AN ASSESSMENT OF VIDEO-BASED BATHYMETRY ESTIMATION IN A MACRO TIDAL ENVIRONMENT

Bergsma, E.W.J.[1] , Conley, D.C.[1]., Davidson, M.A.[1], O'Hare, T.J.[1] and Holman, R.A.[2]

This paper investigates the utility of video systems for estimating coastal bathymetry in a highly energetic and strongly macro-tidal environment using a linear wave theory inversion approach (cBathy). cBathy has been improved recently (Holman, et al. 2013), introducing a non-linear fit procedure of a phase structure over an area around a point of interest and a Kalman filter. cBathy has been extensively tested in micro/meso tidal environments but never in a macro tidal environment. Now the model is put to the test for the first time in these tidal conditions at Porthtowan, Cornwall in the United Kingdom. The combination of the macro-tidal range and energetic waves means that the accuracy of cBathy is compromised. A novel solution for macro tidal areas is presented in this paper where the pixels lose their fixed position and float around based on the corresponding tidal elevation. cBathy and the modified code are subsequently compared to topographical RTK-GPS measurements covering the inter-tidal area during spring tide. Depending on the tide and waves, the accuracy of the depth estimates varies, but during spring tide (6-7 metre tidal range) the results with the tidal correction are improved significantly. A reduction in RMS-error of 25% for the inter-tidal zone can be found in the most extreme cases.

Keywords: video-based bathymetry; sub-tidal; cBathy, inter-tidal; macro tidal

INTRODUCTION

Coastal areas have been sampled to assess the dynamic behaviour of the coastal bathymetry using remote sensing techniques for over half a century. Remote sensing techniques for measuring beach levels exist in many variants from laser scanners to radar and video cameras. The latter approach is utilised in this paper in the form of an ARGUS video camera system. Although utilising camera systems to capture bathymetries and morphological changes has been the subject of research for many years, the topic is still dynamic and evolving. For example the initial version of a linear wave dispersion relationship (wave Celerity) based BATHYmetry estimator (cBathy) based on frequency-domain empirical orthogonal functions was released roughly a decade ago (Stockdon and Holman, 2000). Recent work on video-based wave number determination in the near shore (Plant et al., 2008) enhanced cBathy significantly, resulting in a new version (Holman et al., 2013), hereafter referred to in this paper as the original cBathy (cBathyOrg).

There have been two principle modifications between the first cBathy code (Stockdon and Holman, 2000) and its most recent version (Holman et al. 2013), that make the code more accurate and robust. First, the wave number is now determined based on phase fitting of a single sinusoid per isolated frequency (Plant et al., 2008) instead of the difference in phase between two pixels as before. Secondly, a Kalman-like filter updates the depth estimates in time based on the accuracy of the estimation. The Kalman-like filter especially increases the robustness through a weighted averaging over time using a Kalman gain based on process variability. cBathy now has the potential to provide much sought after, high temporal resolution, up-to-date bathymetries for numerical models which can be used to improve the performance of the numerical hydro- and morphodynamics.

With this potential for bathymetries of high temporal resolution, cBathy requires validation in a range of environments. The latest cBathy version has so far been extensively tested at Duck (USA) and to a more limited extent at beaches in Oregon and Washington states (Holman et al. 2013), where the tidal range can be classified as micro- to meso-tidal. In this paper, cBathy is tested in a strongly macro-tidal environment (spring range >7metres) on the Cornish coast of the United Kingdom. Cornwall is a county located in the south-west of England (light-grey in Figure 1). The coastline typically contains rocky cliffs that often embay stretches of beach, creating pocket beaches. The study site itself is at Porthtowan, a village that faces the Atlantic Ocean on the North West Cornish coast. During high tide the beach at Porthtowan is an embayed by the rocky cliffs and has a width of roughly 250 metres. With low tide however, an alongshore stretch of roughly 1600 metres beach is exposed.

[1] Coastal Processes Research Group, Plymouth University, Drake Circus, PL4 8AA, Plymouth, United Kingdom
[2] College of Earth, Ocean, and Atmospheric Science, Laboratory, OSU, Corvallis, United States of America

