Measurements of Short Ocean Waves during the MBL ARI West Coast Experiment

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Abstract

Within the framework of the *Marine Boundary Layers Accelerated Research Initiative (MBL ARI)* a buoy-mounted optical system was developed for the measurement of the small-scale structure of the ocean surface with high spatio-temporal resolution. The system is capable of measuring two wave slope components in an area of $15 \times 20\,\mathrm{cm}$ with a dynamic slope range of more than ± 1.25 at a sampling rate of 30 Hz. Wave number spectra up to a maximum wave number of 8000 rad/m can be measured with the instrument. During the MBL ARI West Coast Experiment the system was successfully deployed in the field for the first time. Here, we provide a detailed description of the instrument and present first results from the West Coast Experiment 1995.

1 Introduction

Since the beginning of the century, oceanographers have attempted to measure the shape of the ocean surface with different optical techniques, including the sun glitter technique [*Cox and Munk*, 1954], the Stilwell technique [*Stilwell*, 1969], and stereophotography [*Shemdin*, 1988; *Banner*, 1989]. Although the various techniques have been greatly improved over the years, until now, no instrument has provided the spatial resolution to recover the full directional spectrum of the oceanic capillary waves. Estimates of the equilibrium spectra oceanic capillary-gravity and capillary waves therefore still rely mainly on wave number spectra obtained from laboratory experiments [*Jähne and Riemer*, 1990; *Jähne and Klinke*, 1994; *Zhang*, 1994; *Zhang*, 1995].

Short wind waves play an important role in air-sea interaction. They strongly influence the transfer of heat, mechanical energy, momentum, and mass across the atmosphere-ocean interface. Especially the gas exchange rate is correlated with the *mean square slope* of the waves [*Coantic*, 1980; *Jähne et al.*, 1987]. Until now, much of the knowledge about short wind waves has been largely based on measurements conducted in wind/wave facilities. The field data available today have mostly been acquired with point measuring devices such as wave height gauges and laser slope gauges. The resulting frequency spectra cannot be readily converted to wave number spectra due to the large Doppler frequency shift of the capillary-gravity waves by the orbital velocity of low frequency waves. In addition, frequency spectra ignore the directionality of the progation of the waves. Unfortunately, in the field spatial measurements are considerably more difficult than point measurements. Thus only a few spatial measurements of capillary-gravity waves in the field have been published [*Lee et al.*, 1992; *Hara et al.*, 1994, *Hwang*, 1995]. In those studies *scanning laser slope gauges* were used to obtain the fine structure of the water surface. These systems impose some severe limitations on the measurement of small waves. The system used by *Hara et al.* [1994], for example, scans the water surface on the outline of a 10×10 m square with 129 samples. From laboratory measurements we know that the resulting wave number range from 31 to 990 rad/m is not sufficient to resolve the full spectrum of capillary waves. In addition, since no 2-D data is acquired, the 2-D spatial structure of the waves cannot be revealed. In order to gain deeper insight into the dynamics and the energy balance of ocean wind waves, i.e., the energy input by the wind, nonlinear wave-wave interaction, and energy dissipation, it is necessary to measure the spatio- temporal characteristics of short waves with the same kind of sophistication as it is currently available in laboratory settings.

In this paper we introduce a new system for the optical measurement of the fine structure of the water surface in the field. Section 2 contains a detailed description of the new system and its principle of operation. In the following sections, we present first results from the MBL ARI West Coast Experiment including a preliminary comparison of field and laboratory data. An outlook on necessary improvements of the instrument is given in the last section.

2 Description and Principle of Operation

The new system is based on an *imaging slope gauge* used in previous laboratory experiments to obtain a single slope component of the water surface [*Jähne and Klinke*, 1994]. This technique had been limited to laboratory settings due to the power constraints of optical light source involved. Now, the light source consists of two LED arrays which generate perpendicular intensity wedges. By pulsing the LED arrays shortly after each other, but in different fields of an interlaced video frame, quasi-simultaneous measurements of both the alongwind and crosswind slope can be performed with a single camera. In order to avoid velocity smearing in the images, the length of the pulse can be chosen between 0.2 and 2 ms. For an image sector of 15.1×19.2 cm, a maximum slope of ± 1.25 can be measured. This is significantly larger than the slope range of the available scanning laser slope gauges. With a resolution of 240×640 pixel per video field the recoverable

