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COMBINED HEIGHT/SLOPE/CURVATURE MEASUREMENTS OF SHORT OCEAN WIND WAVES

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Abstract. A new optical instrument has been designed for combined measurements of height, slope and curvature of the small-scale waves at the ocean surface. The compact and rugged sensor head contains two light sources and a short-base CCD stereo camera setup. It acquires stereo images of the specular reflections on the water surface representing slope of zero in a sector of about $40 \times 30\,\mathrm{cm}^2$. The instrument determines the mean height of the reflections in the footprint, the probability for slope of zero, and the mean square curvature. Continuous time series with 30 frames per second were recorded. Experiments from the Scripps pier and the research platform Noordwijk are reported.

1 Introduction

In recent years, short ocean surface waves have received increasing attention because of their significance for the processes that take place at the ocean-atmosphere interface, *e.g.*, air-sea gas exchange and the backscatter of radar microwaves from the sea surface. A detailed investigation of short ocean wind waves is required to obtain a better understanding of their influence on these processes.

In previous research, basically three different instruments have been used for spatial measurements of short wind waves: stereophotography, Stilwell photography (Stilwell, 1969), and scanning laser slope gauges (Martinsen and Bock, 1992). Stereophotography has been used by a number of investigators over nearly one century (Kohlschütter, 1906; Pierson, 1962; Banner *et al.*, 1989; Shemdin and Tran, 1992). Despite considerable effort, only a few results have been obtained so far. Our instrument is a new approach to spatial measurements of the shortest waves at the ocean surface including capillary waves.

2 Principle of Combined Height/Slope/Curvature Measurements

The design criteria of the new instrument are based on the analysis of the performance of the previous instruments:

(1) *Artificial illumination.* Dependence on daylight condition is one of the major disadvantages of previous imaging techniques such as Stilwell and stereo photography. In order to achieve an unbiased selection of measuring conditions, an artificial illumination system is crucial.

(2) *Rugged compact sensor.* The instrument consists of a compact and rugged sensor head which is mounted on a boom from a platform with no parts submerged in the water in order to be usable even under rough sea conditions.

(3) *Combined height/slope/curvature measurements.* Height measurements of waves cannot resolve the shortest wind waves, consequently a system was designed which adds slope and curvature to height measurements.

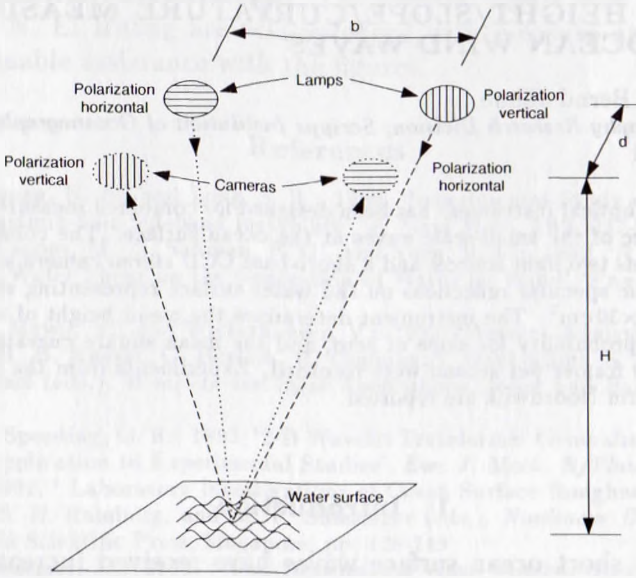

Fig. 1. Illustration of the principle of the height/slope/curvature instrument (HSCI).

(4) *Time sequences.* In contrast to single frames, sequences of stereo images allow for a detailed study of the wave dynamics, including short wave/long wave interactions.

Essentially, the height/slope/curvature instrument (HSCI) can be regarded as a variation and extension of the classic work of Cox and Munk (1954) who used sun glitter images to measure the two-dimensional slope distribution. The system–consisting of two synchronized CCD cameras and two light sources (Fig. 1) – takes stereo images from the specular reflections at the same sector of the water surface. With a single point light source, the two cameras located at different spatial positions would see different specular reflections. This problem is solved by a special arrangement with *two* light sources as shown in Fig. 1. By the use of polarization filters one camera receives light only from the corresponding light source. A detailed description of the instrument can be found in Waas (1992) and Jähne *et al.* (1992). Fig. 2 shows two typical images as obtained by the stereo cameras.

