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6. AUTHOR(S)
B. Jahne, S. Waas, J. Klinke

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093-0230

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13. ABSTRACT *(Maximum 200 words)*

This research focused on measurements of short wind waves in the open ocean with optical techniques using a triple strategy:

1. Optical imaging of short wind waves was reviewed using an unified approach based on the shape from shading and shape from stereo paradigms from computer vision. This analysis revealed the weaknesses of conventional stereo and Stilwell photography. Refraction-based techniques perform much better, but reflection-based can also be used to obtain statistical wave slope data.
2. Laboratory measurements of short wind waves in three different wind wave facilities revealed some surprising new features of the wave number spectra that seem also to be valid for oceanic conditions but in contrast to existing theory.
3. A new optical system, the Reflective Stereo Slope Gauge (RSSG), has been developed that measures the slope and height of large waves and statistical parameters of short waves. The feasibility of the new concept has been demonstrated with measurements at Scripps Pier and the Noordwijk Research Platform. A second-generation instrument will be built for routine measurements in a follow-up project.

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Final Report

Optical Slope/Height Measurements of Small Scale Waves within the SAXON-FPN-Experiment

B. Jähne, S. Waas and J. Klinke
PORD, Scripps Institution of Oceanography, University of California
La Jolla, CA 92093-0230, USA
Phone: (619) 534-860, Fax: (619) 534-8509, E-mail: bjaehne@ucsd.edu

The major goal of this research project was the development of new optical techniques for short wind waves measurements in the open ocean. These techniques should work under the widest possible range of conditions, including high wind speeds. The difficult problem was tackled by a threefold strategy:

1. A theoretical investigation of optical imaging of short wind waves to evaluate and compare the performance of existing technology and to make optimum selections for a new instrument.
2. Laboratory measurements of short wind waves to learn as much as possible from laboratory data for the field conditions.
3. Development and test of a new optical system for combined slope/height wave measurements.

Considerable progress could be reached in all three areas. The prominent results are discussed in the following three sections.

1. Theoretical Investigation of Wave Imaging

Optical wave imaging was reviewed using an unified approach based on the shape from shading and shape from stereo paradigms from computer vision (Jähne et al., 1992a+b). The analysis of existing optical techniques appears rather bleak. Stereo photography using natural illumination has severe drawbacks. First, the height resolution is insufficient to resolve even waves which can be easily resolved horizontally. Secondly, previous investigations did not adequately take the specular nature of light reflection at the water surface into account. Thus two types of errors may occur. For steeper waves a height bias may occur, while for less steep waves no corresponding features may be found in the two images at all. Under optimum conditions (high sea state with rather uniform sky illumination) stereo photography may be used, but even then, only a very narrow range of wave numbers can be resolved. Stilwell photography is also no alternative, because it shares several problems with stereo photography.

The clear winners in the theoretical comparisons are shape-from-refraction techniques which have two significant advantages over the other techniques: First, they are capable of measuring large slopes. Secondly, a remarkably linear relation between one slope component and the image irradiance can be achieved. This technique can be realized in two versions: scanning laser slope gauges and imaging laser slope gauges. While the scanning laser slope gauges have already been used in the ocean by several groups, we used the imaging slope gauge (ISG) for detailed laboratory studies of short wind waves.

2. Laboratory Measurements of Short Wind Waves

The laboratory measurements were performed in the wind/wave facilities of the IMST (University of Marseille, France) at 5 to 29 m fetch, the Delft wind wave flume (Delft Hydraulics, The Netherlands) at 7 to 100 m fetch, and the circular facility wind/wave facility of the Institute for Environmental Physics at the University of Heidelberg (Germany). Image sector sizes of up to 30 cm x 40 cm were used. The wave number spectra cover the range from 30 - 5000 1/m. The results from the quite different wind wave facilities give a clear picture which allows to extrapolate several features of the spectra to oceanic conditions (Klinke and Jähne, 1992, Jähne and Klinke, 1992):

