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cBathy Bathymetry Estimation in the Mixed Wave-Current Domain of a Tidal Estuary.

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ABSTRACT

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The last decade has seen considerable progress in the development of algorithms for nearshore bathymetry estimation based on celerity observations of ocean surface waves. This work has evolved into a robust algorithm called cBathy which produces operational results that compared well to 16 CRAB surveys at Duck, NC, collected over two years (bias 0.19 m, rmse 0.51 m over a 1000 by 500 analysis region). However, cBathy is presently based on a wave dispersion implementation that neglects the effects of currents. In May 2012, cBathy was tested in a tidal inlet environment at the RIVET experiment at New River Inlet, NC, a location with a complex ebb tidal delta and strong tidal currents. Initial analyses without Doppler correction to the algorithm show up to 50% overestimation of depth excursions at tidal time scales, presumably associated with wave-current effects. Data from in situ instruments at the RIVET experiment are used to test the adjustments to the algorithm needed for Doppler shifting and found to explain some, but not all, of the bias. The algorithm also estimates dominant wavelengths and wave directions associated with a suite of incident wave frequencies. Both the dominant frequencies and wave directions were found to vary systematically through the tide as the changing water depths alter dissipation and refraction patterns over the shoals.

ADDITIONAL INDEX WORDS: *Remote sensing, Argus, tidal deltas, wave-current interactions, bathymetry estimation.*

INTRODUCTION

There has long been a strong societal interest in beaches and near-coastal regions. For military interests, home coasts are a point of vulnerability while foreign coasts are locations of clandestine access. On the civilian side, coasts are magnets for recreation, preferred locations for homes and of great value to industry and commerce. Yet coasts and beaches and all of their associated infrastructure and property are increasingly exposed to the environmental threats of storms, flooding and rising sea level.

Mitigation strategies require understanding and knowledge, both of which depend on the ability to measure or predict the past and future state of the coast. Research investment has led to the growth of a competent and very helpful numerical modeling capability that represents the physics of the fluid-sediment system. But the accuracy of models is highly dependent on the quality of inputs and boundary conditions. In particular, nearshore hydrodynamics are highly sensitive to the details of nearshore bathymetry. Bathymetry, in turn, is highly variable in space and time and is notoriously difficult to measure. Thus, it appears that our ability to carry out nearshore prediction will continue to be mainly limited by the very poor availability of up to date bathymetry data.

For focused locations and durations, it is possible to use traditional survey methods to satisfy data needs. For example in 1997, accurate surveys were carried out on essentially daily basis

for 38 days in support of the large SandyDuck field experiment at the Field Research Facility (FRF) at Duck, NC. More recently, mobile jet-ski systems have been used to great advantage for short focused periods or perhaps periodic (annual) surveys (e.g. Ruggiero *et al.*, 2007). But all such efforts are expensive, logistically challenging and either sparse in time or of short duration. Basically no one can afford to support the bathymetry data needs of numerical models on ocean beaches.

This limitation has driven research efforts to find a remote sensing solution for measuring bathymetry without the expense and danger of in situ methods. One such approach, pursued in this paper, is to exploit the depth dependence of wave celerity to invert from observations of wave speed to the corresponding depth. This is not a new idea and was discussed in the literature as early as 1947 in a paper by Williams (1947) in which he described WWII efforts by allied forces to infer depth for invasion beaches based on a small number of air photos of wave progression. While this effort was not successful, improved methods for image acquisition and subsequent signal processing have led to a steady improvement in performance (e.g. Piotrowski and Dugan, 2002; Stockdon and Holman, 1996). Most recently, Holman *et al* (in review) has demonstrated robust results with high spatial resolution using a new algorithm, cBathy, that yields 50 cm rms error for large regions based on sixteen surveys that spanned two years of testing at Duck, NC.

Previous tests of cBathy have been based on open beaches away from strong currents. The goal of this paper is to discuss initial testing of cBathy in a tidal environment where both bathymetry and tidal currents affect the speed of wave propagation. It should be noted that Piotrowski and Dugan (Piotrowski and Dugan, 2002) have done this previously using three-dimensional Fourier Transforms in space and time but their method are incompatible with the spatial resolutions needed for characterizing nearshore sand bars and ebb tidal deltas.

