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Investigation of Ocean Wave Groups using Radar-Image Sequences

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Abstract— **Wave groups have to be taken into account for the design of offshore platforms, breakwaters and ships, because successive waves can cause severe damage to those structures. Further they can excite the resonance frequencies of moored structures like platforms due to non-linear effects or cause capsize of ships. In this paper behavior of wave groups in space and time is analyzed using radar-image sequences of the ocean surface. In addition to 1d sensors like wave buoys, nautical radar-image sequences allow the investigation of wave groups in space and time. Radar-image sequences were acquired by recording the spatial and temporal evolution of the sea surface backscatter, which is modulated through the surface wave field, using the wave monitoring system WaMoS-II. It is based on a nautical radar operating in X-band (9.5 GHz) with horizontal polarization. The instrument is operated on towers in the North Sea and at the coast line in shallow water as well as aboard ships. Wave groups are extracted from radar-image sequences using a method that considers the wave envelope, which is determined spatially and temporally. The amplitude of the wave envelope is determined by calibrating the image spectrum to an in-situ sensor spectrum. It is demonstrated that the method can be employed for the determination of both location and size of wave groups from radar images. The spatial and temporal development of wave groups, their extension and velocities are studied. It is shown that the group velocity of waves measured in shallow and deep water agree in average value with the group velocities resulting from linear wave theory and shows a clear oscillation of the group velocities in 2d.**

I. INTRODUCTION

Wave groups are the result of superposition of elementary wave components (e.g. sinusoidal waves) moving in similar direction with slightly different wave lengths and periods. The groups on the ocean surface, characterized by amplitudes above a threshold, move with their own group velocity. The group velocity is important because wave energy is propagated with this velocity. In deep water the speed of individual crests and troughs is called phase speed and is usually greater than group velocity. We will show wave groups on the ocean that move with different velocities.

In this paper the distribution and the properties of individual wave groups in spatial-temporal dimensions are investigated for typical sea states. An algorithm is developed and tested utilizing nautical radar-image sequences. The wave groups from radar-image sequences are further investigated regarding their measured group velocity in comparison with the theoretical group velocity.

The radar backscatter from the ocean surface, called sea clutter, is modulated due to the surface waves. Because a nautical radar measures in space and time it is a suitable instrument to measure the spatial and temporal behavior of the sea surface. For digitizing the time series of radar images a wave monitoring system (WaMoS II) was developed at GKSS Research Center and is now in operational use for sea-state measurements [1]. The nautical radar operates at 9.5 GHz (X-band) with horizontal polarization in transmitting and receiving at grazing incidence [2]. It covers the area within a radius of $\approx$2 km with a varying resolution in range and azimuth of $\approx$12 m. The radar antenna rotates with 2 s period of revolution. An image sequence consists of at least of 32 images and the total time span for recording a sequence is $\approx$1 minute.

The radar-image sequences were recorded at two different locations in the North Sea, regarding to study the behavior of wave groups for different water depths. The first installation is on the island of Helgoland, where the water depth is shallow. The second radar is installed on the Norwegian Oil Platform "Ekofisk 2/4 k" representing deep water.

II. THE METHOD

The group properties of a wave record of the sea-surface elevation in time at one location can be described with its wave envelope function [3]. For radar-image sequences the 3d spatial-temporal wave envelope has to be determined. The theory and the method itself are described in detail in [4].

An image sequence $G(x, y, t)$ gives the intensity of the backscatter from the ocean surface, which is modulated due the propagating surface waves in space and time. A scheme of the algorithm is shown in Fig. 1. The method can be applied in the same way to single images with some differences as described in [4]. In the first step the image sequence $G(x, y, t)$ is transformed into the wave-number frequency domain with a 3d Fast Fourier Transformation (3d FFT), resulting in a complex 3d spectrum. The spectral signal of the linear waves, which are only considered in this study, is well-located on a surface in the wave-number frequency space defined by the dispersion relation of linear surface gravity waves [5]:

$$\omega^2 = gk \tanh kd \qquad (1)$$

where ω is the angular frequency, k the wave number, g the constant of gravity and d the water depth. This function is used

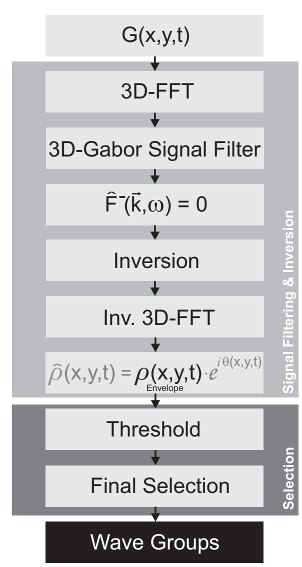

Fig. 1. Scheme of the Algorithm.

