8] with no zero padding is applied to estimate the volumetric wave spectrum $F(f, k_x, k_y)$, where f denotes frequency and k_x, k_y are the wave numbers along X and Y, respectively. The 3D spectrum fully characterizes the observed space-time correlations of the wave surface since the latter is in one-to-one correspondence with the former. For example, slicing the 3D spectrum at constant k_y values allows to estimate the wave dispersion properties in the domain $[f, k_x]$ as shown in fig.4.

Array analysis for waves longer than the view area. Directional properties of waves longer than the average length of the stereo-surveyed area are estimated by an iterative maximum likelihood method [9] routinely used for the analysis of measurements from pressure gauge of wave staff arrays [10]. To apply such



a

b *c*

F i g . 2 . Example 3D reconstruction. without smoothing of the disparity map (*a*), selected area for Fourier transform in the spatial domain (*b*), with a smoothing of the disparity map (*c*). All dimensions are in meters. The grey shade gives the elevation. The small circles arranged in a star pattern are the positions of the virtual wave gauges used for array analysis. The arrow in (*c*) points to a surface discontinuity that appears to be cause by the pixel discretization of the epipolar lines.

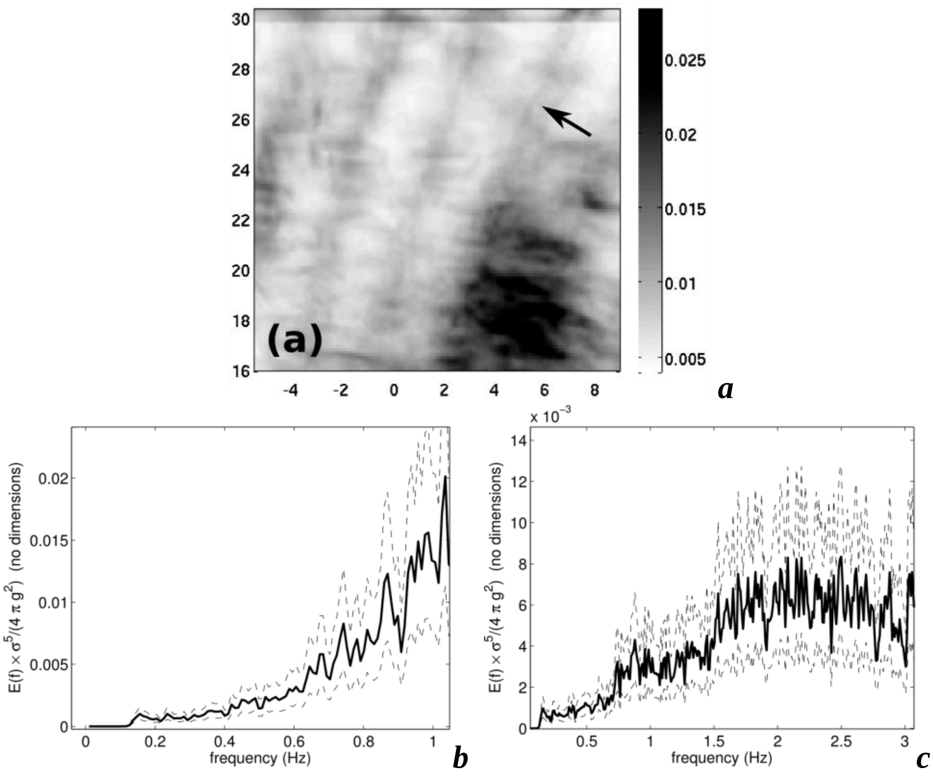
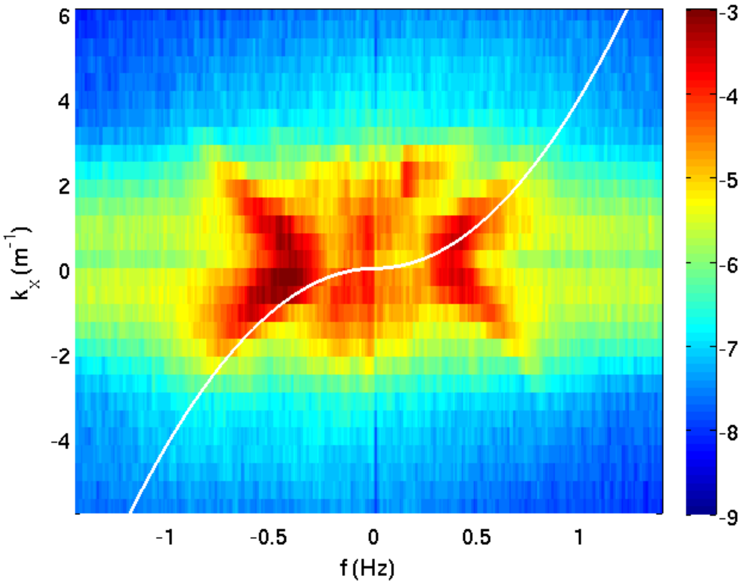