In the following methods section, we discuss the cBathy algorithm both without and with the inclusion of mean flows. We also describe quickly the RIVET field experiment. In results, we first present the performance of cBathy on the open beach site of Duck, then those from the tidal inlet experiment. Finally we discuss some interesting observations of wave directions over the tidal inlet and particularly the changes in wave direction with tide height.

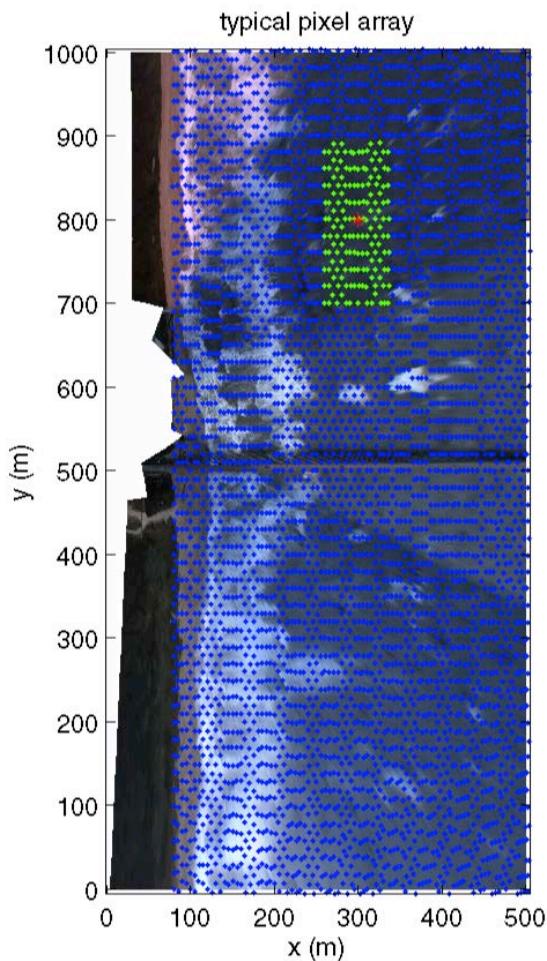


Figure 1. Typical pixel time series array for cBathy analysis at Duck, NC. 17-minute time series are collected at any point (half omitted for clarity). Wavenumbers at each analysis point (example shown as red asterisk) are based on cross-spectral phase relationships between pixel pairs in a center-weighted surrounding tile (green pixels). Background is a merged, rectified snapshot assembled from five separate camera views.

METHODS

Depth estimation in the standard cBathy algorithm exploits the linear dispersion relation, available in many texts (e.g. Dean and Dalrymple, 1991),

$$\sigma^2 = gk \tanh(kh) \quad (1)$$

where σ is the radial frequency (2π divided by the wave period, T), k the radial wavenumber (2π divided by the wave length, L), g the acceleration due to gravity and h the water depth. The algorithm includes three phases and is more complicated than can fully described here. But the heart of the algorithm in phase I is a robust method to estimate the vector wavenumber, \mathbf{k} , at a series of candidate frequencies, σ , following a method introduced by Plant *et al* (Plant *et al*, 2008). The input data are an array of 17-minute pixel time series (Holman and Stanley, 2007) at locations that span the domain with spacing appropriate for the resolution of the dominant incident waves (blue dots in Figure 1). The wavenumber at any example location (red asterisk, Figure 1) is found by fitting a planar surface to the cross-spectral phase between all pixel pairs within a center-weighted domain (green pixels, Figure 1). The two components of wavenumber are then determined from the components of the spatial gradient of that surface. The analysis point is then swept through locations in the domain to provide a map of these quantities. From the suite of frequencies and wavenumbers, a best single depth is estimated in phase II using equation (1), along with confidence intervals on that value. A map of these values is returned hourly. In phase III, these hourly estimates are averaged using a temporal Kalman filter. The many missing details from this cursory description are described in Holman *et al* (in review).