1. In all three facilities a $k^{-3.5}$-dependence of the height wave number spectrum was found for wind speeds larger than about 4 m/s. This range extends to smaller wave numbers (wave numbers up to a limit of about 50 m^{-1} could be measured) for higher wind speeds. The upper limit of this range is at about $k \approx 1000\,m^{-1}$. Because of the insensitivity of this equilibrium range to the geometry of the facilities (width and fetch), we can infer that a similar spectral shape for oceanic wave number spectra should be found. Contrastingly, the spectral gap around the minimum phase speed and the secondary peak in the capillary wave range found at low fetches and wind speed is not likely to be relevant for oceanic conditions.
2. For long fetches (> 10 m), the cutoff wave number is nearly independent of wind speed and fetch. This cutoff appears to be an universal property of the wind-generated wave field and is also expected to be found in wave number spectra obtained from measurements in the open ocean. The wind speed independence of the cutoff strongly rules out the possibility that the spectral density of the shortest

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TABLE 1. Summary of the most important features of the wind wave facilities used for the experiments, including the width and depth of the water channel, the maximum fetch, and maximum wind speed.

Location	Width m	Depth m	Fetch m	Wind speed m/s
Linear facility IMST, Univ. of Marseille (France)	2.6	0.70 - 1.0	40	14
Linear facility Delft Hydraulics (Netherlands)	8.0	0.80	100	15
Circular facility, Heidelberg Univ. (Germany)	0.3	0.05 - 0.3	12[1]	10

[1] circumference of annular water channel

waves is determined by the balance between wind input and viscous dissipation. Additional evidence for this hypothesis is given by earlier results from the small circular facility at Heidelberg University which showed that in the range of 4–35°C neither the cutoff, nor the spectral density of capillary waves depend on temperature [*Dutzi*, 1984], although the viscosity of water changes by a factor of three in this temperature range. The only explanation for this that a) viscous damping does not seem to be the dominant dissipation mechanism for short wind waves and b) capillary waves are not predominantly generated directly by wind, but by steep short gravity waves. These conclusions agree with the early findings of *Cox* [1958] who showed that in the absence of wind steep, mechanically generated waves also generate parasitic capillary waves.

3. A less certain conclusion can be made about the friction velocity dependence of the spectral densities. Without doubt, there is a clear general trend from rather weak dependence of the spectral densities for short gravity waves (6 cm) towards a much steeper increase for capillary waves. However, the increase is less steep at higher fetch. Extrapolating this trend to field conditions as found in the open ocean, it seems that the spectral densities of short waves at low wind speeds are higher in the ocean and less dependent on the friction velocity than the spectral densities measured in limited-fetch facilities. It is also expected that the strong S-shaped form of the increase (first slow, than steeper, and then slower again especially found at 100 m fetch in the Delft facility) is much weaker. These conclusions are less certain for lower wind speeds although at high wind speeds all facilities show a surprisingly uniform behavior. Thus we might expect very similar spectral densities at high wind speeds in the ocean.
4. Finally, a preliminary analysis of the angular dispersion of the waves indicates that except for measurements with additional mechanically generated planar waves of the JONSWAP type, the angular spread seems to depend on wave number, wind speed, width of the as well as on the fetch. Since the angular spread increases with increasing width of the facilities it might be even wider in the ocean.

Summarizing, these results indicate that although the geometry of the respective wind-wave facilities bears large influence on the angular dispersion of the spectra, the unidirectional spectra are hardly affected hereby. However, it must be noted that since the shapes of the unidirectional wave number spectra differ considerably for short- and long-fetch conditions, it is in general not useful to extrapolate short-fetch data to oceanic conditions. In this sense the inclusion of the 100 m fetch condition from the Delft facility and particularly the circular facility of Heidelberg University with unlimited fetch was revealing.

Despite the interesting clues that can be inferred from wave number spectra, the spectral analysis of the wave image data imposes severe limitations. Neither can the energy balance of small-scale waves be determined unambiguously, solely by analyzing mean wave number spectra, nor is it possible to study temporal characteristics of the wave field, e.g. mean life times and coherency lengths of individual wavelets, or the energy cycling in the wave field. These aspects are especially important for a better understanding of the physical processes that determine the radar backscatter of microwaves. Thus the determination and analysis of mean wave number spectra can only be regarded as a first step in the evaluation of the variety of information contained in the wave image data.

TABLE 2. Summary of the image sectors, the spatial resolution, and the corresponding Nyquist wave numbers. The first figure in each column is in along- the second in cross-wind direction.

