CopterCurrents
High Resolution Surface Current Fields
Measured by a Small UAV

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ABSTRACT

Within this paper, we describe a methodology called CopterCurrents to retrieve high-resolution ocean surface currents utilizing video sequences of ocean surface gravity waves. The video sequences were acquired by an off the shelf quadcopter utilizing a small, nadir looking 4k video camera. For stabilization of the video, the camera is mounted on an actively controlled gimbal. For geocoding of the video data, the aircrafts data logger records all flight data collected by the drone. Within the first processing step, the data are corrected for lens distortion and geocoded to a rectilinear coordinate system at water level. In the next step, the directions, lengths as well as phase velocities of the imaged surface waves are extracted from the geocoded video sequence. Finally, the properties of the surface waves are used to estimate the surface current vector, by retrieving the difference of the observed phase velocities to that given by the linear dispersion relation of surface gravity waves. To demonstrate the capability as well as applicability of CopterCurrents, we acquired video sequences in different environments and compared the resulting current fields to measurements obtained by other instruments such as an acoustic Doppler current profiler.

Keywords: Surface currents, ocean waves, video processing, UAV, drone, remote sensing, dispersion filter

1. INTRODUCTION

High-resolution surface current fields in rivers and coastal areas are of major interest for engineers and researchers. In particular as the currents are one of the most important drivers of morphological changes and often a major source of complications for engineering projects. Therefore, 2D current maps with high spatial and temporal resolution are an important source of information for the design and planning of engineering projects. In general, the measurement of 2D surface current fields with high spatial and temporal resolution is challenging and very costly to obtain. Typically, surface currents are measured by acoustic Doppler current profilers (ADCP), which measure the speed and direction of a fluid at a single point (Eulerian measurements) along a vertical profile, or by surface drifters, which describe the path of a water body at the surface (Lagrangian measurement). To obtain a surface current map in space and time, land based high frequency (HF) radars are often used [1]. Unfortunately, HF-radars measure surface current fields with spatial resolutions > 500 m and temporal resolutions > 30 minutes. In order to overcome these limitations, numerical circulation models are utilized, which are complex, require a lot of additional input such as bathymetry and tidal levels, and are still not an ideal solution for high-resolution current fields. In the last decade, microwave radars (marine radars) have been utilized to obtain surface currents [2]. However, the methods utilized for marine radars are limited to the smallest waves the radars can resolve, which are typically > 15 m and therefore often a drawback in inlets, harbors and rivers as well as under low wind and wave situations.

Within this paper a very cost effective method is being introduced and applied to retrieve ocean surface currents utilizing a video sequence of surface waves that are acquired in the range of visible light by an off the shelf drone. The methodology is based on the dispersion relation of ocean surface gravity waves [3], which has been successfully applied to marine radar image sequences [4, 5] as well as to airborne video sequences [6]. In contrast to the previous airborne application [6], today's off the shelf quadcopters allow to geocode video imagery without the need of ground control points within the image utilizing a truly low cost instrument [7, 8]. The methodology can also be extended to estimate the vertical current shear near to the surface by considering waves of different wave lengths.

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2. ACQUISITION SYSTEM

All video data utilized within this study were acquired with the Phantom 3 Professional, an off the shelf quadcopter from DJI (Figure left hand side). The Phantom 3 carries an Ultra-High Definition (4069 x 2160 pixel) video camera with acquires video imagery with a frame rate of up to 25 Hz. The camera is equipped with a 1/2.3 CMOS chip and a 20 mm (35 mm format equivalent) rectilinear lens with f/2.8 at ∞. The lens covers a 94° field of view with near to no barrel distortion as well as negligible chromatic aberration. At a flight height of 100 m the pixel resolution is approximately 0.04 m. For stabilization of the camera, the quadcopter is equipped with an active 3-axis gimbal, which very successfully accommodates for pitch, roll and yaw movements of the aircraft (Figure 1 right hand side). The pitch can be controlled within -90° to +30° at a maximum angular speed of 90°/s and an angular control accuracy of ±0.02°. For all video acquisitions within this paper, the camera was operated at nadir (down looking) and set to Ultra-High Definition (4069x2160 pixel) with a frame rate of 25 Hz. All videos were stored on the cameras internal Micro SD card.

Figure 1: On the left hand side the Phantom3 Professional from DJI on the right hand side the Brushless gimbal with the 4K video camera mounted below the aircraft.