3 Experimental Set-Up and Data Evaluation

Two CCD-cameras and the light source, a 300 W DC Xe arc lamp are placed in a compact box of about 1 m x 0.25 m x 0.2 m. A stereo base of 30 cm was chosen. The cameras are equipped with an electronic shutter (1/60 s to 0.1 ms) and a remotely controlled iris diaphragm. In order to suppress upwelling radiation, the HSCI operates in the near infrared wavelength range (840-1000 nm) which is strongly absorbed by water. The distance from the HSCI to the water surface

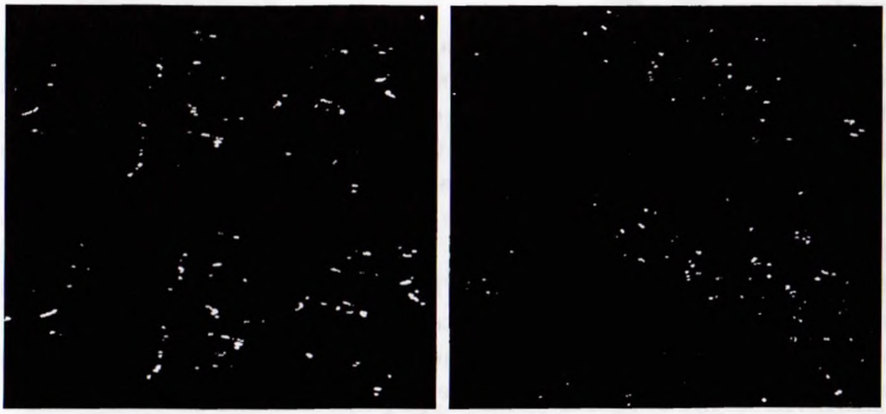

Fig. 2. Examples of HSCI images; the image sector is $27 \times 36\text{cm}^2$; wind speeds: left: 2.4 m/s; right: 6.4 m/s. The top half of each image represents the first field, the bottom half the second field (time difference: 17ms).

is sensed by an ultra-sonic distance meter. The mean distance to the water surface was 4.5 m, the observed area has a size of about $40 \times 30\,\text{cm}^2$. The height resolution is ± 0.5 Pixel in the video image corresponding to ± 1 cm for the wave height.

Continuous sequences of stereo images were recorded on a laser video disk recorder. The red and green channels are used for the stereo images.

A successful use of the HSCI depends entirely on a fast and automatic processing of the stereo images. Although stereo image processing is generally a difficult task, the special illumination technique and the physical properties of the wave field facilitate the stereo processing considerably and ensure an unambiguous correspondence between the features in both images.

The stereo image processing is based on a fast correspondence algorithm. The image is segmented and the individual reflections are found by a fast labeling algorithm. Then a correlation technique is used to find corresponding reflections in the two images. Since the correlation is restricted to the small fraction of the image sector covered by specular reflections, the algorithm is about 10–100 times faster than a standard correlation algorithm covering the whole image sector. In total, only about 10 s are needed to process one 512×256 stereo image pair using an i860 RISC processor.

4 Measured Parameters

Long Wave Height and Slope. The elevation of the water surface can be determined if corresponding features are found in both images. At the location of these features, the height of the waves can be calculated. Since only a small fraction of the water surface is covered, it is not possible to reconstruct the complete shape, especially the capillary waves are not resolved. The data can be used, however, to perform height measurements of the mean wave height over the whole image sector.

Probability for Slope of Zero. A specular reflection is observed at the image plane whenever the slope of the water surface is perpendicular to the light ray. In this way, the position of a reflection on the image plane is directly related to the slope of the reflecting facet at the water surface. Because of the finite size of the lamps (25 mm diameter), a reflection is observed whenever the slope is within ± 0.0014. It is important to note that the relation between the slope and the image coordinates depends only on the focal length; thus there is no bias in the slope signal due to the wave height. If a tele lens is used, only reflections with slopes close to zero are detected. The total area covered by specular reflections then gives a good approximation for the probability of slope of zero. From this quantity, the *mean square slope*, can be estimated.

Curvature and Statistics of Specular Reflections. Since the HSCI covers only a narrow slope range, it essentially measures the points at the water surface that are flat, i.e., points having slope of zero. The distribution, size, and number of the specular reflecting facets characterize the short waves. With some training, it is possible to make a good estimate of the wind speed just by visual observation of the images (provided that capillary waves are not damped by surface films). The number of reflections may be closely related to the spectral density of capillary waves. It is obvious that if only a few and less steep capillary waves are present, much fewer and brighter reflections will occur than when the surface is rougher. Longuet-Higgins (1957) showed in an early paper, that the number of the reflections is directly related to the mean square curvature and it is possible to infer the energy spectrum from statistical properties of a Gaussian surface. The moments of the two-dimensional spectrum can be deduced by considering the statistical properties (average number of zero-crossings, average number of maxima and minima) of the surface along a line in a number of different directions. With these moments it is possible to obtain a convergent sequence of approximations to the spectrum. We intend to investigate these relations in more detail from simultaneous measurements with the HSCI and a wave slope imaging instrument from which two-dimensional wavenumber spectra can be computed.