Facility	Image Size (m)	Spatial Resolution (mm)	Wave Number (m^{-1})
Marseille, 9/89	0.310 0.253	0.606 1.054	5186 2981
Marseille, 12/89	0.439 0.359	0.857 1.496	3666 2100
Marseille, 12/89	0.190 0.154	0.372 0.642	8445 4893
Delft, 10/88	0.664 0.473	1.297 1.971	2424 1701
Delft, 10/90	0.320 0.250	0.625 1.042	5027 3217
Delft, 10/90	0.160 0.125	0.313 0.521	10553 6434
Delft, 10/91	0.165 0.135	0.322 0.563	9739 5592
Heidelberg, 3/90	0.180 0.140	0.352 0.583	8936 5389
Heidelberg, 12/90	0.180 0.140	0.352 0.583	8936 5389

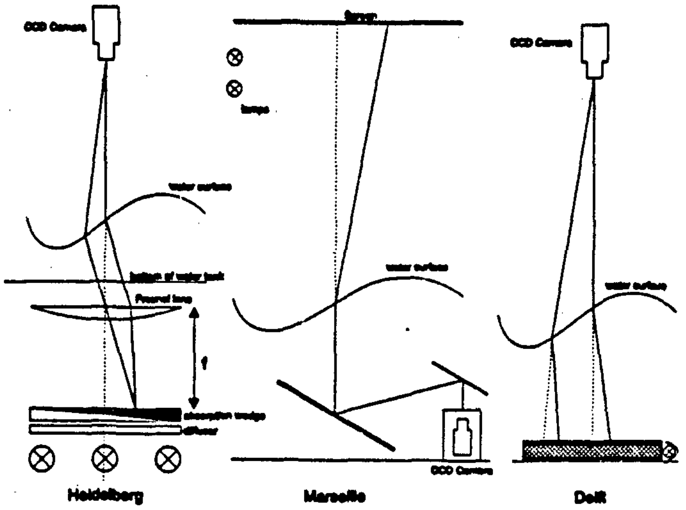


Fig. 1. Schematics of the imaging wave slope visualization instruments as used a) at the circular wind wave facility Heidelberg, b) the Marseille wind wave tunnel, and c) the large wind wave flume of Delft Hydraulics.