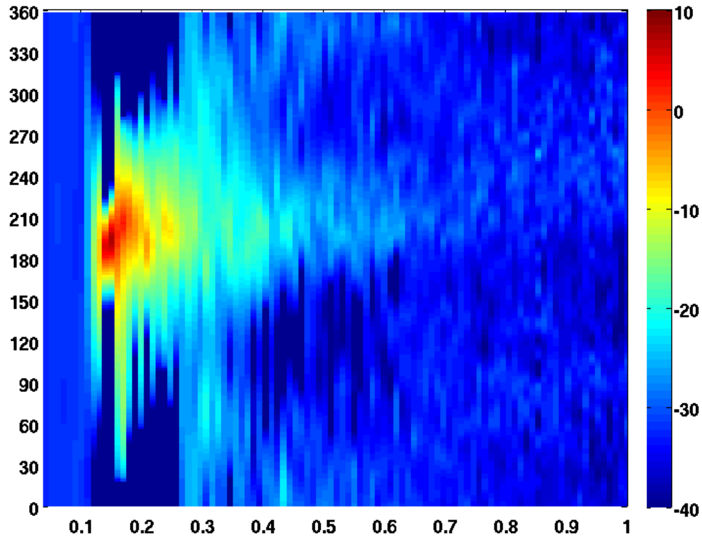
Fig.3. Map of mean square slopes from the 3D data processed with smoothing, the high slope region are visible, as pointed by the arrow (*a*), non-dimensional frequency spectrum from time series obtained with the unsmoothed data (*b*), same but from the smoothed data (*c*). Dashed lines show confidence intervals.

method, we use wave elevation time series at the locations shown by dots in the star-shaped pattern of fig.2, *c*. This provides the co-spectra needed for the directional analysis. The estimated spectrum shown in fig.5 exhibits a week bimodality for frequencies above 0,3 ~ Hz, that is larger than 1,5 times the wind sea peak frequency.

Summary and perspectives. Stereo-video data can provide quantitative information on the directional spectra of ocean waves. Although other studies have focused on short gravity waves combining a three-dimensional reconstruction technique together with a sky radiance modulation transfer function [11 – 12], here we have demonstrated the capability of the WASS system [4 – 6] to provide the directional spectrum of both short and long waves, the latter retrieved via standard array processing techniques [10]. Furthermore, WASS can be applied to study fundamental problems in wave modelling such as wave dissipation [13]. Indeed, WASS can be exploited to process both sea surface topography and detailed whitecapping positions [14]. Finally, we point out that a recent promising variational technique for WASS [5 – 6] can also be applied to recover both longer and shorter waves.



F i g . 4 . Slice of the 3D spectrum at k_y = 00, on October 2, 2009 at 9:35 UTC. The white line marks the linear dispersion relation.



F i g . 5 . Logarithm of the frequency-directional spectrum with frequencies on the horizontal axis (in Hz) and directions on the vertical axis (in °).

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