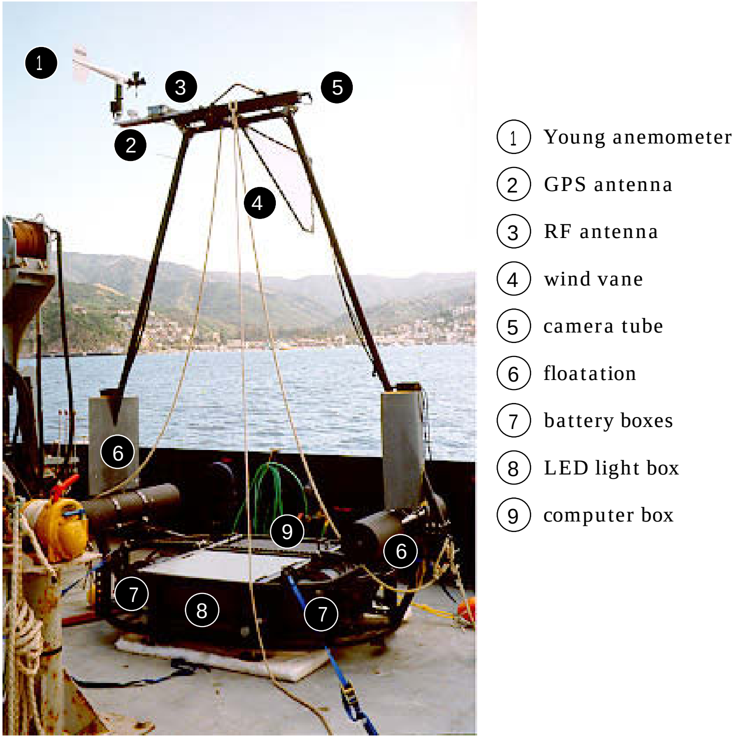

Figure 1: Instrument package on the stern of the R/V New Horizon during the MBL ARI West Coast Experiment in April 1995. The instrument weighs approximately 500 kg and overall dimensions of the instrument are $2.5 \times 1.7 \times 3.4$ *m.*

wave number range is at least 170–4000 rad/m.

The whole optical system is mounted on the frame of a buoy (see Figure 1) which follows the orbital motion of the longer waves and is critically damped to prevent instability in rougher conditions. The buoy is designed with rather shallow frame to provide minimum flow distortion in both the water and the air. The onboard computer for data and image acquisition is remotely controlled via a radio link from a distance of up to 20 km. Battery power allows free-floating operation for a duration of approximately eight hours. In addition to the 2-D imaging slope gauge, the buoy is equipped with a Young wind speed anemometer, a Global Positioning System receiver (GPS), as well as a digital gyro sensor system which provides stabilized pitch, roll, and magnetic azimuth data. An ultrasound distance meter is used to measure the distance of the camera to the water surface at a rate of 7 Hz.

The system is launched from the R/V New Horizon with the help of a crane. Once deployed, the wind vane forces the instrument to turn into the wind (Figure 2). Due to the effect of ambient and direct sunlight, the operating period for the imaging slope gauge is currently limited to the time from

Figure 2: Freely drifting instrument after deployment from the R/V New Horizon during the MBL ARI West Coast Experiment 1995.

dusk to dawn. Through a radio link, the GPS receiver and the Young wind speed anemometer on the buoy are monitored constantly, to provide the position and drift of the buoy as well as the local wind speed. This is especially important since the instrument was mostly deployed at night. During a single deployment period a total of 6000 single image frames can be recorded digitally at any time. The maximum length of an image sequence at 30 Hz sampling rate is 6.7 s, or 200 image frames. The image data is downloaded to a shipboard computer via Ethernet after recovery of the instrument.

3 First Results

During several deployments from the R/V New Horizon more than 20000 images were recorded. Figure 3 shows examples of corresponding alongwind and crosswind images from deployment in Monterey Bay on May 3, 1995 with wind speeds around 5 m/s. The image pair on the left several trains of capillary waves on the front face of a shorter gravity waves are visible. The image pair on the right shows microscale wave breaking.

The short wave image sequence in Figure 4 illustrates the potential of the instrument for the study of intermittent phenomena and the measurement of phase velocities of capillary waves. The consecutive images show the evolution of several capillary wave trains with different propagation directions. The time delay between the first and the last image is just 100 ms.