The automatic hovering system of the Phantom 3 Professional allows an accuracy of the selected position within ± 0.5 m in the vertical and ± 1.5 m in the horizontal. The hovering accuracy is maintained at wind speeds of up to 8 m/s. During the entire flights all flight information, such as geographical position, height, heading as well as the tilt, roll and yaw angle of the aircraft and gimbal are recorded by the aircrafts data logger. The positioning and gimbal accuracy as well as the geocoding has been investigated by Holman et al. [9] showing an overall excellent performance for observation of the ocean surface.

3. METHODOLOGY

In a first step all video data are corrected for the lens distortion and then geocoded to a rectilinear coordinate system at the level of the water surface (UTM 32). For this purpose the quadcopters recorded telemetric data, e.g. latitude, longitude and flight height, are utilized. To show the overall performance of the system a video image sequence of the Elbe River was acquired near the city of Lauenburg, Germany (Figure 2). For this sequence, the quadcopter was hovering over the river acquiring several minutes of video data. Within the video sequences (typically 30 to 60 s) the propagation of surface waves can be observed in space and time. These videos allow to measure surface wave properties such as the wave length and phase velocity, which in turn enable to retrieve the surface current vector. The surface current results from the difference of the observed phase velocity to that given by the linear dispersion relation of surface gravity waves,

$$\omega = \varpi(\boldsymbol{k}) = \sqrt{g\ k\ tanh(k\ d)} + \boldsymbol{k} \cdot \boldsymbol{U} = \varpi_0(k) + \boldsymbol{k} \cdot \boldsymbol{U}, \tag{1}$$

were $\boldsymbol{k}$ is the wave number vector, g the gravitational force, d the water depth and $\boldsymbol{U}$ the two-dimensional near-surface current, commonly known as velocity of encounter. This physical property of surface waves is also being utilized very successfully for retrieving ocean surface currents from HF-radar [1] as well as from marine radars [4, 5].

At an altitude of 100 m the ground resolution is approximately 0.04 m, which allows resolving wave lengths greater than 0.08 m. In the following example of the Elbe River the investigation has been limited to surface waves within 0.3 m and 3 m. Due to the high frame rate of 25 Hz aliasing [3, 8] is a minor issue when analyzing these data sets and has been neglected. In a next step, the geocoded video data are transformed from the space-time domain into the wavenumber-frequency domain using a 3D Fast Fourier Transformation (FFT). In the wave number frequency domain the energy of the

Figure 2: Single image from the video sequences of the Elbe River collected in front of Lauenburg, Germany.

surface gravity waves is located on the so-called dispersion shell, which is defined in (1). Figure 3 shows a wavenumber frequency plain with the dispersion shell (curve) fitted to the data. The shape of the dispersion shell is changed due to the velocity of encounter, which is the sum of the drone's velocity and of the near surface currents. Within the final step, the velocity of encounter is estimated by a simple least squares fitting technique [3, 8]. Finally, the surface current is retrieved

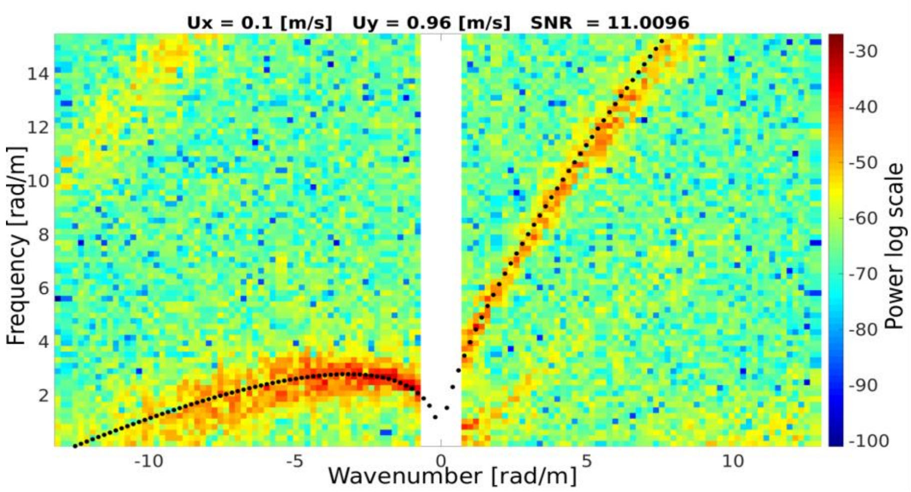

Figure 3: Wave number frequency plain along the main flow direction of the Elbe River retrieved from a box of 20 m x 20 m in the main flow of the Elbe River (yellow square indicated in Figure 2).

by removing the contribution of the drone's movement from the velocity of encounter. This entire method is named "CopterCurrents" and the source code, designed in MATLAB, has recently been made available at the GitHub depository (https://github.com/RubenCarrascoAlvarez/CopterCurrents).