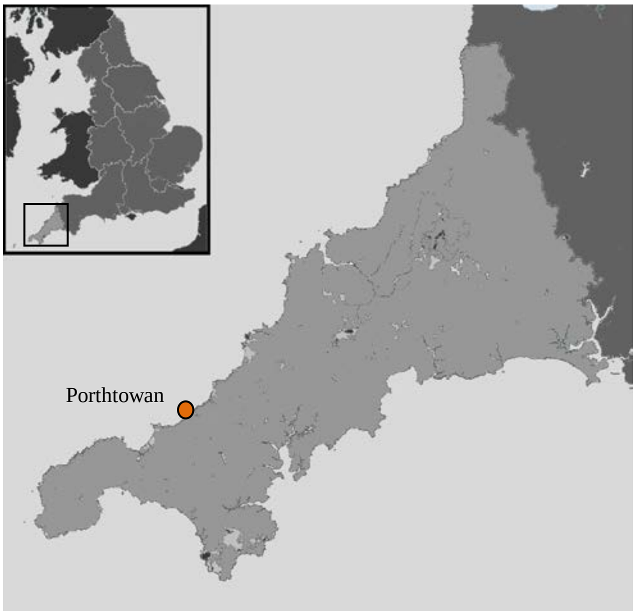

Figure 1. Top left corner shows the United Kingdom and a small part of Ireland. The middle tint grey indicates England in the bottom left corner Cornwall is indicated by the black box. The location of the field site at Porthtowan in Cornwall is shown by the orange dot.

Porthtowan beach is exposed to a macro tidal environment with spring tides over 7 metres in range. The high tidal range in combination with an offshore average measured significant wave height of approximately 1.5 metres, makes Porthtowan a mixed-energy mostly wave dominated environment. Data from an offshore wave buoy shows a considerable difference in wave height during the winter months (October – March) compared to the summer months (April – September). The average measured significant wave height for the summer is approximately 1.25 metres while in winter the mean Hs reaches 1.85 metres. Besides, wave conditions (mostly during storms) can be energetic, e.g. a maximum significant wave height of 5.6 metres was observed by the offshore wave buoy in autumn 2013. During the stormy winter of 2014 a significant wave height of 7.5 metres was observed. The beach at Porthtowan has been subject to several morphodynamic studies over the last years and the beach is classified as an intermediate, barred to low tide bar/rip beach (Poate, 2011).

METHOD

In order to deploy and test the cBathy routines, a video camera system is required on site. At Porthtowan an ARGUS video camera system containing four cameras is mounted at 44 metres above Mean Sea Level (MSL) (with X, Y location 225m, 850m). The system is mounted on the southern cliff, monitoring the beach northwards alongshore. The video system is set to collect pixel intensities of selected pixels (commonly referred to as "time-stack"). The four cameras together cover an area of roughly 700 metres alongshore and 800 metres cross shore as shown by the red lines in Figure 2.

Application of cBathy

As mentioned in the introduction, the depth estimations are, in essence, based on the depth inversion using the linear dispersion relationship, and the core of the cBathy routine consists of three consecutive phases. After preparation of the system, the cBathy system is composed of a frequency dependent analysis, frequency independent depth estimation and finally a running-average depth estimation utilising a Kalman filter.

Before one can employ the cBathy routines, the camera system has to be set to collect and save pixel intensities. The cameras are programmed to collect the pixel intensities on a regular grid (within the red lined area in Figure 2). Typically, the shortest occurring (historical) wave lengths are used to determine the required cross-shore resolution of the pixel array. Wave statistics covering a period of 2006 to 2013 (Coastal Observatory) near Porthtowan shows a minimum monthly zero crossing wave period of roughly 5 seconds. Taking into account the standard deviation of the measurements gives a typical minimum wave period of 4 seconds. Using an iterative solution for the linear wave dispersion relation gives a wave length of roughly 16 metres. Consequently, the cross shore (x) spacing is chosen to be 4 metres and since the variations alongshore are expected to be limited, an alongshore (y) spacing of 10 metres is considered sufficient.

