Ocean Surface Winds
Retrieved from Marine Radar-Image Sequences

Heiko Dankert, Jochen Horstmann, and Wolfgang Rosenthal
GKSS Research Center, Max-Planck-Str. 1, 21502 Geesthacht, Germany, Email: dankert@gkss.de

Abstract—A new method for wind-field retrieval with spatially and temporally high-resolution using marine radar-image sequences is presented. The method is based on analyzing the movement of wind gusts, which become visible in radar image sequences after filtering. In contrast to previous methods, this new technique requires no calibration phase of the radar system. The retrieved wind directions are compared to wind directions of the recently developed method, where wind directions are extracted from wind induced streaks that are orientated in wind direction. Wind speeds are derived from the backscatter of temporal integrated radar-image sequences using an empirical model function, which was parameterized by training a Neural Network. The different methods are applied to radar image sequences acquired by a marine X-band radar mounted aboard an offshore platform in the North Sea. The radar derived winds from more than 1300 radar-image sequences are compared to in-situ wind data measured at the platform. In contrast to traditional offshore wind sensors, the retrieval of the wind field from the backscatter of the ocean surface makes the system independent of the sensors motion and installation height and reduces the effects due to platform induced blockage and turbulence effects.

I. INTRODUCTION

Ocean wind field sequences are determined with spatial and temporal high resolution from marine radar-image sequences. Thereby the local wind vectors are determined directly from the motion of the wind gusts using a optical flow based motion estimation technique, called OFM. This new method is independent from in-situ measurements and calibration-free. The technique extends a recently introduced method, called Local Gradients Method (LGM) [1]. Here the wind directions are derived from wind induced streaks, and the wind speeds from the backscatter of the temporal integrated radar-image sequences using an empirical model function, which was parameterized by training a Neural Network (NN).

Marine radar-image sequences are also used to determine ocean surface elevation image sequences [2], [3], wave groups [4], current fields and bathymetry in inhomogeneous areas like coastal zones or areas with current gradients [5]. Further radar images are operationally measuring two-dimensional wave-spectra and significant wave heights [6], and the mean near surface current [7].

The local wind field generates a small-scale roughness on the sea surface. This small-scale roughness induces the radar backscatter and therewith the mean radar cross section (RCS). This allows the backscatter to be empirically related to the wind. The small scattering elements are oriented in the wind direction. Therefore, the RCS of the sea surface depends on the wind speed and on the azimuthal angle between the antenna viewing direction and wind direction. Due to this dependency the wind vector can be deduced from radar images of the sea surface.

In this paper wind gusts are extracted from the radar-image sequences by applying filtering techniques to remove signals not due to the local wind field, e.g. ocean waves. Thereby a radar-image sequence is sub-divided into two or more sub-sequences (typically 27 images), which may overlap each other in time. Each subsequence is then integrated over time to remove signatures with higher temporal variability, e.g., ocean surface waves. Only static patterns and signatures with frequencies lower than the integration time remain. Additionally the dispersion relation of surface waves enables to locate the signal of surface gravity waves within the wave-number frequency domain of a Fourier-transformed radar image-sequence [7]. The method generates radar images where the backscatter effects of wind gusts are visible. From these two or more radar images the movement of wind gusts and therewith the velocity and direction of the wind pattern of each point in the investigated area is determined using tensor-based motion estimation techniques.

The investigated radar-image sequences were recorded by the wave monitoring system (WaMoS), which has been developed at GKSS Research Center. For verification of the OFM the gust propagation directions from more than 1300 radar-image sequences from the Norwegian Oil Platform "Ekofisk 2/4k" are compared with in-situ data from a wind anemometer and with directions derived by the LGM.

II. INVESTIGATED DATA

A nautical radar operates at 9.5 GHz (X-band) with horizontal (HH) polarization in transmit and receive near grazing incidence. It covers an area within a radius of ≈ 2000 m with a resolution of ≈ 12 m in range. The radar antenna rotates with period 2 s. All analyzed data sets were taken by the Wave Monitoring System (WaMoS), that enables digitizing time series of sea clutter images. The here investigated 8 months of radar-image sequences from February until September 2001, representing 1332 acquisition times with wind speeds up to 17 ms⁻¹ and were recorded in the Norwegian Ekofisk oil field from platform "2/4k". Each image sequence consists of 32 images representing ≈ 82 s. Fig. 1 shows the platform Ekofisk 2/4 k, the location of the installed radar system and an example radar-image sequence. For comparison the wind speed and direction were measured by an wind anemometer and a wind vane, mounted close to the radar antenna.
filtered out. The filtered image sequence $\sigma'(\vec{r}, t)$ is retrieved by performing an inverse 3-D FFT. The moving average $G(\vec{r}, \tau)$ is determined.