Within this study, the methodology has been extended to retrieving surface current shear by extracting the currents for different wave number intervals [10]. As the retrieved currents are a weighted average of the current at the surface down to the penetration depth of the wave (approximately half the ocean wavelength), the current shear can be retrieved by estimating the currents at different wavenumber intervals. The contribution to the surface currents are largest at the surface and decrease exponentially with depth. In case of a linear current profile, the video-derived current corresponds to an effective depth of 7.8% of the wavelength.

4. RESULTS

To test the entire methodology several flights were performed over the Elbe River at the city of Geesthacht and Lauenburg, Germany. In a first attempt video data were collected from the weir across the Elbe River at Geesthacht, were the current direction and flow pattern in front of the open gates of the weir are nicely depicted by the current field retrieved via CopterCurrents (for details, refer to Horstmann et al. [7]). An initial validation of the methodology was performed at the Elbe River in front of Lauenburg (Figure 2). The drone-retrieved currents (Figure 4) were compared to ADCP data collected by a small boat over the entire area imaged by the drone. These results showed an overall root mean square error of 0.09 m/s with a negligible bias [8].

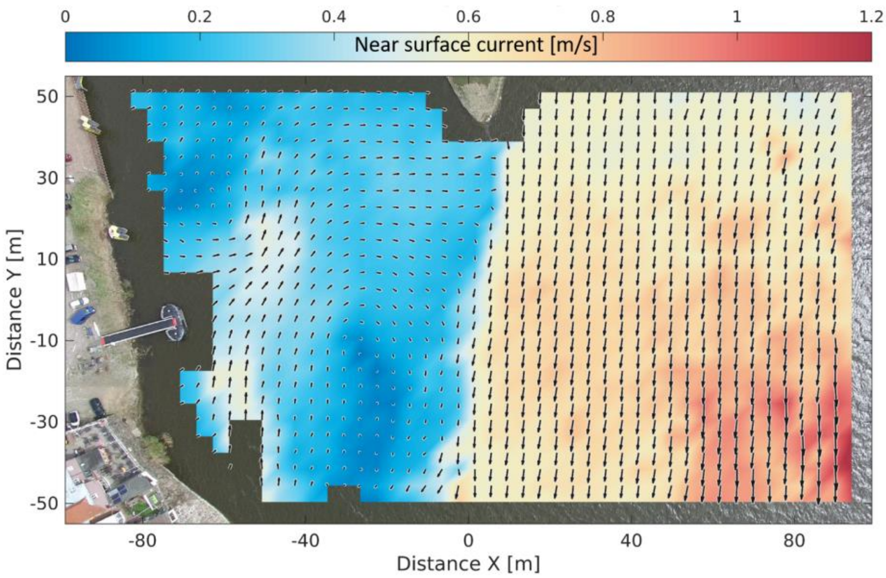

Figure 4: Surface current field resulting from the image sequence of the Elbe River (Figure 2) in front of Lauenburg.

Within this study, the CopterCurrents method is extended to retrieve the upper surface current shear by estimating the currents from different intervals of wavelengths. For testing the method two areas were selected in the Elbe River in front of Lauenburg as indicated in Figure 5 and 6. The first area is located in a channel to the port of Lauenburg with very low

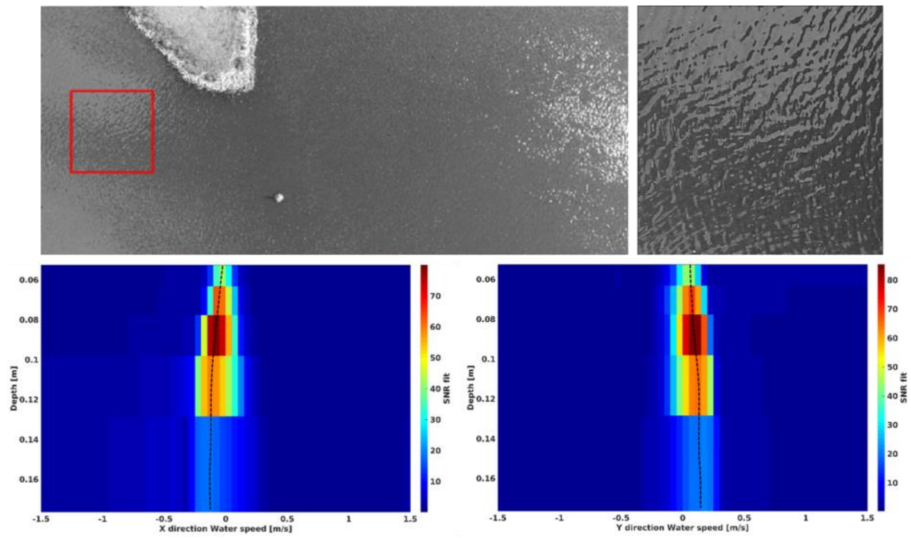

Figure 5: Surface current shear in the channel to the port of Lauenburg with low current speeds. The shear in X-direction (lower left) and Y-direction (lower right) as retrieved from the video data.