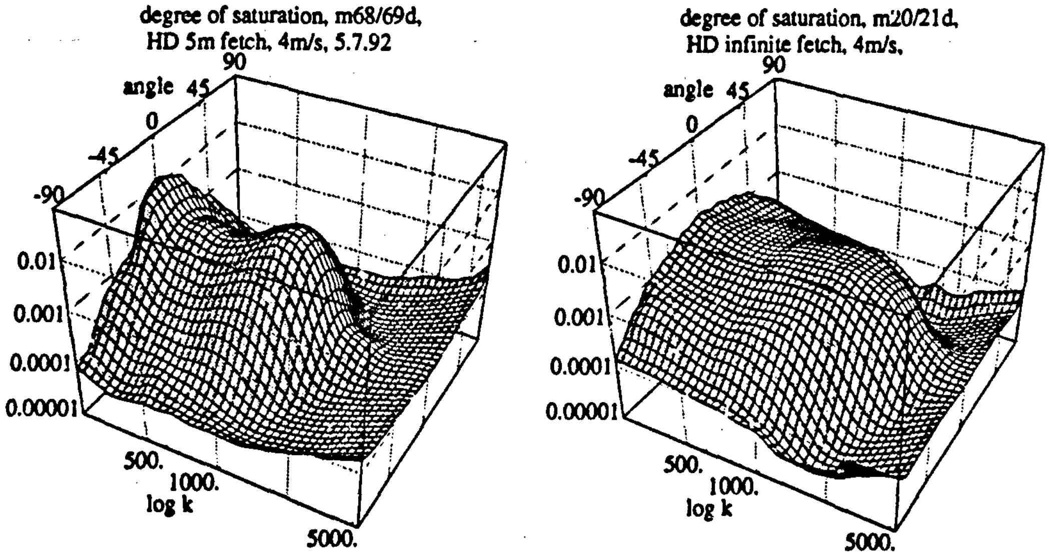
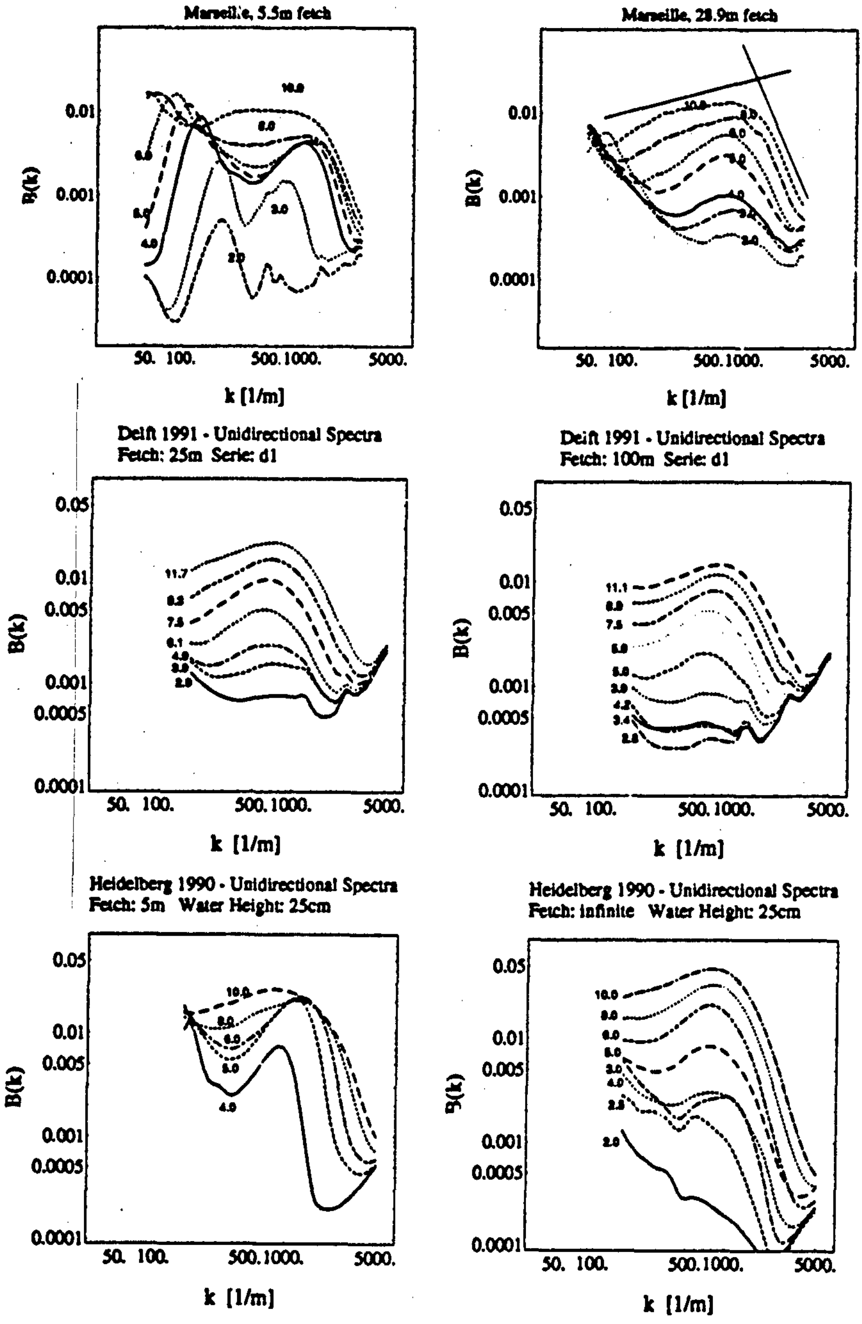


Fig. 2. Examples of two 2D wave number spectra from the Heidelberg facility. The degree of saturation $B(k)$ is plotted logarithmically in a log-polar wave number coordinate system at 4 m/s wind speed: a) 5 m fetch; b) infinite fetch.



