

Predicting instantaneous subsurface velocity using surface velocity

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INTRODUCTION

Instantaneous measurements of water velocity at depth in the nearshore are rich with information about orbital velocities, longshore and cross shore currents, and forces that lead to sediment transport. Yet measurements of detailed subsurface velocities are scarce owing to the difficulties involved in installing and maintaining instruments such as acoustic velocimeters in high energy environments like the surf zone [Thornton & Guza, 1986]. Deploying in-situ instruments to measure velocity profiles often involves heavy machinery (e.g. cranes, waterjets, tripods, boats) and after deployment the instruments can be buried, broken, or biofouled owing to strong waves, currents, and biological activity. To address these difficulties, researchers have been developing and improving remote sensing methods capable of measuring wave height, wave period, bathymetry, and surface current velocity, among other useful nearshore parameters [Holman & Stanley, 2007; Brodie et. al., 2018; O’Dea, 2021]. Specifically, Chickadel et. al. [2003] and Holland et. al. [2001] show that cameras and particle image velocimetry (PIV) techniques can be used to accurately measure the velocity at the surface in the surf zone. Here, we build on these recent advances in coastal remote sensing by exploring how remote camera measurements can be used to quantify the relationship between the cross-shore components of instantaneous velocity at the surface, u_s and the corresponding velocity at depth in the water column, u_{wc} . This work aims to address the question: how well can we use velocity at the surface and linear wave theory to obtain information about velocities at depth in the nearshore?

METHODOLOGY

We collected instantaneous velocity data at the Field Research Facility (FRF) in Duck, North Carolina on May 14th and 15th of 2015. To measure velocity in the water column, we installed a cross shore transect on the north side of the FRF pier consisting of four acoustic doppler velocimeters (ADV) (Figure 1). To measure velocity at the surface, we relied on video footage taken from the upper platform of the coastal research amphibious buggy (CRAB). The camera was approximately 8m above the water surface and the field of view (FOV) was centered on each ADV angled towards the longshore. We used the Argus suite of open-source computer vision software to remove the distortion caused by the wide-angle lens on the GoPro Hero4 Black. Using the undistorted frames, we used PIVlab [Thielicke & Stamhuis, 2014], a Matlab based PIV program, to derive an array of velocity vectors for each video frame. We took the spatial mean of the velocities in the PIV region of interest, then downsampled the u_s time series from 30Hz (camera recorded at 30 frames per second) to match the ADV frequency of 2Hz.

The ADV data was processed following Elgar et. al. [2001 & 2005]. We obtained the wave and wind environmental conditions for the times that the videos were recorded on May 14 and 15th from a wave buoy in 17m water depth and wind gauge at the end of the FRF pier.

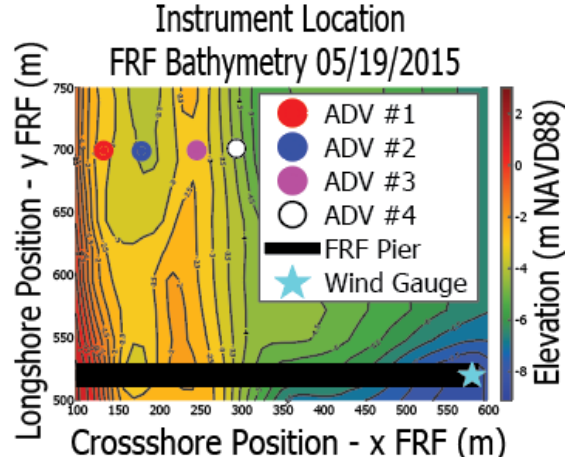


Figure 1: FRF bathymetry (colored contours, blue is deep and red is shallow) on 5/19/2015 overlaid by ADV locations (red, blue, pink, and white circles), FRF pier (black line), and location of the wind gauge (teal star)

Once we had camera measurements of u_s and ADV measurements of u_{wc} , we compared the spectral energy distribution of u_s and u_{wc} during each video to validate the velocity of the surface measured using the PIV method. To translate u_s observed by the camera to the depth of the ADV and maintain directionality, we used the square root of the velocity variance equation (Eq. 1), derived from the orbital velocity equation [Elgar et. al., 2001]:

$$u_{wc_p} = u_s \frac{\cosh(kz_{wc})}{\cosh(kz_s)} \quad (1)$$

where z_s is the water depth at the surface ($z_s=0$), z_{wc} is the water depth of the ADV measurement volume, u_s is the surface velocity, u_{wc_p} is the predicted velocity at depth, and k is the wave number. We used the pressure data from the ADV to calculate k , which was the same for both z_s and z_{wc} . We quantified the error between the calculated (Eq 1) and measured u_{wc} with the normalized RMSE (nRMSE).