The extension of this algorithm to account for mean currents is also well known,

$$\sigma - \mathbf{k} \bullet \mathbf{U} = [gk \tanh(kh)]^{1/2} \quad (2)$$

where the extrinsic frequency, σ , is modified by a Doppler term which is the vector dot product between the wavenumber, k , and the mean flow, \mathbf{U} . The magnitude of this effect can be seen by solving for depth,

$$h = \frac{1}{k} \tanh^{-1} \left[\frac{\sigma^2 \left(1 - \frac{\mathbf{U}}{c} \cos \theta \right)^2}{gk} \right] \quad (3)$$

where c is the wave celerity ($=\sigma/k$), U the magnitude of the mean flow and θ , the angle between the directions of wave progression and current flow. Sensibly enough, the modification depends on the ratio of c and the magnitude of U in the wave direction, inverted through a hyperbolic tangent function.

Tests of the impact of tidal flows were carried out during the RIVET field campaign at New River Inlet (NRI) in May, 2012 during a large experiment to investigate the combined wave-current-bathymetry dynamics of a complex tidal inlet. Figure 2 shows the measured bathymetry for the region. Six cameras, located at the top of a 33 m tall tower at the location show by an asterisk, allowed a 200° field of view covering from the western shoreline part way into the inlet. A fixed PUV sensor, installed by Jim Thomson of the University of Washington Applied Physics Lab (APL) and mounted on a marine piling located slightly offshore from the cameras ($x = -45$, $y = -495$), provided ground truth data throughout the 21 days of sampling against which cBathy could be compared.

RESULTS

Figure 3 shows an example cBathy test from November 22, 2010, at Duck, NC. The left panel shows ground truth while the right is the cBathy result for that day. cBathy does a remarkable job reproducing the bathymetry in general but also most of the alongshore variable details of the inner bar and trough region. 16 such comparisons, computed over a two year sample period, yielded mean and rms errors of 0.19 and 0.51 m, respectively.

Figure 4 compares a phase III cBathy result for May 17, 2012, at the RIVET experiment with the ground truth map measured by the FRF staff using GPS and accurate fathometers. The pattern of the ebb tide delta and the recently dredged channel (top of figure) are well described by the cBathy result. However there are differences, for instance at the landward (left) end of the channel, some absolute depths over the ebb tidal delta and some of the details of smaller channels on the delta. The overall agreement is good, with a bias of less than 1 mm (a testament to the law of averages and a long career!) and an rms error of 0.52 m.

Hourly (phase II) cBathy depth estimates were compared to hourly depth variations due to the tide and measured by the APL pressure sensor (Figure 5). cBathy clearly sees the tide level variations but typically overestimates their magnitude. It is reasonable to speculate that these errors may be due to current-induced Doppler shifting of the dispersion relationship.

The APL fixed instrument allowed study of the magnitude of this Doppler shift to wave celerity (equation 2) based on direct measurements of time-varying depth and currents. The relative angle between the tidal currents and the directions of wave progression, θ , was different for each wave frequency but was estimated based on the individual wave direction estimates provided by cBathy. Wave direction turned out to be very sensitive to tidal elevation.

Figure 6 illustrates an example tidal cycle from May 18, 2012. The middle panel shows depth varying from a morning high tide to a mid-day low and an evening high. The lower panel shows the corresponding current magnitude expressed as the component of flow projected in the direction of the flood channel in which the APL instrument was located (positive values correspond to flood currents). Currents and tidal elevation are seen to be in phase, indicating that the tides are in the form of progressive waves in this inlet. The upper panel shows the relative depth error due to the neglect of the Doppler terms in the dispersion relationship. It is the ratio of depths found using equation (1) to those found using equation (3). The Doppler correction term in equation (3) is estimated from the in situ measurements of the current magnitude and direction combined with wave direction estimates from cBathy (to estimate θ , the relative angle between the current and wave propagation directions).

The upper panel shows that the depth error due to the neglect of the Doppler term is a depth overestimate for flood currents (when wave propagate with the flow so are faster) and an underestimate on ebb (propagation against the current). For these particular cases, the error is roughly 10-20%, in the right sense but a bit smaller than the errors seen in Figure 5. Stronger currents in the main channel would yield larger errors.

The deviation of error predictions in the upper panel of Figure 6 later in the day is related to the different directions of wave propagation for each of the analyzed frequencies. The importance of variability in wave direction is discussed in the following section.