Marseille, 5.5m fetch

Marseille, 28.9m fetch

Delft 1991 - Unidirectional Spectra
Fetch: 25m Serie: d1

Delft 1991 - Unidirectional Spectra
Fetch: 100m Serie: d1

Heidelberg 1990 - Unidirectional Spectra
Fetch: 5m Water Height: 25cm

Heidelberg 1990 - Unidirectional Spectra
Fetch: infinite Water Height: 25cm

Fig. 3. Unidirectional wave number spectra from the three facilities at wind speeds and fetches as indicated

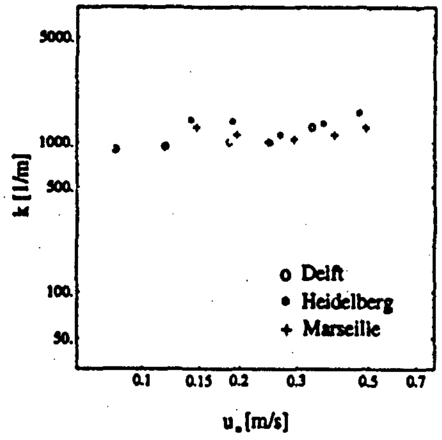


Fig. 4. Cutoff wave numbers for the longest fetch in each facility

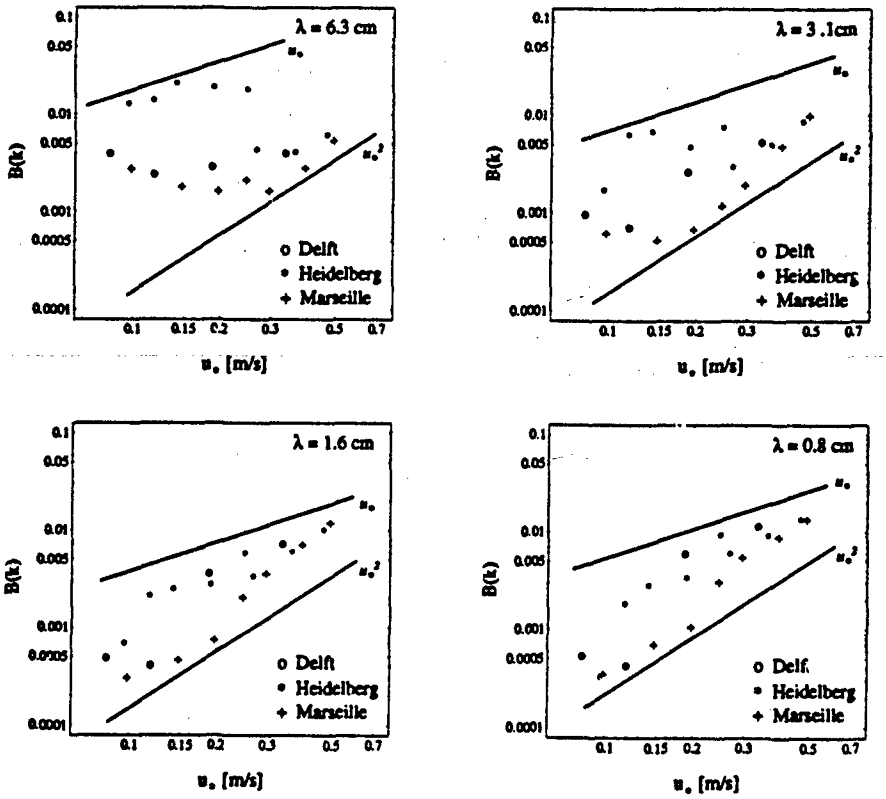


Fig. 5. Friction velocity dependence of the spectral densities for four different wavelengths extracted from the unidirectional spectra at the longest fetch of each facility

3. The RSSG: A New Optical Instrument for Field Measurements

A new optical instrument, named *Reflective Stereo Slope Gauge (RSSG)*, has been designed. The design criteria of the new instrument were based on the theoretical analysis of previous instruments:

1. Artificial illumination, since dependence on daylight conditions turned out to be a major disadvantage of previous instruments.
2. Rugged, compact sensor to be operated from platforms and ships also at high sea states.
3. Combined slope/height measurements; since stereo systems cannot resolve the shortest wave, slope measurements are added to measure these waves.
4. Measurements of continuous time sequences to study the dynamics of waves, including short wave/long wave interactions.

