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Evaluation of video-based linear depth inversion performance and applications using altimeters and hydrographic surveys in a wide range of environmental conditions

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ABSTRACT

The performance of a linear depth inversion algorithm, cBathy, applied to coastal video imagery was assessed using observations of water depth from vessel-based hydrographic surveys and in-situ altimeters for a wide range of wave conditions ($0.3 <$ significant wave height < 4.3 m) on a sandy Atlantic Ocean beach near Duck, North Carolina. Comparisons of video-based cBathy bathymetry with surveyed bathymetry were similar to previous studies (root mean square error (RMSE) = 0.75 m, bias = −0.26 m). However, the cross-shore locations of the surfzone sandbar in video-derived bathymetry were biased onshore 18–40 m relative to the survey when offshore wave heights exceeded 1.2 m or were greater than half of the bar crest depth, and broke over the sandbar. The onshore bias was 3–4 m when wave heights were less than 0.8 m and were not breaking over the sandbar. Comparisons of video-derived seafloor elevations with in-situ altimeter data at three locations onshore of, near, and offshore of the surfzone sandbar over ~1 year provide the first assessment of the cBathy technique over a wide range of wave conditions. In the outer surf zone, video-derived results were consistent with long-term patterns of bathymetric change ($r^2 = 0.64$, RMSE = 0.26 m, bias = −0.01 m), particularly when wave heights were less than 1.2 m ($r^2 = 0.83$). However, during storms when wave heights exceeded 3 m, video-based cBathy over-estimated the depth by up to 2 m. Near the sandbar, the sign of depth errors depended on the location relative to wave breaking, with video-based depths overestimated (underestimated) offshore (onshore) of wave breaking in the surfzone. Wave speeds estimated by video-based cBathy at the initiation of wave breaking often were twice the speeds predicted by linear theory, and up to three times faster than linear theory during storms. Estimated wave speeds were half as fast as linear theory predictions at the termination of wave breaking shoreward of the sandbar. These results suggest that video-based cBathy should not be used to track the migration of the surfzone sandbar using data when waves are breaking over the bar nor to quantify morphological evolution during storms. However, these results show that during low energy conditions, cBathy estimates could be used to quantify seasonal patterns of seafloor evolution.

1. Introduction

Accurate observations of surfzone bathymetry are critical to simulating nearshore waves and currents and the subsequent sediment transport and morphological change, as well as storm-induced overtopping and flooding. Vessel-based acoustic hydrographic surveys provide temporally infrequent, but spatially dense data, whereas in-situ acoustic altimeters provide temporally dense, but spatially sparse observations of seafloor elevation (Moulton et al., 2014). Both acoustic techniques provide bathymetric data with errors on the order of 0.1 m across the surf zone. Depth inversion methods using optical, infrared, and radar imagery estimate bathymetry from wave speed observations with

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high spatial and temporal resolution (Holman et al., 2013), but accuracy over a range of environmental conditions is not well quantified. Although in development for more than 20 years, remote sensing methods rarely have been used in applied coastal engineering projects to quantify surfzone bathymetry, and initial tests to calculate surfzone sediment volumes have poor skill (Rutten et al., 2017). A potential application is to use the data as boundary conditions for numerical models of surfzone processes (Radermacher et al., 2014; Díaz Méndez et al., 2015; Smith et al., 2017). For example, using remotely sensed data to estimate the position of the sandbar in a surfzone bathymetric grid significantly increases the fidelity of numerical simulations of surfzone circulation (Holman et al., 2014; Wilson et al., 2014). Another application is to use the data to track sediment exchange between the beach and surfzone sandbar for regional sediment management (Moritz et al., 2007). Improved assessment of algorithm skill in a wide range of environmental conditions, and evaluation of the ability of remote-sensing-based bathymetry estimation techniques to quantify surfzone sandbar morphology and seafloor evolution through time are needed for practical implementation in coastal engineering.

Optical nearshore remote sensing techniques exploit the image signature of shoaling and breaking surface gravity waves in the surf zone (Holman and Stanley, 2007). The morphology of surfzone sandbars can be estimated qualitatively from time-averages of pixel-intensities that map where waves break (Lippmann and Holman, 1990; Alexander and Holman, 2004). In addition, surfzone bathymetry can be estimated quantitatively from time-averaged images of wave breaking (a proxy for wave dissipation) that are assimilated into numerical models that solve for water depth (Aarninkhof et al., 2005; van Dongeren et al., 2008), as well as from wave speeds estimated from the video imagery using either linear (Stockdon and Holman, 2000; Dugan et al., 2001a) or nonlinear (Holland, 2001; Catálan and Haller, 2008) dispersion relationships.