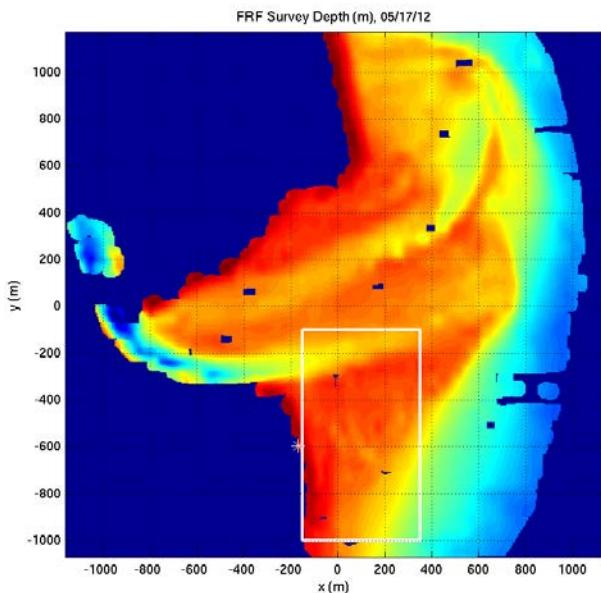


Figure 2. Surveyed bathymetry (courtesy of FRF) for May 17, 2012 with offshore to the right, inlet to the left. The white asterisk (left side of box) and box mark the camera tower location and video region of analysis, respectively. Deep blue blotches are dropouts in the interpolation due to data sparsity.

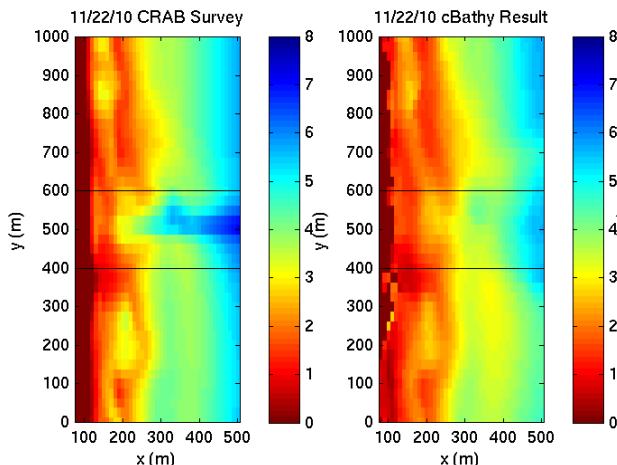


Figure 3. Ground-truth (left) and cBathy-derived (right) bathymetry (meters) for an example survey, Nov 22, 2010, at Duck, NC. The beach is on the left, open ocean on the right. A concrete pier at $y = 500$ m makes comparisons invalid in the region between the black lines since optical views are obstructed and in situ surveying interrupted. The bulk comparison mean and rms differences over 16 such surveys carried out over two years were 0.19 m and 0.51 m, respectively. Note how well sand bar details are estimated.