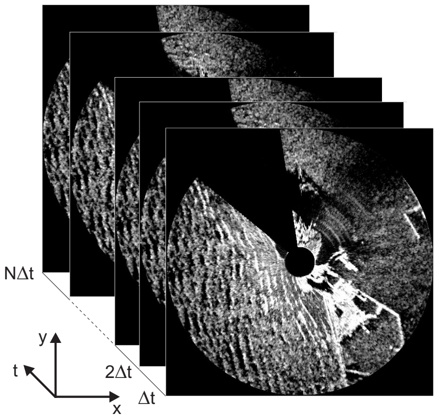

Fig. 2. Image sequence of the radar backscatter digitized by the Wave Monitoring System (WaMoS II) at the island of Helgoland (Germany). The backscatter signal is recorded spatially and temporally. A wave field is visible, travelling from west to east approaching the shore line of the island and thereby changing its direction due to refraction.

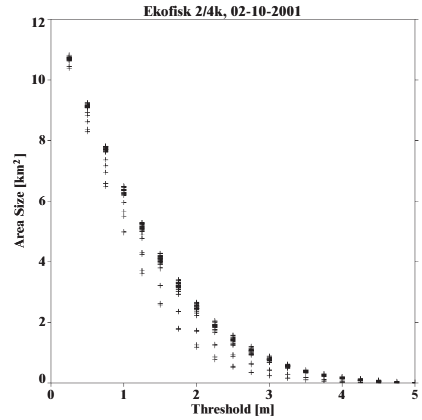

Fig. 3. Total wave group area size for various thresholds. Each threshold is applied to all inverted envelope images of a sequence. For each threshold level the area size is similar over the image sequence because the groups are not disintegrating in deep water due to dispersion.

for a pre-selection of the Fourier coefficients in the spectrum of a multimodal wave field with image features that are not resulting from ocean surface waves.

A 3d-Gabor filter is chosen as bandpass filter of the complex Fourier coefficients around the spectral peak to retrieve a smooth envelope. In case the overlaying wave systems overlap, the individual modes have to be segmented. The remaining spectrum consist only of the dominant harmonics around the spectral peak. To retrieve the complex envelope function of the remaining signal the complex Fourier coefficients with negative frequencies are eliminated from the spectrum.

In the next step, an inversion technique is applied to the complex image spectrum $\hat{F}(\vec{k}, \omega)$ to obtain the ocean wave field [6]. The spectral amplitudes of the image spectrum $\mathcal{I}(\vec{k}, \omega)$ and the ocean wave spectrum $\mathcal{E}(\vec{k}, \omega)$ are connected by an image transfer function:

$$\mathcal{I}(\vec{k}, \omega) = \alpha |\vec{k}|^{\beta} \mathcal{E}(\vec{k}, \omega), \qquad (2)$$

The exponent $\beta \approx 1.2$ has been retrieved by studying modulation effects like tilt modulation and shadowing. The calibration constant α is retrieved by comparison of the spectral zero-order moment of the image spectrum with in-situ measurements of the significant wave height.

After applying a 3D inverse Fourier transform the complex envelope of the wave field is determined in the spatial and temporal domain. The dominant wave groups, given by the modulus of the complex envelope, the amplitude, are filtered by thresholding. The obtained group areas are analyzed regarding to their size, length, velocity and number of waves in a group. These parameters are used to discriminate between the groups for a final selection.

III. RESULTS

Two different data sets have been chosen, one from a shallow water area with an average depth of 10 m (Helgoland), the other one is recorded in deep water ("Ekofisk 2/4 k" platform). Both image sequences have been acquired by WaMoS II. The Helgoland image sequence consists of 64, whereas the "Ekofisk 2/4 k" data set of 32 images. The resolution (of ≈15 m) works as a low-pass filter so that only waves longer than ≈45 m are imaged. In Fig. 2 the image sequence from Helgoland is exemplary shown. All the areas that are retrieved by the method are counted and measured here in regard to the area size. Fig. 3 gives the relation between threshold level and total area size for each inverted image of the image sequence from Ekofisk. For each threshold level the area size is similar over the image sequence because the groups are not disintegrating in deep water due to dispersion. The speed of wave groups, defined by the velocity at the "gravity" center of energy of the selected propagating envelope surface weighted by the potential energy ρ^2, which is termed group velocity C_g, is theoretically described by one-dimensional theory for variable water depth. The phase velocity of the individual waves C is defined as ωk^{-1}. The results from linear theory been used for a first comparison with the phase velocities and group velocities in two dimensions. The determination of 2d velocities is done using a differential-based motion estimation technique [7].