In a preliminary analysis of the acquired image data, directional satura-

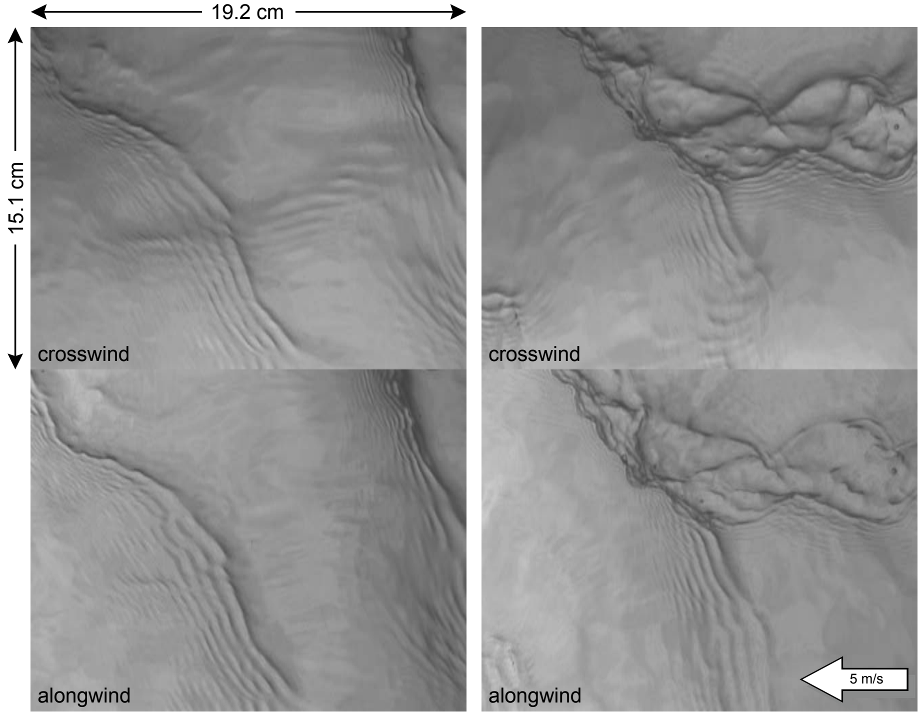

Figure 3: Two image pairs taken at a wind speed of about 5 m/s. The wind is blowing from right to left. Crosswind images are shown in the top half and the corresponding alongwind images are shown in the bottom half. The image sector is 15.1 cm in crosswind and 19.2 cm in alongwind direction.

tion *wave number spectra* for wind speeds around 5 m/s were obtained from 12 5 s image sequences (150 along/crosswind image pairs at 30 Hz sampling rate). The spectra were averaged to produce the directional spectrum in Figure 5 f. The laboratory spectra in Figures 5 a-e show how the wave field develops with increasing fetch.

An overall similarity in the spectral shape of the lab and field data with regard to the wave number dependence exists, however, several differences are noticeable. First, the angular dispersion of the field data is much wider and not symmetric with regard to the wind direction. This asymmetry, however, may have been caused by a swell system propagating obliquely to the main wind direction. Also, we find an increased saturation level at high wavenumbers for the field data.

The unidirectional wave number spectra shown in Figure 6 confirm this finding. The lab spectra on the left are ensemble averages of 200 images over a 5 min period, while the ocean spectra on the right are averages of 150 images over a 5 s period. It is noteworthy to point out that the spectral