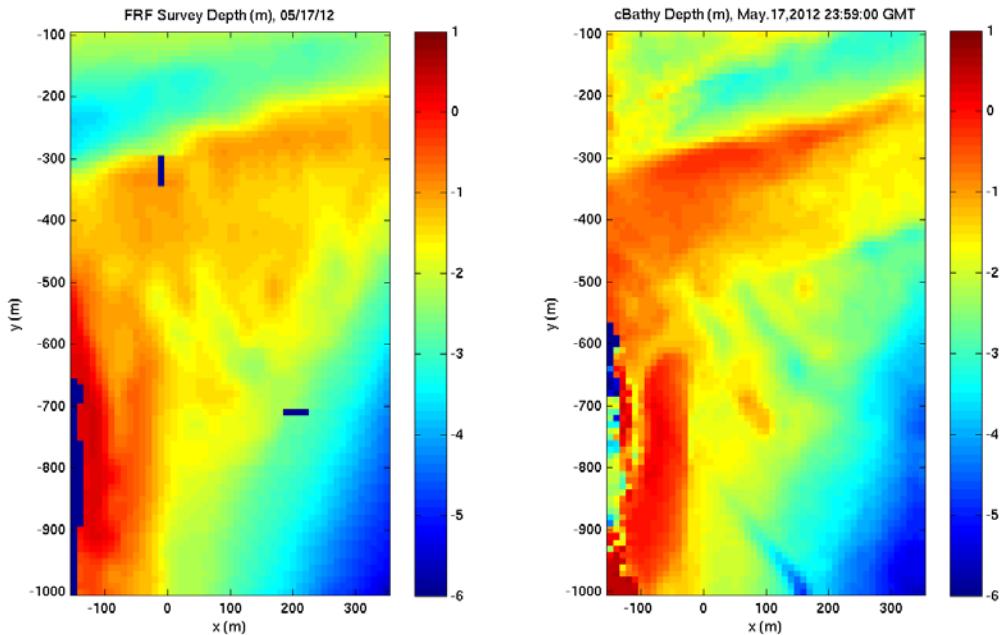


Figure 4. Ground-truth (left) and cBathy-derived (right) bathymetry (meters) for an example day, May 17, 2012. The ebb tidal shoal is well represented (0.0007 m bias and 0.52 m rmse) although there are also clearly errors, for example in the tidal channel at the top of the images, that might be related to the effects of currents on the algorithm. The cBathy results are from phase III, so have been smoothed in time with a Kalman filter.

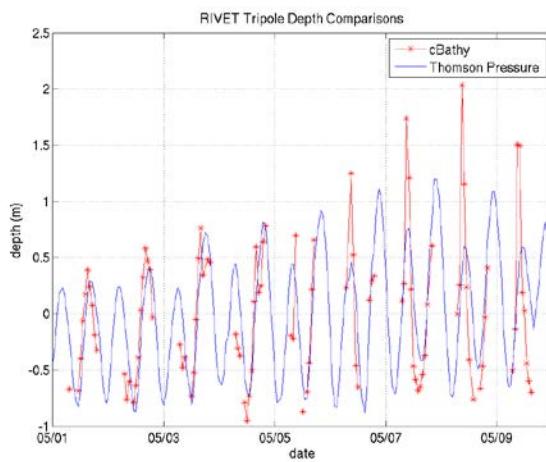


Figure 5. Time series of tidal depth variations at the APL PUV sensor (blue) for the first half of the RIVET experiment compared to hourly (unfiltered) cBathy Phase II estimates for daylight hours (red). cBathy clearly sees, but tends to over-estimate, the tidal amplitude. Date is in mm/dd format.

DISCUSSION

The results described here are obviously just a beginning to the analysis, initially aimed at determining the magnitudes and sense of errors due to Doppler shifting. They are also based on a forward model in which currents are determined by independent measurement.

In practice, current data will only rarely be available. Instead, we wish to solve for both depth and vector currents based only on time varying observations of wave propagation in the form of suites of frequency-wavenumber pairs. This will work only if there is a frequency dependence to the Doppler terms in equation (3), $U\cos(\theta)/c$. Such a frequency dependence can arise either through the celerity term, c , or through the relative wave angle term, θ .

For much of the region under consideration (white box, Figure 3), depths are small, so most waves are non-dispersive (celerity independent of frequency). For example, for a typical depth of 1 m, only waves shorter than 3.5 s show any dispersion. Thus very high frequency waves (with very short wavelengths) must be resolved to separate out depth and current effects.

The situation can be improved if there exists variability in wave angle, θ , relative to the current. This leads to the needed frequency dependence in the Doppler term, for example as was shown in Figure 6.

Figure 7 illustrates the strong refractive processes that occur at this site. Both panels are merged, rectified snapshots (Holman and Stanley, 2007) from May 10, 2012. The left panel, at high tide,

shows mostly waves arriving from the right (offshore) and refracting slightly onto the ebb tidal delta. However some of these waves have also propagated into the channel where they have refracted strongly to the south (down) due to a combination of bathymetry and refractive turning on the flood currents. These waves cross the offshore wave trains at approximately 90°, yield a very complicated set of fluid dynamics over the shoal. The right panel shows that this phenomenon is not present at the following low tide.

While these tide-dependent processes complicate the fluid dynamics of the region, they also provide frequency-dependent variations in wave direction that can be exploited by cBathy to solve for tidal currents.

CONCLUDING REMARKS

cBathy, a bathymetry estimation algorithm developed for open ocean beaches, has been shown to provide a reasonable approximation to bathymetry even in a complex tidal delta environment, when tidal effects are averaged using a Kalman filter. Moreover, unfiltered estimates provide a fair approximation of the time-varying tidal height but over-estimate the tidal range due to Doppler effects on wave celerity. For tests from a small flood tidal channel, the error due to Doppler is 10–20% and is consistent with expectations. Simultaneous solution for bathymetry and currents by cBathy requires a spread in incident wave direction, something that is surprisingly evident in New River Inlet.