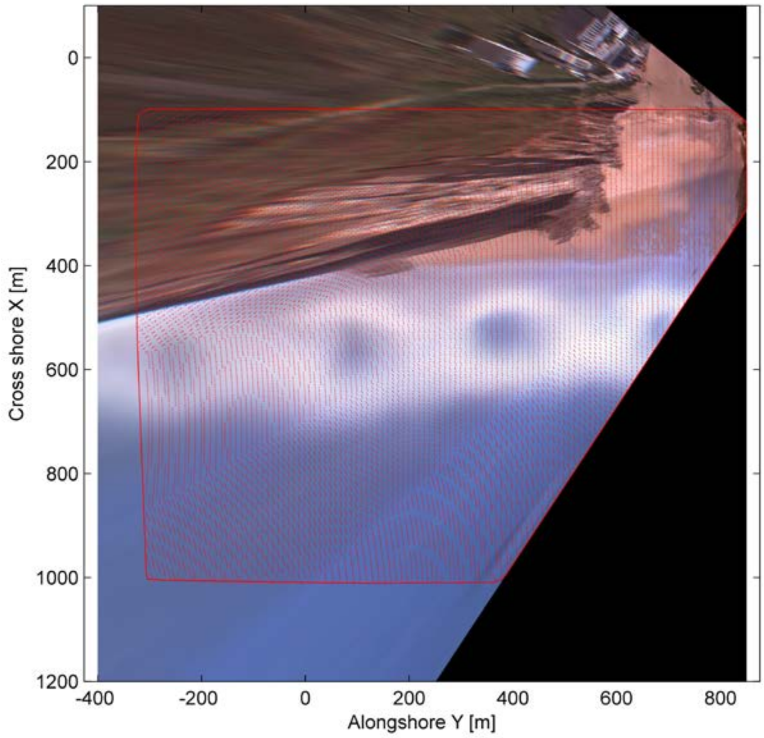

Figure 2. A rectified merged ARGUS timex image at Porthtowan utilising four cameras. The red line indicates the boundaries of the user defined pixel stacking area and the small dots represent the actual pixel stack location. The stretched pixels on the cliff face (100 to 400 metres in X and -300 to 400 metres alongshore) are excluded from the cBathy analysis.

Pixel intensities are collected by the camera system on a frequency of 2Hz for 2048 samples (17 minutes and 4 seconds), a convenient number for subsequent Fast Fourier Transformation procedures, applied at first in the cBathy routines. The cBathy analysis is not carried out on every point of the stacking grid but a second (coarser) grid with points of interest covering roughly the same area as the stacking grid (red lined area Figure 2), where the spacing in the x direction is 10 metres and the alongshore spacing is set to 25 metres. Around every single user-defined analysis point on the grid an area around the point of interest (referred to as “tile”) of by default two times the spacing for x in the x-direction and y in the y-direction, is used for subsampling the data. Collected pixel data located within the tiles is subsequently used for further analysis using the four (default) most coherent frequencies to determine a non-linearly fitted wavenumber based on spatial gradients in pixel intensities (in frequency space).

$$\upsilon'_{\text{obs}} = \upsilon'_{\text{mod}} + \varepsilon(x_p, y_p) \Leftrightarrow \tan^{-1}\left(\frac{\text{Im}(\upsilon_{\text{obs}})}{\text{Re}(\upsilon_{\text{obs}})}\right) = \tan^{-1}\left(\frac{\text{Im}(\upsilon_{\text{mod}})}{\text{Re}(\upsilon_{\text{mod}})}\right) + \varepsilon(x_p, y_p) \tag{1}$$

where υ_{obs} is the observed spatial wave structure (from the EOF analysis), ε is Gaussian distributed white-noise which is minimized in the non-linear fitting (Least Squares) procedure and υ_{mod} the modelled wave structure follows:

$$\upsilon_{\text{mod}} = \exp(i[k\cos(\alpha)x_p + k\sin(\alpha)y_p + \Phi]) \tag{2}$$

In this expression, k is the optimum wave number, α represents the incoming wave angle and Φ is a scaling factor of the wave phase. Equation 1 is iteratively fitted with Levenberg-Marquardt based routines per isolated frequency.

Phase one is completed by estimating four (default) wave numbers per tile for the four most apparent frequencies. From the four wave numbers a single best fit wave number must be derived, since just simply taking the average of the wavenumbers will introduce an error to the depth estimates. In phase two, the four dominant frequencies are used to obtain the best fit single depth by non-linear fitting using a Hanning filter weighting. The final and potentially the most important step for improving the depth estimate, is to take a running average of bathymetries via the application of a Kalman-like filter. The applied Kalman-like filter is a temporal weighted average between two estimates and takes into account the temporal and spatial variability of the morphology.

Modifications in the cBathy code

The cBathy code is described as a robust tool in Holman et al (2013), implying that this tool is applicable in all sorts of hydraulic environments. cBathy is originally developed in the micro/meso tidal regions of Duck and Washington State. In the past year, cBathy has also been tested in a meso tidal, more wind sea environment at Egmond, the Netherlands. However, the code has never extensively been tested in a highly energetic strongly macro-tidal environment.

Initial tests with the cBathy code applied at Porthtowan showed reasonable results but with an overestimation of the depth in the most onshore parts of the domain. A dependency on tidal elevation and wave height was found for the inter-tidal domain. The depth estimates were more accurate during neap tides compared to spring tide periods. Holman et al (2013) suggested an accuracy dependency on the wave height and this can also be found at Porthtowan. With greater wave heights the estimation is less accurate. If we include the tidal range over the day a trend can be observed in which the least accurate estimates (large RMS error) are found during spring tides as presented in Figure 3.