The new system is based on light reflection and an extension of the classic sun glitter work of Cox and Munk. Instead of the sun an artificial light source with two lamps is used to ensure a good correspondence between the reflexes obtained in the two images. Table 3 shows a a summary of the characteristics of the RSSG as used at different campaigns. The two cameras are looking straight down. Therefore the observed reflexes mark positions at the water surface where the slope is zero. From the parallax of the reflexes, the height can be measured, while the number, size, brightness and spatial distribution give detailed statistical information about the small waves.

In two measuring campaigns at Scripps pier and Meetpost Noordwijk, the stereo camera system has been tested extensively. During the MPN experiment from November 16 to December 4, 1990 about 300,000 stereo images have been recorded. The images were taken simultaneously to the radar measurements of TNO/TU Delft and the meteorological measurements of KNMI. Two types of recordings were performed:

1. Continuous records with 30 frames/sec. Such a recording was taken for 8 min and includes 14,000 frames. Synchronization with radar is accurate within a 1/60 s.
2. Statistical records with 1 frame/sec over 25 min (1500 frames).

Together with the test measurements at Scripps pier, the measurements cover a wide range of wind speeds from 0–15m/s.

Advanced digital image processing techniques were used to analyze the stereo images. Using a hybrid feature- and correlation-based algorithm, a robust estimate of the parallax was possible in less than 10 s on an PC-based i860 RISC processor. Nevertheless it takes 10 to 15 hours to analyze a time series of 60 sec, consisting of 3600 stereo image pairs.

The accuracy was studied in two ways:
1. Direct calibration with artificial target (Figure 6).
2. Comparison with ultrasonic distance meter (Figure 7).

Figure 8 shows an example of a times series with different parameters extractable from the stereo images. Slope and height distribution, joint slope/height distribution and number, size and brightness of reflexes can be studied and their dependance from the presence of small waves be detemined. The so far evaluated series give a first impression of the information that can be obtained by the RSSG. The statistical base is yet not wide enough, to provide *physically* usable information.

The new instrument proved to be successful even in the first prototype version. We will continue processing of the stereo images and also built an improved system into which a number of improvements will be incorporated based on the experience of the prototype instrument.

TABLE 3. Summary of the characteristics of the RSSG as used at the Scripps pier and the Noordwijk research platform in the North Sea.

Height above mean water level	H	4.5 m
Stereo base (s)	s	0.3 m
Dist. lamp/camera	d	0.15 m
Diameter lamp	d_{lamp}	25 mm
Base/height-ratio	s/H	0.067
Video cameras		Pulnix TM 740
Image size		6.6 mm x 8.8 mm
Focal length	f	100 mm
Depth of focus	Δg	±1 m
Range of height		± 1 m
Resolution (height)		2 mm
Range of angle (one image) (of whole instrument)	ϕ	±2.56/1.89° ≈ ±30/30°
Observed area on water surface		36cm x 27cm

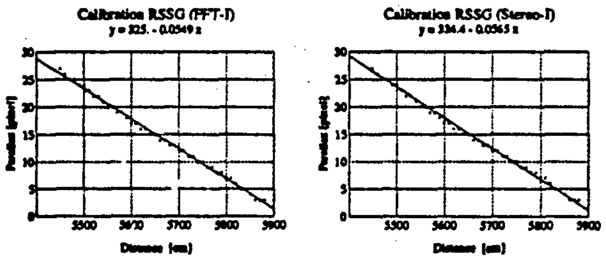


Fig. 6. Calibration with artificial target, distance: 545-585 cm.