Under the assumption the image brightness $G(\vec{r}, \tau)$ changes only due to motion of the wind pattern (frozen turbulence), the total time derivative needs to equal zero:

$$ (\nabla G)^T f + G_t = 0, \quad (3) $$

where $f = [f_x, f_y]^T$ denotes the optical flow (velocity components), $\nabla G$ defines the spatial gradient, and $G_t$ is the partial time derivative $\partial G/\partial t$. Assuming the optical flow to be constant within a small neighborhood $U$, (3) is solved by a local weighted least squares estimate of (3) on individual pixels within $U$ [9]. This yields into a linear equation system:

$$ \begin{bmatrix} \langle G_x G_x \rangle & \langle G_x G_y \rangle \\ \langle G_y G_x \rangle & \langle G_y G_y \rangle \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix} = - \begin{bmatrix} \langle G_x G_t \rangle \\ \langle G_y G_t \rangle \end{bmatrix}. \quad (4) $$

with

$$ \langle a \rangle = \int_{-\infty}^{\infty} U((\vec{r} - \vec{r}^\prime)) a d\vec{r}^\prime, \quad \langle G_y G_q \rangle = B(D_p \cdot D_q), \quad (5) $$

where $B$ is a smoothing operator, and $D_p, D_q$ are first-order derivative operators in spatial-temporal directions. Thereby optimized 3-D Sobel operators for computation of the derivatives are applied by derivation in the proposed direction (x, y, or t) and smoothing in the orthogonal directions [9]. Its solution $(f = A^{-1})b$ gives the estimated local velocity at each point of $G(\vec{r}, t)$ in space and time. With this technique wind fields can be investigated spatially and temporally and no calibration of the images or training of a NN is necessary.

Before computing the optical flow, the mean RCS images of $G(\vec{r}, t)$ are iteratively smoothed and sub-sampled to obtain a so-called Gaussian pyramid. The image reduction is necessary, because the wind gusts have a typical spacing of 100 m to 500 m.

After computing all local velocity components, some points have to be discarded. A zero-determinant of matrix $A$ of (4) gives those points, where no optical flow is determinable. Due to the applied convolutions the image-border points in space and the first and last images in time are not usable. Areas with other information like shadows or platform structures are masked out.

All usable local velocity components within a sub-area of interest are smoothed. The main wind direction $\Phi$ is then selected from a smoothed histogram of the calculated local wind directions. The main wind direction is defined by the global maximum in the histogram.

Fig. 2 shows an example image of a retrieved time series of a high-resolution wind-vector field. The mean wind direction of $\Phi = 128^\circ$ agrees excellent with the in-situ value $\Phi = 126^\circ$. The modulus of the wind vectors gives the local gust velocity. The measured average wind speed of 14 ms$^{-1}$ is in good agreement with the in-situ wind speed of 15 ms$^{-1}$. Areas with a strong variability are visible.
IV. VALIDATION

The wind gusts are visible in the generated moving averages of the radar-image sequences (see Fig. 2) and propagate globally aligned in wind direction. Using the optical flow based motion estimation as introduced in this paper the propagation directions of the gust are determined.

In this paper the OFM is tested with data sets from Ekofisk for comparison with measurements made before with the LGM, and because of the huge amount of available acquisition times. From each radar-image sequence with $N_t = 32$ images a temporal 27-moving average has been determined, consisting of $N_r = 5$ images. Thereby each image is an average of 27 radar images. 5 images are a minimum requirement, because the temporal convolution process is only exact at the inner points of the convolution-filter mask. This makes the first and last images unusable. The number of those discarded images is dependent on the width of the applied convolution mask. E.g., for the applied 3x3x3 optimized Sobel-Filter and following additional binomial filtering processes only the center image of the moving average sequence with 5 images can be used. Therefore only the resulting velocity components, determined by the OFM, of the center image (image 3 of 5) of the moving average are further processed.

For comparison with in-situ wind vectors and wind vectors from the LGM, all usable local velocity components within the whole center image are smoothed. The main wind vector is then selected from smoothed histograms of the calculated local wind directions and wind velocities.