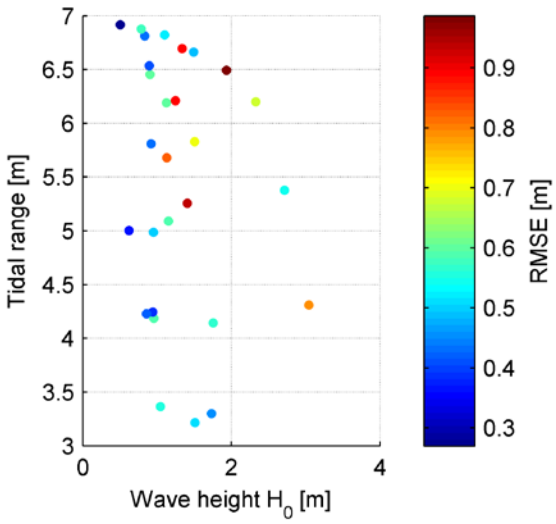

Figure 3. The root-mean-square error calculated over the covered inter-tidal area at Porthtowan depending on corresponding tidal range and offshore wave height over a period from July to September.

The cBathy routines take tidal elevation into consideration as a vertical correction. After phase two, the frequency independent depth estimation, cBathy incorporates tides by adding a certain water level elevation relative to the geometry-related user-defined reference level. This will result in a reference level-corrected depth estimation, so the depth estimations are now comparable in time and corrected for the Kalman like filter application. However, another consequence of the tide is that the pixel locations are moving in the horizontal based on tidal elevation. The pixel location and the changing distance between the pixels gains importance when the horizontal shift increases. In the original cBathy, the pixels are considered to have a permanent location. Consequently, one of the first areas of additional consideration was inclusion of tide dependent pixel locations into the code.

The actual location of the pixels is mostly used in the non-linear fitting procedure of phase one, firstly as a seed, where the difference in observed phase between two pixels is used ($d\phi/dx$ and $d\phi/dy$), and secondly in the fitting of a sinusoid to the observed wave structure requires accurate pixel positions.

Over the sub-sampled domain, an observed spatial structure of an isolated progressive wave derived from pixel intensities is matched with the phase of the single sinusoid of equation 1. If the model fits the sinusoid to the incorrect positions it will either under or overestimates the wave length and therefore the depth. To understand this horizontal shifting of the pixel positions in greater detail, some more background is required in the way ARGUS and cBathy deal with image (pixel) and real world coordinates.

The ARGUS cameras use a projective transformation and fixed known points (Ground Control Points – GCPs) to determine what real world coordinates (X,Y,Z) belong to a certain pixel coordinate (U,V). So, every U and V coordinate in the camera image has a certain X, Y and Z location in the real world using goniometric rules. As one can imagine following goniometric rules, the X, Y location changes for a specific pixel coordinate when the elevation (Z) changes (as shown in Figure 4). The original cBathy code however, uses fixed pixel locations in the real world based on a user defined elevation (Z) given for the geometry solution represented by the orange squares in Figure 4. In both low and high tide situations the orange square stays the same in size and position.

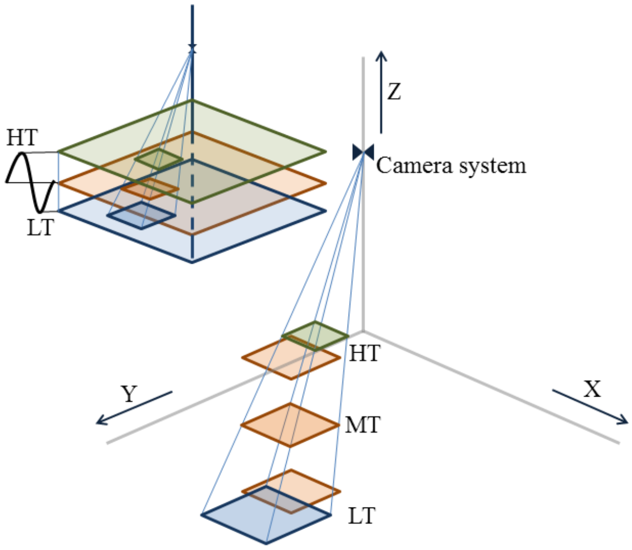

Figure 4. Schematic representation of a squared area with the same stacking pixel points. The orange square is the square representing the initial collected pixels at mid-tide (MT). In the 2013 cBathy code the XY positions are fixed so while moving up (HT) and down (LT) the square remains the same. In the green and blue square the pixel locations are tide dependent; this results in a squeezing effect of the pixel location during high tide and an expansion effect for low tide. The square becomes smaller (HT) and bigger (LT).