The cBathy algorithm (Holman et al., 2013) requires a time series of imagery of waves in intermediate and shallow water to estimate depth. The algorithm combines cross-spectral phase measurements with a weighted nonlinear least-squares solution to the linear dispersion equation (Plant et al., 2008). The temporal evolution of cBathy-estimated bathymetry is smoothed with a time-averaging Kalman filter based on present and prior bathymetric estimates along with uncertainty estimated from the least squares fit. Video-based cBathy bathymetry estimates have been compared with vessel-based bathymetry surveys for a range of beaches (Table 1), but rarely with waves bigger than 1.7 m, and never for waves bigger than 2.0 m because of the difficulty of performing in-situ surveys in the presence of large waves. Root mean square differences between cBathy-estimated and surveyed seafloor elevations in previous studies range between 0.51 and 2.05 m (Table 1, (Holman et al., 2013; Rutten et al., 2017; Radermacher et al., 2014; Holman and Stanley, 2013; Wengrove and Henriquez, 2013; Bergsma et al., 2016)). Errors frequently are largest in shallow water near the shoreline, where (1) linear theory may not be valid; (2) the rapid cross-shore depth changes (over a cBathy sample domain or smoothing distance) cannot be resolved; and (3) wave speed estimates can be distorted by wave runup. Errors in cBathy depth estimates are correlated with wave height and water depth in some locations (Holman et al., 2013). cBathy estimated uncertainties may be related to observed errors, but are often too small in magnitude (Holman et al., 2013), and have not been evaluated during storms.

Sources of error in cBathy include inaccurate parameter extraction from the imagery data and inaccurate representation of the physics (e.g., environmental conditions outside of the algorithm assumptions). For example, the linear dispersion relationship may be inaccurate as waves shoal and break in the surf zone, underestimating wave speeds by 20–40% (Holland, 2001; Catálan and Haller, 2008; Guza and Thornton, 1980; Thornton and Guza, 1982; Elgar and Guza, 1985a; Okamoto et al., 2010). The implementation of linear theory in (Holman et al., 2013) may be inaccurate as waves shoal and become nonlinear, as well as near the shoreline as waves break and transition to swash (Inman et al., 1971; Suhayda and Pettigrew, 1977). Incorporating wave nonlinearity into bathymetric inversions from wave speed reduced errors inside the breakpoint to O(10%) in a laboratory study (Catálan and Haller, 2008), similar to the performance of linear wave theory outside the surf zone. The performance of cBathy when wave height exceeds 2 m has not been evaluated, and thus, it is unclear how errors in the estimated phase speeds of nonlinear waves breaking over the sandbar affect the estimation of the bathymetry.

Here, new field measurements are used to assess video-based cBathy estimates of the position and movement of nearshore sandbars and of seabed elevation changes over seasonal time-scales for a large range of wave conditions ($0.3 < H_s < 4.6$ m, where the significant wave height H_s is defined as 4 times the standard deviation of sea-surface-elevation fluctuations) on a micro-tidal ocean beach. The bathymetry was surveyed frequently over a large area with vessel-based systems, and seabed elevation was measured nearly continuously over a year at three nearshore locations with in-situ altimeters. The high-spatial resolution vessel-based surveys were used to assess the ability of video-derived bathymetry to correctly characterize the sandbar position and elevation, the dominant morphologic feature in many sandy surf zones. The altimeter data were used to assess cBathy's performance both during a range of wave conditions and over long time periods, as well as to assess cBathy's

Table 1

cBathy Performance Statistics From Prior Work, Organized By Decreasing H_s.

Date	Hs (m)	Tp (s)	Bias (m)	RMSE (m)	Tide (m)	Location	# Obs.	Reference	Notes
2009–2011	0.25–2.00	–	0.19	0.51	0.98	Duck, NC USA	16	Holman et al., 2013	
Mar-2013 to Mar-2014	<1.65	–	0.59	0.79	–	SandEngine Netherlands	6	Rutten et al., 2017	$-10 < depth < -5$ m
Mar-2013 to Mar-2014	<1.65	–	−0.01	0.34	–		6		$-5 < depth < -1$ m
Mar-2013 to Mar-2014	<1.65	–	−0.92	0.34	–		6		$-1 < depth < 0$ m
13-Jul-13	–	7.1	−0.41	0.56	>3	Agate Beach, OR, USA	1	Holman et al., 2013	
17-May-12	1.19	5–7	0	0.52	–	New River Inlet, NC, USA	1	Holman and Stanley, 2013	
10-Apr-14	1.16	10.5	–	1.06	2.78	Porthtowan, Cornwall, England	1	Bergsma et al., 2016	
20-Feb-13	0.64	5.8	−0.18	1.01	1.4–1.9	Kijkduin, Netherlands	1	Wengrove and Henriquez, 2013	$\widehat{h}_k$ results
17-Apr-14	0.52	10.4	–	2.05	6.03	Porthtowan, Cornwall, England	1	Bergsma et al., 2016	
01 to 04 Jul-13	<0.50	–	–	0.48–0.66	–	SandEngine, Netherlands	1	Radermacher et al., 2014	
17-Feb-13	0.22	8.5	−0.5	1.27	1.4 to 1.9	Kijkduin, Netherlands	1	Wengrove and Henriquez, 2013	$\widehat{h}_k$ results
	Average:		−0.26	0.91					