Fig. 4 shows the result for the deep water case from "Ekofisk 2/4 k". The upper image shows the center of energy of all selected wave groups. The threshold for wave envelope height is 3.00 m. The travel direction of all groups is varying, but goes in average with the main travel direction of the single waves. The lower plot shows the phase velocity of the single waves (dashed curve) and the group velocity (solid curve) with their mean values C_g = 6.0 ms^{-1} and C = 15.1 ms^{-1} for the highlighted wave group path. The lines give the velocities regarding the linear wave theory, which are determined with

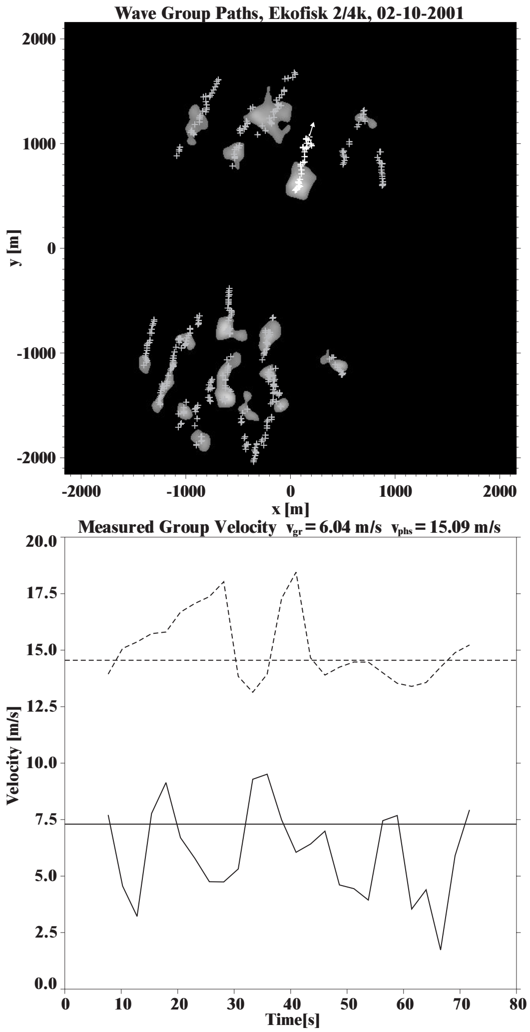

Fig. 4. The upper image shows the center of energy of all selected wave groups of an Ekofisk data set. The threshold for wave envelope height is 3.00 m (white area). The travel direction of all groups is varying, but goes in average with the main travel direction of the single waves. The lower plot shows the phase velocity of the single waves (dashed curve) and the group velocity (solid curve) with their mean values (top) for the highlighted wave group path. The lines give the velocities regarding the linear wave theory.

the frequency and wave number at the spectral peak. Phase and group velocity are oscillating around their theoretical values. The group velocity is in average lower. For shallow water theoretically phase and group velocity have the same value. Measuring the velocities it has been found that sometimes the group velocity is higher, sometimes lower than the phase speed of the single waves, but they are similar in average. One possible explanation for varying group velocities in deep water is, that single waves that originate at the rear of a group, move forward through the group travelling at phase velocity and disappear at the front of the group. Thereby the center of energy is traveling faster then with group velocity. Observing the wave envelopes gives an energy transfer in two dimensions and therefore also addresses the wave crests. Determining the angle of the measured group-velocity vector validates the observation and shows that wave groups are, therefore, not only travelling with the waves. Furthermore, one can see how the wave group is developing and is varying in both amplitude and horizontal dimensions. A transversal modulation of the wave groups by other waves systems might be an explanation. The 2d change in size of the wave groups is especially interesting because it may be correlated with the background horizontal currents in the area [8].

IV. Summary

The Properties of individual wave groups in radar-image sequences, recorded with the WaMoS II system, have been studied by quantitative measurement and analysis of wave groups spatially and temporally. An image sequence of linear surface gravity waves is band-pass filtered and the temporal envelope is defined at each point. The filtering and determination of the complex envelope function are performed in the Fourier domain. The radar-image sequences are inverted to give the 2d sea-surface elevation. The retrieved groups are investigated with regard to their area size and maximum amplitude. The spatial and temporal development of wave groups, their extension and velocities has been measured. Comparison of measured wave group velocities in shallow and deep water gives an agreement of the average value with the group velocities resulting from linear wave theory and shows a clear oscillation of the group velocities in 2d. Overall, the application of the algorithm on nautical radar-image sequences shows the applicability of these data for detection and measuring of wave groups in spatial and temporal dimensions.

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