For cBathy one is only interested in the pixel intensities on the sea surface, which moves up and down over time due to among other things the vertical tide. In the case of a macro-tidal situation, such vertical elevations range 4 metres or more. If one considers a square of pixel projections in the real world at mid-tide (assuming zero metres elevation, presented by the orange square at “MT” in Figure 4) and the tide goes up (HT) and down (LT), in the same square the pixels are respectively closer together during high tide and further apart at low tide (as shown with the green and blue square respectively). The shrinking and expansion of the distance between the pixel locations is important since this distance is used to determine an initial wave number based on the rate of change in phase of the wave and after a non-linear fit is applied to the most coherent structure over the tile domain. In other words, if the distance between the pixel locations shrinks, the current version of cBathy will overestimate the wavelength and therefore overestimate the depth. The shrinking and expansion is illustrated in Figure 4 where the green and blue squares indicate the tide related pixel locations updated during the process of cBathy.

Now the horizontal shift of the pixels is identified, the question arises whether this is a significant issue. If one looks at a micro tidal environment (<2 metres tidal elevation) the shift will be relatively small and a fixed XYZ location can be assumed with the acceptance of a small introduced error. However, in a macro tidal environment the shift can be as much as hundreds of metres, as indicated in Figure 5. The horizontal shift close to the camera is limited due to larger vertical angles from beach to camera. Further away from the camera one can expect to gain larger accuracy improvements by adopting the correction procedure of the pixel locations. This means that not only the contractions and expansion of the distance between the pixels cause under and over estimation based on the tidal elevation but the depth is also estimated with pixels that are in reality at a completely different part of the beach.

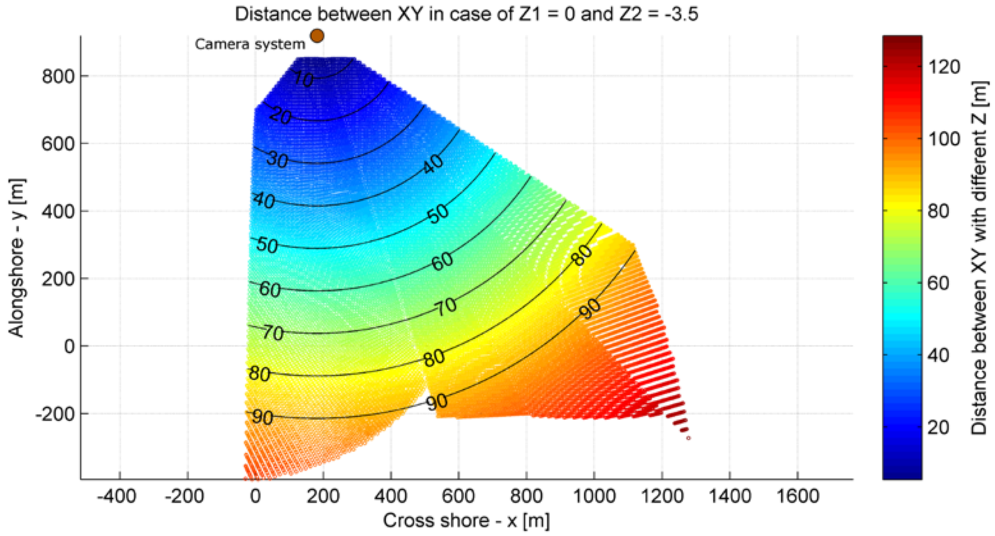

Figure 5. Representation of the distance (horizontal shift) between the locations at mid (Z = 0 meters) and low tide (Z = -3.5 meters) for the same pixel. Close to the camera (upper part of the figure at X,Y = 181.5m,919m) the horizontal shift is limited while further away from the camera the distance between the high and low tide position of a pixel up to 128 meters.

In the cBathy procedure, every single point of interest (where the depth is estimated) is surrounded by its own sub-sampled tile wherein pixels are selected, on coherency and dominancy, for the depth estimation. For the implementation of tide dependence, the tile structure around the point of interest stays intact and fixed (as the area covered by the orange tiles in Figure 3). The modification is that the pixels are tide dependent and float around within the tile area; in and out the tile coverage. The horizontal shift (dx, dy) of pixels is recalculated following equation 3 for every time step and subsequently pixels are reselected when they are located in the tile area for that specific time step.

$$(dx(t), dy(t)) = \frac{\eta_{tide}(t)}{z_{cam}}\left(x_{ref} - x_{cam}, y_{ref} - y_{cam}\right) \tag{3}$$

in which η is the tidal elevation, $(x, y, z)_{cam}$ are coordinates of the camera system location and $(x, y)_{ref}$ are respectively the x and y coordinate of the pixel at the reference level (zero in this case). With the pixels virtually floating around in the overall domain, only pixels that are within the area around the point of interest are selected for every time step. It is likely that the modified code selects different pixels in the same subsampling domain, especially in case of low and high spring tide. This modification is called TPix and refers to the tide dependent grid position of the pixel intensities; cBathyTPix.