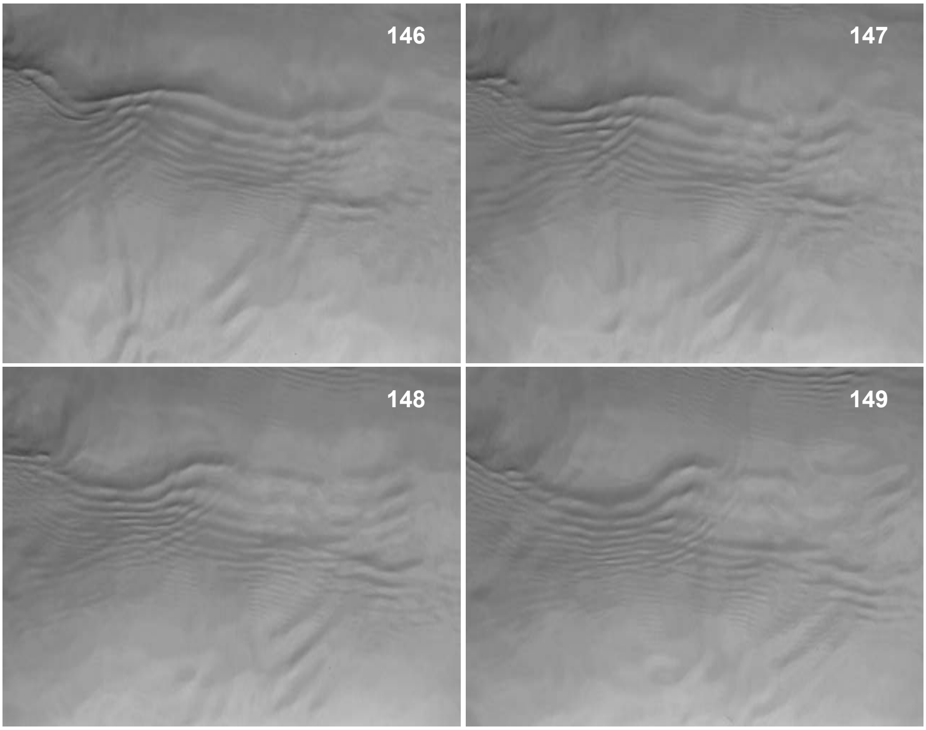

Figure 4: Four consecutive crosswind images out of a sequence of 150 images. The time delay between each images is 33 ms.

cutoff in the unidirectional spectra occurs around the same wave number for the lab and the field data.

4 Conclusions and Outlook

From the shortcomings of the existing scanning laser slope gauges stemmed the need for a field- suitable optical instrument with increased wave number resolution. The presented instrument allows the measurement of the sea surface fine structure with unrivaled spatial and temporal resolution. Additional sensors on the buoy provide the necessary meterological data as well as information on the background wave conditions.

It turned out that instrument needs to be modified to facilitate the deployment and recovery from a ship. However, once deployed, the buoy rides very stable on the larger waves, even in wind speeds up to 12 m/s; the wind vane helped to steer the buoy into the wind. One drawback is that currently the stabilizing weight is mounted relatively high and requires trimming of the system for different wind forcing. Another disadvantage is that oper-