RESULTS

The spectral analysis shows that u_s and u_{wc} have a very similar peak frequency (Figure 2). This is in good agreement with the peak frequency measured offshore in 17m water depth, 0.21Hz, considering that wavelength decreases due to shoaling and diffraction as waves propagate to shore and water depth decreases [Holman & Haller, 2013]. There is more energy at the surface than within the water column and this difference increases as frequency increases which is consistent with theory and observations that show orbital velocity magnitude is attenuated with depth [Craig, 1996] and more energy is attenuated higher in the water column in higher frequency waves [Wiberg & Sherwood, 2008].

The velocity variance (Eq 1) predicted u_{wc_p} from camera measurements with moderate skill for each of the five videos (Figure 3). Across all five videos, the nRMSE

value was 14.04%.

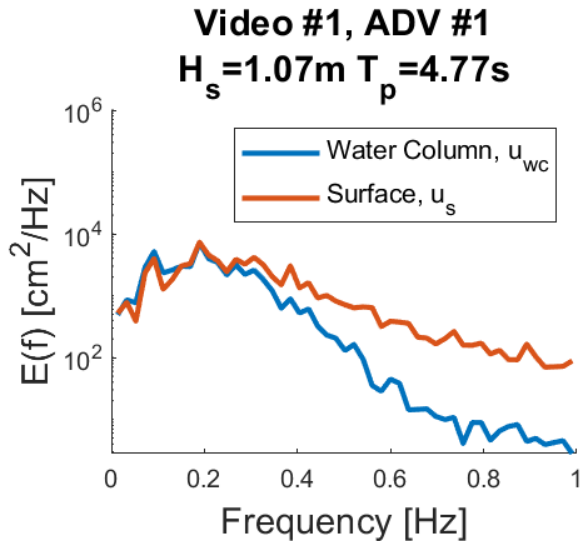


Figure 2: Example of the power spectral density (y-axis) vs frequency (x-axis) of co-located cross-shore velocity measurements at $z = -1.42\text{m}$ below mean water level (blue), and at the surface (orange) for Video #1.

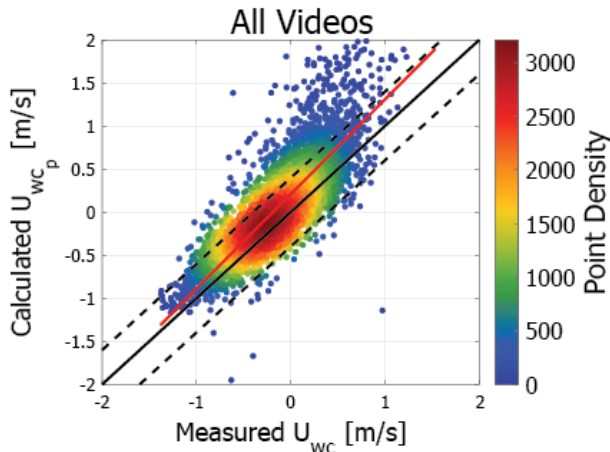


Figure 3: Predicted u_{wc_p} (y axis) vs measured u_{wc} (x axis) for all instances of camera measurements (dots). Lines are 1:1 slope (solid black), the linear fit (red), and one standard deviation (dashed black). The color spectrum shows point density, where red is a larger amount of observations in time and blue is a smaller amount of observations. The bulk of the observations occur along the 1:1 line where waves are small. Accuracy is increased in the trough (negative), especially for larger waves, compared to crests (positive).

These results suggest that a relationship between the velocity at the surface and at depth, derived from linear wave theory, is capable of translating the velocity down the water column in the surf zone with some skill (<15% nRMSE). This suggests surface camera measurements may be used to calculate a depth profile of velocity in shallow water, though more experiments are needed to refine the relationship. For instance, this method relies on water depth to calculate wave number. We will discuss

how the camera derived velocity accuracy varies with incident wave conditions across the video measurements, and the potential of combining our method with algorithms such as cBathy [Holman et. al., 2013]. We thank DoD, NSF, and Northeastern University for funding, and Steve Elgar, Britt Raubenheimer, the WHOI field crew, and the CHL FRF for the data and field assistance.

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