RESULTS

The bathymetry estimations of the original version of cBathy and the TPix modification are compared to topographic data collected using a quad bike using a RTK-GPS system. The inter-tidal section of the beach at Porthtowan is surveyed every month as part of an on-going topographic surveying scheme. The monthly surveys are carried out during spring tide in order to cover the largest area possible with this land-based survey. A single survey typically covers a kilometre alongshore and cross shore from the spring high tide mark until spring low water line. After collecting the topography, the data points are Loess interpolated (following Plant et al, 2002) with length scales 5, 10 and 30 metres, resulting in, for example, the left hand picture of Figure 6. Although the Kalman like filter in the cBathy procedure implies a form of spatial smoothing, we treat the data points as single data points as if the data is collected in a conventional way. This means that we also apply the Loess interpolation method on the cBathy depth estimations as with the collected survey data. Subsequently the RTK-GPS data is compared to the depth estimates on the identical interpolation grid.

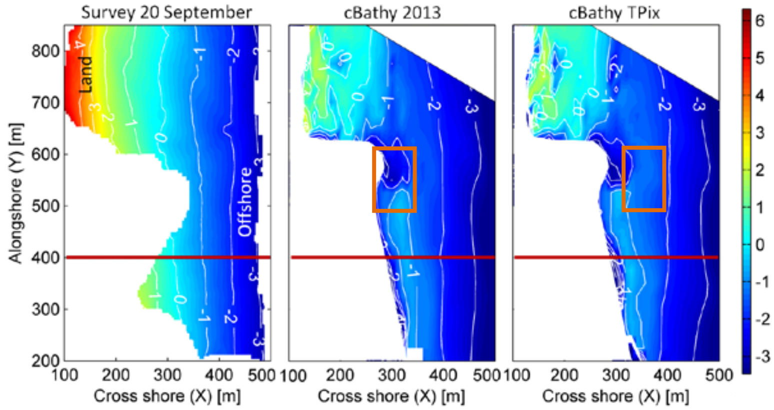

Figure 6. On the left hand side the Loess interpolated topographic survey (20 September 2013) is presented while on the right two bathymetry estimates using cBathy 2013 code (in the middle) and on the right side the TPix modification is used. The red squares indicate an area on the cliff face or close to the cliff that passes the quality controls that neither represents a realistic topography nor wave celerity based depth estimations and can be a result of a tile boundary process.

For the comparison an arbitrary survey day was selected, in this case the topographic survey of 20 September 2013, as presented as the plot on the left in Figure 6. The middle and right plot of Figure 6 area are the estimated bathymetries respectively with cBathyOrg and cBathyTPix. That the surveys are carried out during spring tide gives the opportunity to examine the impact of the modification where it should have the largest contribution (as indicated in Figure 3). A comparison between the survey data and estimates is especially interesting where we expect cBathy to work properly, meaning where linear wave theory is valid. For example, Figure 6 shows that in the shallowest most landward areas the bathymetry is not represented by cBathy with great fidelity. This can be accounted to the introduced non-linearity of the incoming waves when the water depth decreases and so the validity of linear wave theory in that region. In addition, the most landwards areas of the domain have less temporal coverage by water which means less data points compared to deep water. The two orange squares are covering a rocky area just in front of the cliffs; one can confidently state that the variation in depth is too large for cBathy to estimate the depth accordingly.

The mean focus for the comparison is on the deeper parts of the intertidal beach, -1m to -3m bed level and the deeper parts are merely qualitatively assessed by noting the similarities in pixel intensities. Figure 6 demonstrates that in the inter-tidal zone cBathy overestimates depth. The elevation contour at -2m for the surveyed data is fairly constant around 450m offshore, while in both methods estimates this contour to be approximately around 400 metres offshore. On the other hand, the -3 metres contour of both bathymetry estimates seems to be closer matching to the survey. The -3 metres contour in the survey plots is roughly around 490m offshore and in the estimation plots are roughly 470m offshore. A cross sectional plot is presented in Figure 7 in order to gain more insight into the actual bathymetry comparison.