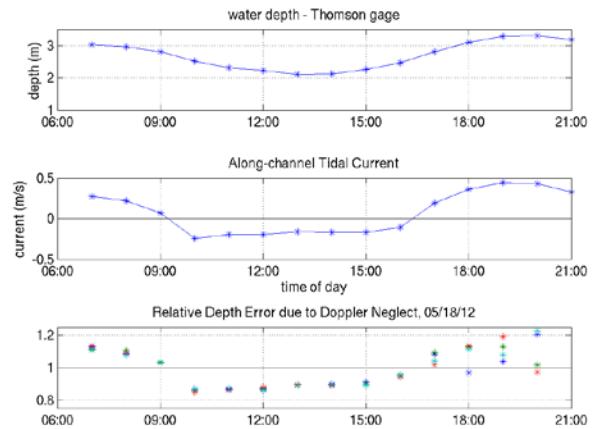


Figure 6. Example time series for one tidal cycle from May 18, 2012. The upper panel shows the depth variation with low tide around mid-day. The middle panel shows the corresponding along-channel tidal current magnitude. The lower panel shows the ratio of the depth estimated neglecting the Doppler term to that estimated including that term. A number greater than 1.0 means that cBathy without Doppler correction over-estimates depth. Different symbols correspond to different wave frequencies.

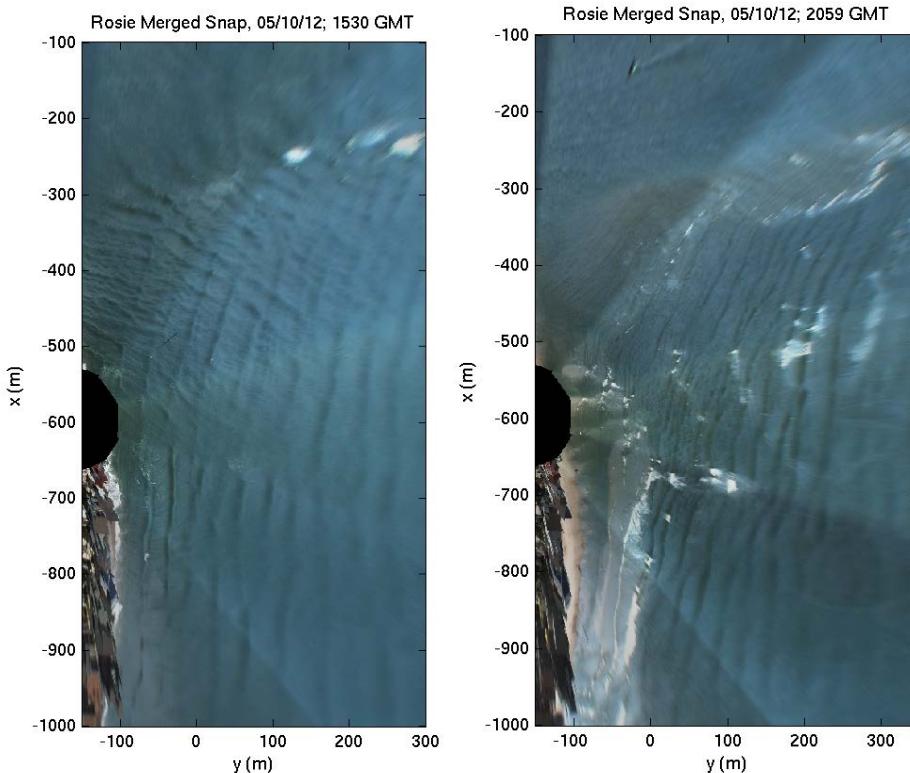


Figure 7. Merged snapshots from May 10, 2012 at high tide (left panel) and low tide (right panel). Waves mainly approach the beach from offshore (the right) but also enter the tidal channel (top) and refract strongly toward the south (bottom) to form the visible crossing pattern and complicated dynamics. In contrast, the strongly refracted waves are absent at low tide.

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