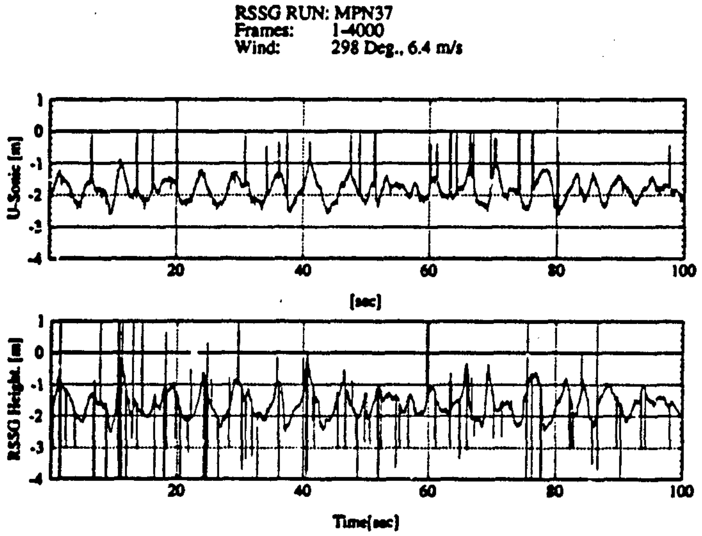


Fig. 7. Comparison between height measurements with u-sonic (top) and stereo images (bottom). Drop-outs in the RSSG height measurements occure when only very few reflexes are contained in the image. Too steep slopes cause drop-outs in the u-sonic measurements, because no sound is reflected to the sensor.

RSSG RUN: MPN27
Frames: #1-3000
Wind Speed: 5.1 m/s
Wind Dir.:   248 Deg.

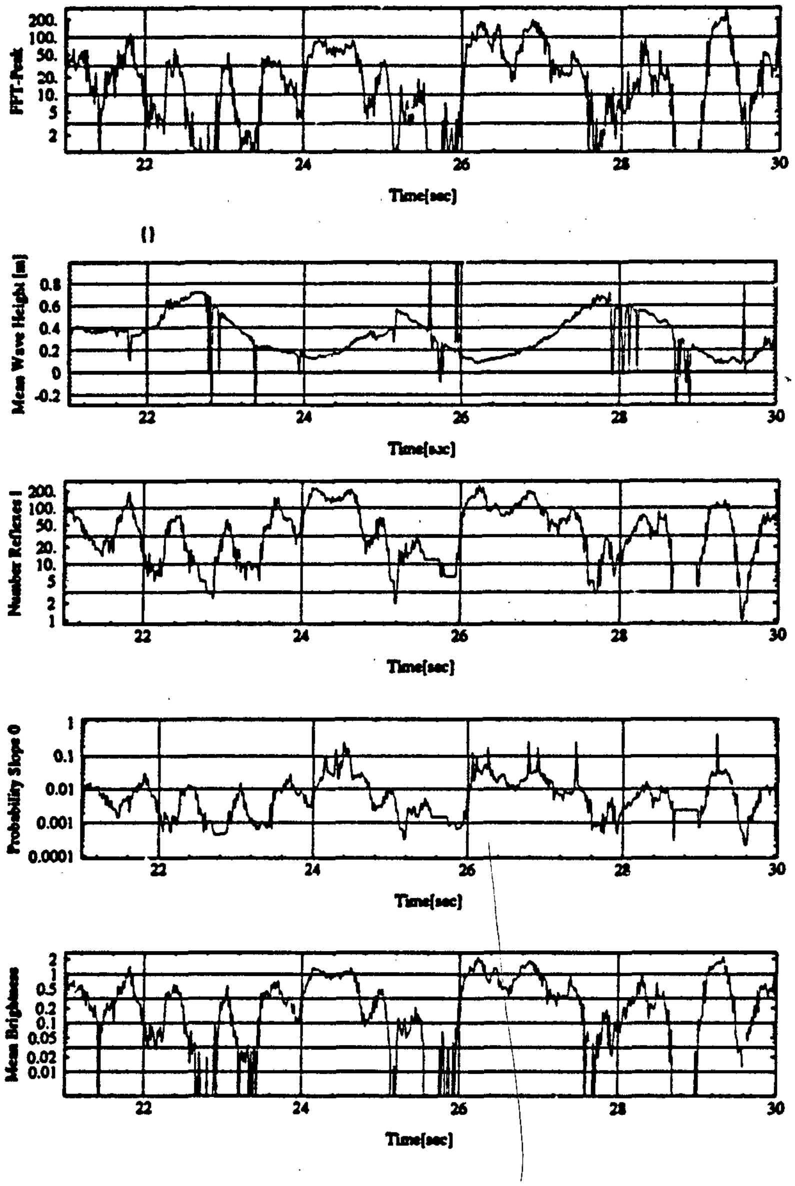


Fig. 8. Time series, 10 sec; FFT-peak: (measure for correlation), mean wave height, number reflexes, probability slope 0, mean brightness; windspeed: 5.1 m/s

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