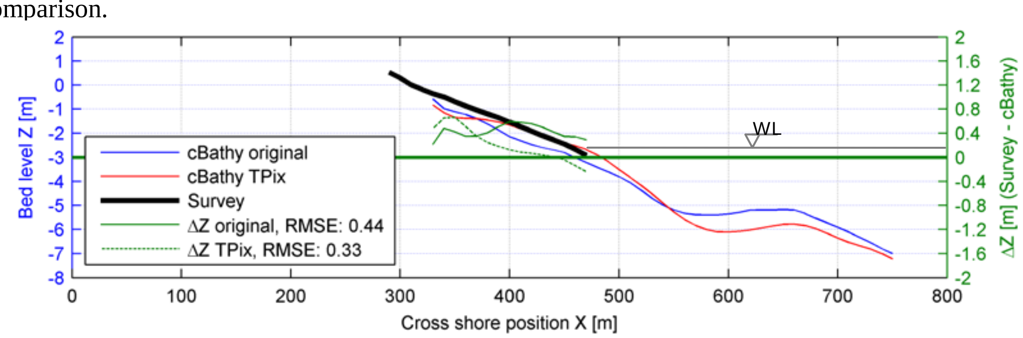

Figure 7. Cross shore cross section of the estimated beach profiles (blue lines), beach survey (black line) and comparison between the beach survey and the estimated bathymetry (green lines). The collected survey data is Loess interpolated as well as the Kalman results of the depth estimates. The grey line represents the water level at low water.

Figure 7 shows a representative cross section to illustrate the difference in results between the two bathymetry estimators. The cross section shown is at 400 metres alongshore, indicated by the red line in Figure 6 and presented in Figure 7. The survey corresponds to the black line in Figure 7 while the blue lines indicate the cBathy bathymetry estimates and the green lines the difference between the survey and bathymetry estimates.

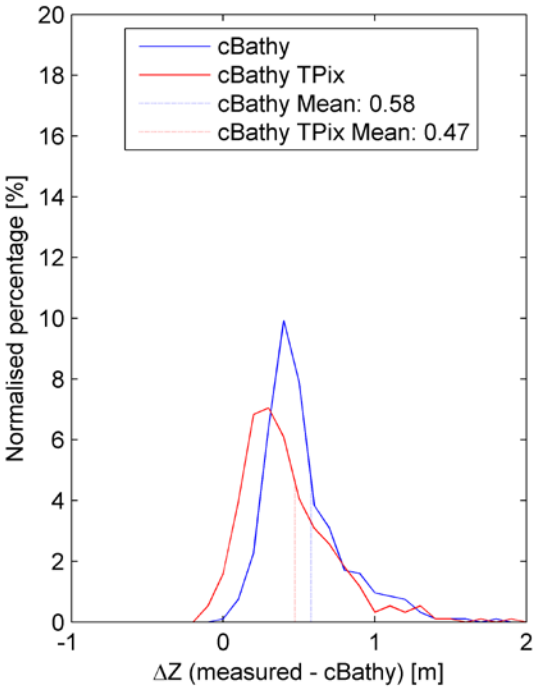

Figure 8. Distribution of the difference (ΔZ) between the survey and the cBathy bathymetry estimations over the whole survey domain for 20 September 2013 (spring tide). The mean of ΔZ for the TPix implementation (0.47 meters) is ~18.9% smaller in the inter-tidal zone compared to the 2013 cBathy code (0.58 meters). In terms of standard deviation the original 2013 cBathy code is smaller (0.28 meters) while the spreading for the TPix implementation is larger (0.32 meters).

The effect of the TPix is most apparent in the form of the biggest difference between the two estimators in the sub-tidal regions. Interestingly, the two bathymetry estimates behave differently concerning the bar structure around 550 to 650 metres offshore, unfortunately outside the region covered of the beach surveys. Distinctive differences can also be observed in the inter-tidal where the TPix implementation tends to agree better with beach survey. With an accuracy of 0.4 metres with the TPix to 0.6 metres with the original 2013 cBathy code at this specific location the accuracy shows a 33% improvement.

Considering the root mean square error (RMSE) of the topographic survey versus the bathymetry estimator, shows that the TPix code follows the beach survey more closely in comparison to the original 2013 cBathy code, with a RMSE of 0.33m for the TPix implementation compared to a RMSE of 0.44m for the original 2013 code, almost 25% improvement in RMSE gained on that specific day.

For the inter-tidal region, the distribution of the ΔZ concerning the beach survey of 20 September 2013 is depicted in Figure 7. The distribution of ΔZ shows a greater standard deviation for the TPix implementation but a smaller mean (μ) ΔZ compared to the original 2013 cBathy code. Figure 7 shows roughly 18.9% more accuracy using the tide dependent pixel locations for the spring tides compared to the original 2013 cBathy code.