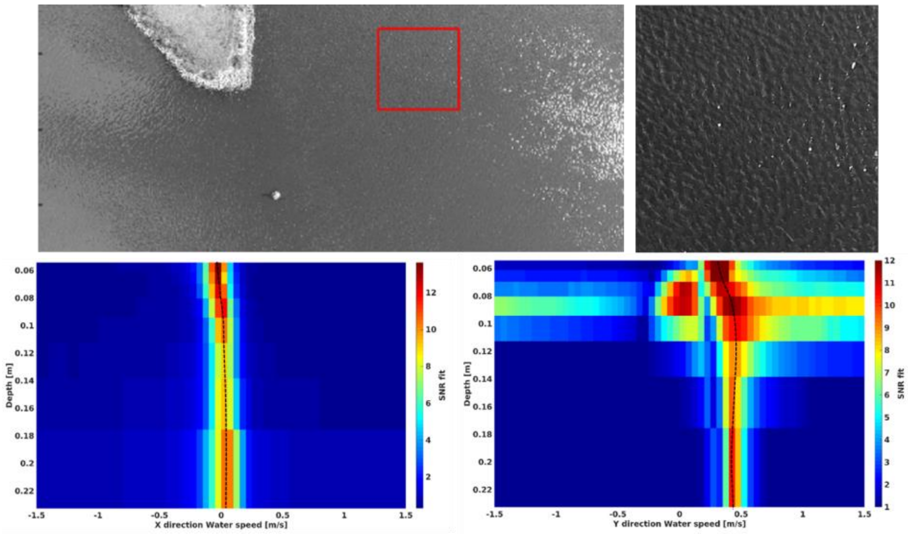

Figure 6: Surface current shear in the main flow of the Elbe River with current speeds of 0.5 m/s. The shear in X-direction (lower left) and Y-direction (lower right) as retrieved from the video data.

currents (Figure 5) and the second within the main flow of the Elbe River (Figure 6). During the acquisition, the winds were blowing upstream with approximately 7 m/s. Within the channel to the port of Lauenburg (Figure 5) there is nearly no vertical shear in X- and Y-direction, respectively. Note, that in this case the shear can only be estimated in the upper 0.12 m due to the lack of longer waves. The vertical shear in the main flow of the Elbe River is depicted in Figure 6. A significant shear can be observed in the upper 0.1 m in particular along the main flow direction.

5. CONCLUSION AND OUTLOOK

A methodology, namely CopterCurrents, was developed to extract surface current fields with a spatial resolution of < 5 m and a temporal resolution of up 10 s utilizing video recordings of an off the shelf small drone. A preliminary validation was performed by comparing the current fields to ADCP measurements, which resulted in an overall error of < 0.1 m/s [8]. Within this study, several flights were conducted under different environmental conditions to further test the capability of the method. The video data have been converted to surface current fields and the SNR has been utilized as a first kind of quality parameter for the measurements. Due to the small size of the quadcopter, measurements can only be performed at wind speeds below 8 m/s and are limited to flight durations of approximately 20 min within a range of 1 to 2 km. The overall performance of CopterCurrents has shown very promising results under various conditions e.g. current fronts, bathymetric jumps, small scale eddies and river flow fields. Therefore, the entire source code of the CopterCurrents toolbox has been made available at the GitHub depository (https://github.com/RubenCarrascoAlvarez/CopterCurrents).

CopterCurrents has been extended to estimate the vertical current shear. The method was applied to video data acquired over the Elbe River showing significant surface shear in the upper 0.1 m. To validate the method an experiment has been carried out in the Bear Cut Inlet, in Miami, USA, in 2018. Several flights were undertaken with co-located drifter and ADCP measurements as well as by deployment of various objects in the water (e.g. bamboo plates and oranges) to retrieve the current velocity via particle tracking velocimetry (PTV) from the drones video data. The main goal of the Bear Cut Inlet experiment was to investigate the upper surface shear observed with the extended version of CopterCurrents in more detail. Preliminary results showed a clear dependence of the copter retrieved surface currents on the local wind conditions in particular in the upper 0.1 to 0.2 m. An in depth analysis of the data is ongoing. The results will be presented during the Maritime Situational Awareness Workshop in Lerici, Italy and will be published shortly.

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