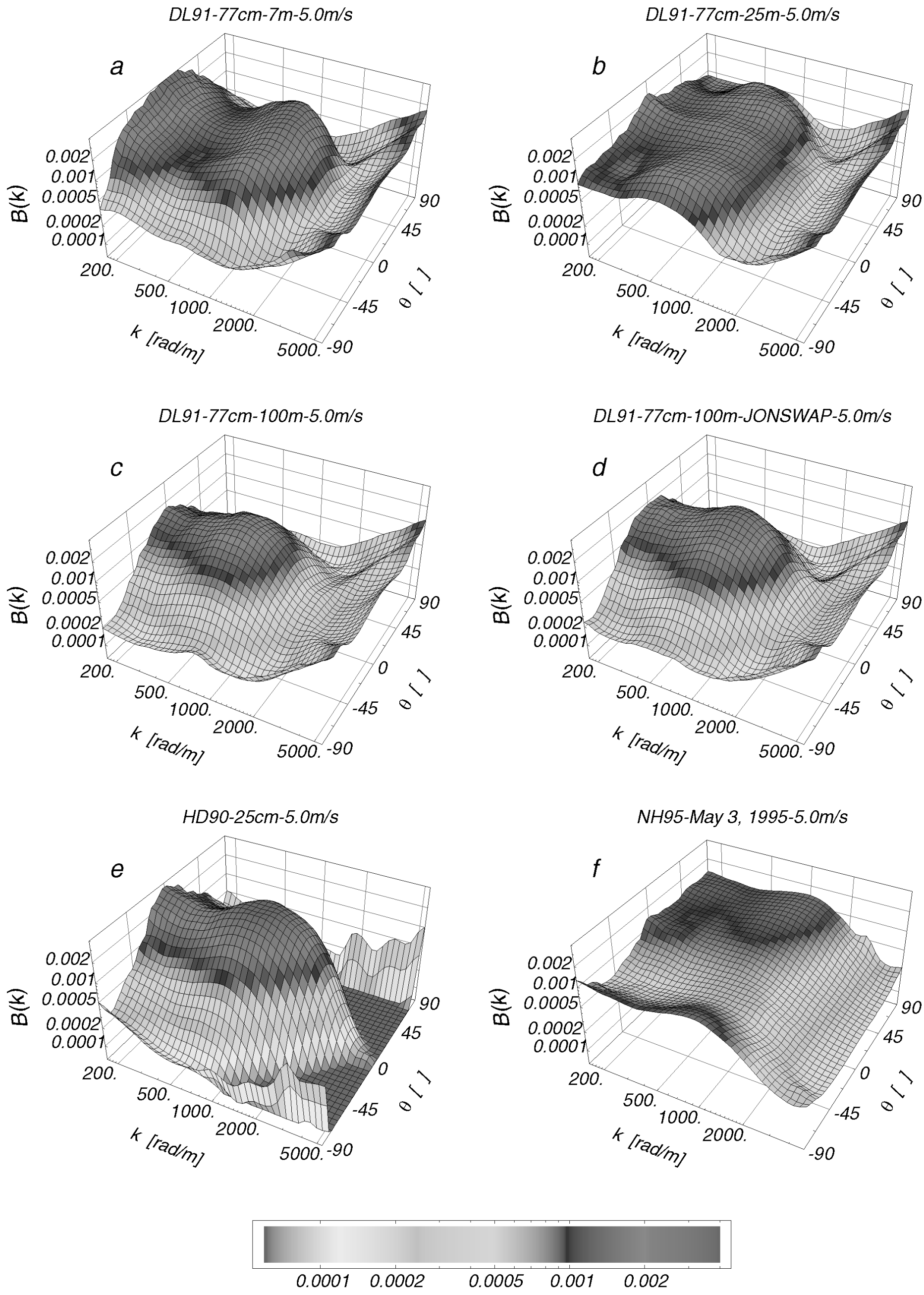

*Figure 5: Comparison of directional wave number spectra at 5 m/s wind speed: **a** Delft facility (1991) at **a** 7 m fetch; **b** 25 m fetch; **c** 100 m fetch; **d** 100 m fetch with JONSWAP-type mechanically generated waves; **e** Heidelberg facility infinite fetch (1990); **f** MBL ARI West Coast Experiment 1995. The spectra are twelve 5 s averages for the field and 5 min averages for the lab data. (For color figure, see Plate 11.)*

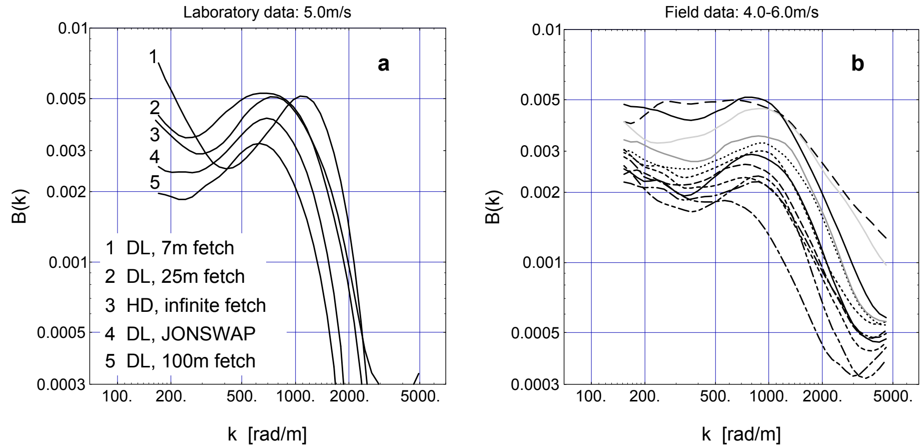

Figure 6: Comparison of unidirectional wave number (integrated over all propagation angles): a) laboratory experiments at wind speeds of 5.0 m/s. Facilities and conditions as indicated; b) MBL ARI experiment 1995 at wind speeds between 4.0 and 6.0 m/s.

ation of the imaging slope gauge is possible only between dusk and dawn. By using multiple cameras with electronic shutter it should be possible to overcome this constraint and to utilize the instrument also in broad daylight conditions.

A first data set of wave slope image sequences was acquired during the MBL ARI West Coast Experiment 1995, the data only provide a first insight into high resolution ocean wave spectra and are neither sufficient for a more quantitative comparison with the available laboratory data, nor are they sufficient for a systematic study of intermittent processes.

However, these first deployments of the buoy in open ocean conditions provided valuable hints for the improvement of the system. We found that especially for deployment of the buoy in higher wind conditions it is necessary to lower the center of mass in order to counteract the torque by the wind drag on the upper structure. Currently, these modifications are incorporated into the system so that it will be available for additional field measurements off the Scripps Pier in fall of 1995. These measurements should allow for a more systematic study of short ocean wave spectra, especially with regard to wind speed dependence and the effect of wind speed variation.

Acknowledgements

This research was performed within the framework of the ONR MBL ARI and the NSF CoOP projects. Financial support from the U.S. Office of Naval Research (N00014-93-J-0093) is gratefully acknowledged. The authors would like to express their sincere thanks to their colleagues from Woods Hole Oceanographic Institution for the excellent cooperation during the West

Coast Experiment off the Coast of California in April 1995. Special thanks are due to Dr. Erik Bock, chief scientist on the R/V New Horizon during the MBLARI cruise, Jochen Dieter, Horst Haussecker, and Sven Weber for their invaluable help in preparation of and during the actual field experiment. In addition, we would like to acknowledge the support by David Malmberg and the other personnel of the Scripps Marine Science and Development Shop.

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