Although only one cross section is presented in this paper, a consistent improvement in the bathymetry estimation is found after the TPix code implementation compared to the original 2013 cBathy code. Clear differences can be found between the two bathymetry estimators, especially during spring tides. The difference is less during neap tides. This is in line of the expectations, the horizontal shift of the pixel location is lower at neap tides and most often similar pixels are used in the analysis. During spring tide the vertical range is larger compared to neap tide and so is the horizontal shift.

The performance and application of cBathy in the high tide nearshore areas is restricted. Wave breaking, resulting wave rollers and swash make it either too far off the linear wave dispersion relationship and so highly non-linear or the cBathy quality control parameters such as a minimum depth or maximum frequency are not met. Partially this inaccuracy can be forestalled by the Kalman filter but the shallowest parts with high tide are exposed to these limits of the cBathy approach.

Nevertheless, significant gain of accuracy in the inter-tidal zone is reached by including the tide related pixel locations and using only the pixels in the range of the tile around the analysis point. The new pixel locations representing actual pixel locations are closer to reality and therefore result in better wavenumber estimations. As Figure 7 shows, the mean of the difference between the depth estimators and survey data moves closer to zero after the TPix implementation. A greater standard deviation is consistently found for the TPix implementation, possibly owing to the extra degree of freedom in the sense of different pixels used over the whole analysis while the original 2013 code used a single set of pixels during the analysis, but this suggestion requires more investigation to be conclusive.

The improvement with cBathyTPix in the inter-tidal zone is promising for the sub-tidal zone. The cBathy 2013 code tends to be more accurate seawards as graphs show in (Holman, et al. 2013). In absence of bathymetric data, timex image data during low water is used to assess the bar location (Lippmann and Holman, 1989). In Figure 9, a rectified timex image indicates the crescentic sub-tidal bar position as the higher pixel intensities. The red line in Figure 9 represents the position of the cross section as showed in Figure 7 and the black line points out the approximate bar position, roughly around 650 meters cross shore. This is in quite good correspondence with the cross sectional data as presented in Figure 7, where the crest of the sub-tidal bar can be found around 660 meters cross shore.

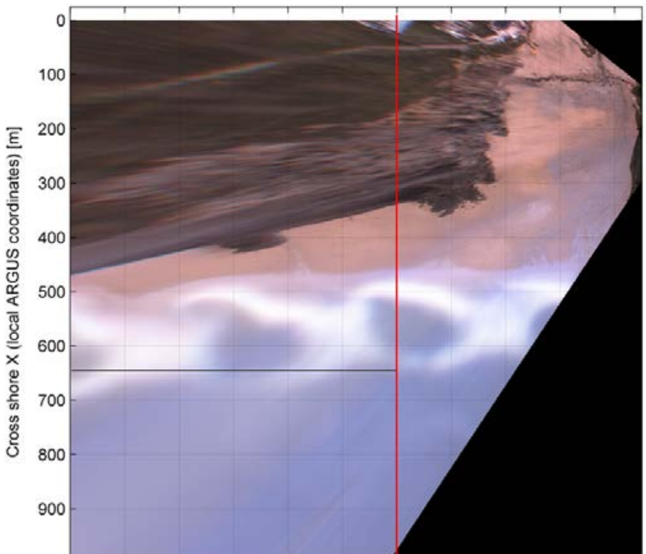

Figure 9.Rectified ARGUS timex image at Porthtowan on 20 September 2013 at low tide (WL = -2.85 meters). Offshore is in the bottom of the plot and north is to the left. The red line represents the alongshore position of the cross shore profile as presented in Figure 7. The black line points out the approximate cross shore position of the sub-tidal bar.

Another useful measure is the shoreline position. In this case, a nice absolute value is harder to pick since the timex images show swash motions, but a rough estimation will be that shore is between 450 to 490 meters cross shore. The horizontal grey line in Figure 7 indicates the vertical position of low water level for the day. The grey line intersects with the blue (cBathyOrg) and red (cBathyTPix) line. These intersections suggest that the shoreline position for cBathyOrg is in the lower end of the 400s between 400 and 450 metres cross shore. For the cBathyTPix application however the shoreline can be found to be in the higher end of the 400s, approximately around 475 meters cross shore.

CONCLUSIONS

The original 2013 cBathy code (Holman, et al. 2013) is successfully deployed in a macro-tidal environment at Porthtowan in the United Kingdom. Introducing tide dependent pixel locations results in more accurate cBathy performance, especially in macro-tidal environment, and significant improvements, up to 25% RMSE reductions, are achieved with the TPix application.

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