Fig. 3 gives two scatter plots with in-situ wind directions and wind speeds against the radar retrieved values by OFM. The retrieved directions by the OFM are within the given reference directions (Fig. 3a). The correlation coefficient is $\approx 0.96$ and the standard deviation is $32^\circ$. There is a bias in the retrieved wind directions of $8^\circ$. Fig. 3b shows the scatter plot for in-situ wind speeds against main gust velocity. The correlation coefficient is $\approx 0.64$, standard deviation $2.7 \text{ ms}^{-1}$, and bias $0.5 \text{ ms}^{-1}$. Table I shows a full inter-comparison between in-situ sensor, LGM, and OFM.

For comparison with in-situ wind vectors and wind vectors from the LGM, all usable local velocity components within the whole center image are smoothed. The main wind vector is then selected from smoothed histograms of the calculated local wind directions and wind velocities.

Fig. 3 gives two scatter plots with in-situ wind directions and wind speeds against the radar retrieved values by OFM. The retrieved directions by the OFM are within the given reference directions (Fig. 3a). The correlation coefficient is $\approx 0.96$ and the standard deviation is $32^\circ$. There is a bias in the retrieved wind directions of $8^\circ$. Fig. 3b shows the scatter plot for in-situ wind speeds against main gust velocity. The correlation coefficient is $\approx 0.64$, standard deviation $2.7 \text{ ms}^{-1}$, and bias $0.5 \text{ ms}^{-1}$. Table I shows a full inter-comparison between in-situ sensor, LGM, and OFM.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
<th>wind direction [$^\circ$]</th>
<th>wind velocity [ms$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>in-situ</td>
<td>OFM</td>
<td>0.96</td>
<td>7.9</td>
</tr>
<tr>
<td>LGM</td>
<td>OFM</td>
<td>0.95</td>
<td>7.4</td>
</tr>
<tr>
<td>in-situ</td>
<td>LGM</td>
<td>0.99</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**TABLE I**

**MAIN STATISTICAL PARAMETERS RESULTING FROM COMPARISON OF 1332 WIND VECTOR VALUES BETWEEN IN-SITU SENSOR, LGM, AND OFM.**

V. SUMMARY

A new method, called OFM, for retrieval of high-resolution ocean wind field sequences from marine radar-image se-
sequences was introduced and applied on data sets from the Ekofisk oil field. The method determines the local velocity of wind gusts, which can be extracted in the radar-image sequences. This is done by determining a temporal n-moving average from an image sequence. Only static patterns and signatures with frequencies lower than the integration time remain. In this temporal moving average the movement of wind gusts and therewith the velocity and direction of the wind pattern of each point in the investigated area is determined using tensor-based motion estimation techniques under the assumption of frozen turbulence.

The OFM was compared to in-situ wind measurements considering a data set of 1332 radar-image sequences with co-located wind measurements up to 17 ms$^{-1}$. Further the retrieved gust propagation directions and velocities were compared to wind vectors that were extracted by the LGM.

Comparison of the directions to in-situ data resulted in a correlation of $\approx 0.96$ and a standard deviation of 32°, similar as compared to the orientations retrieved by the LGM from the wind streaks. Comparison of the main wind gust velocities to in-situ wind speeds resulted in a correlation of 0.67 and a similar standard deviation. The minimum retrievable gust velocity is $\approx 4$ ms$^{-1}$ due to the ocean surface roughness dependency of the RCS.

The presented comparisons are preliminary results. The quality of these results is strongly dependent on the number of given images in the moving average. For the Ekofisk data sets, that have been used here, only 5 images could be used. By increasing the number of radar images per data set to 64, 128, or 256 it is expected that the results strongly improve. Such long radar-image sequences are recently investigated. Fig. 4 shows the result of such a long-time image sequence that consists of 256 images and has been recorded from a mixed-cargo vessel during a journey in the East Atlantic in 2000. Thereby a high-resolution ocean wind field image sequence could be retrieved giving information about the spatial-temporal properties of the near surface wind field in the measurement area.

The OFM can also be used to remove the 180° ambiguity of wind orientations derived from wind-induced streaks.

ACKNOWLEDGMENTS

The authors were supported by the European Commission in the framework of the EU project MaxWave. All radar-image sequences were kindly made available by the company OceanWaves.

REFERENCES