5 Results

The performance of the HSCI was checked in two ways: Fig. 3 left shows the calibration in the lab with an artificial target, Fig. 3 right shows a comparison of the HSCI with the ultrasonic distance sensor.

As an example for the potential of the HSCI, the evaluation of a sequence of 500 stereo images (2 frames/s) from the Scripps Pier is shown. Fig. 4 (middle) shows the wave height averaged over the image sector. Fig. 4 (bottom) shows the total number of reflections. This figure is a good measure for the mean square curvature. Fig. 4 (top) shows the mean probability for slope of zero. This quantity is inversely proportional to the mean square slope of the waves integrated over *all* wavelengths. Both quantities show large fluctuations

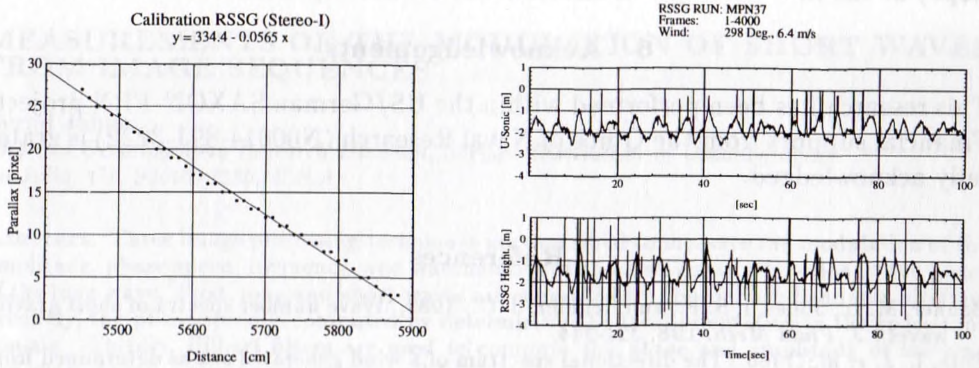

Fig. 3. Left: Calibration with an artificial target. Right: Comparison of the stereo data with an ultrasonic distance sensor. Some drop-outs in the height measurements occur when zero or only very few reflections are contained in the image.

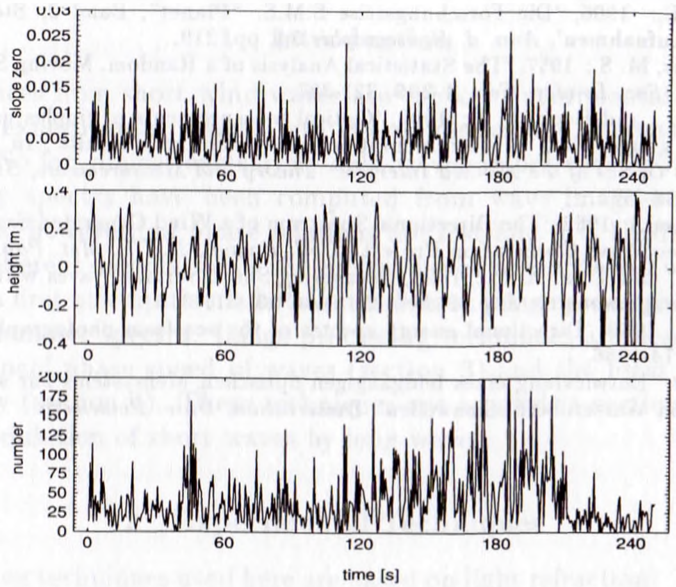

Fig. 4. Top: Probability for slope of zero measured as part of the surface area covered by the reflections. Middle: Time series of the wave height averaged over the image sector of $40 \times 30\,\mathrm{cm}^2$. Two frames have been taken per s; the wind speed was 2.5 m/s. Bottom: Time series of the number of reflections in the stereo images.

in conjunction with the height of the long waves. A striking event appeared at about 210 s in Fig. 4 (bottom): the number of reflections is drastically reduced, while the probability of the mean square slope is only slightly decreased. This event was caused by slick entering the image sector and significantly damping the capillary waves. The total mean square slope is only slightly affected, since the capillary waves account only for a small fraction (at most 20% of the wave slope) at the low wind speeds encountered in this experiment.

6 Acknowledgements

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