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Initialization and Setup of the Coastal Model Test Bed: Integrated Bathymetry

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) introduces the implementation of the integrated bathymetry product in the Coastal Model Test Bed (CMTB). Nearshore numerical models such as CSHORE (Johnson et al. 2012), CMS – Coastal Modeling System (Lin et al. 2008), STWAVE (Smith et al. 2001), etc., are frequently employed by engineers and scientists to model complex physical processes. These models rely on accurate and appropriately smooth bathymetries to operate properly. This CHETN addresses the process by which new bathymetric surveys are gridded, smoothed, splined, and incorporated into a background grid with the regional Digital Elevation Model (DEM) used to fill the remaining portion of the modeling domain. The script used to generate these bathymetries is available in the MakeBathyInterp repository on Bitbucket (Bak 2018).

COASTAL MODEL TEST BED (CMTB) BACKGROUND: Research into nearshore coastal processes is aimed at understanding the physics governing waves and currents, as well as the effects they have on sediment transport and the resulting morphological change. Predictive nearshore hydrodynamic and morphological models incorporate these physics to help scientists and engineers solve real-world problems involving intricate natural systems in a cost-effective manner. As the state of the science progresses, new physics packages are added, or new models are developed. With each of these new packages, model predictions are validated using field measurements. Oftentimes these field data sets are limited to a handful of meteorological events or only a few locations. This limited data then leave uncertainties in how the models perform outside of the conditions over which they were validated.

The U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Field Research Facility (FRF), Duck, NC, has collected nearshore data for over 35 years, and this extensive and sustained data collection effort has resulted in numerous advancements in the knowledge of nearshore processes (Bennett and Mulligan 2017; Chun and Suh 2017; Costley et al. 2017; Haines et al. 2017; Moulton et al. 2017; Safak et al. 2017). Recently added to that effort are the near real-time numerical models of the CMTB. Data relevant to nearshore models collected at the CHL FRF include wave height, wave period, wave direction, water level, nearshore current, bathymetry, wind speed, wind direction, barometric pressure, etc. These extensive, high-fidelity measurements provide a unique opportunity to systematically evaluate the strengths and weaknesses of various coastal models. This allows for numerical model testing and validation in a near real-time capacity and evaluating over a broad range of conditions and over long durations. Deficient model physics can be identified, which in turn can help direct field and observation efforts to develop better physical relationships or parameterizations. Numerical models with the refined model physics or parameterizations can easily be repeated and re-evaluated in the CMTB framework, thus leading to efficient model improvements.

The CMTB is a real-time validation environment for nearshore numerical models used by U.S. Army Corps of Engineers (USACE) districts and ERDC (Bak et al. 2017). The data retrieval and archival processes rely heavily on the Network Common Data Form (NetCDF) file-type and the Thematic Real-time Environmental Distributed Data Services (THREDDS) data server technology, which facilitates and simplifies model verification. The CMTB workflow process is developed in Python 2.7, and the open-source architecture of Python allows the platform to exist on multiple systems without purchasing expensive licenses.

MODEL BATHYMETRY: One of the more critical inputs into most nearshore hydrodynamic models is the bathymetry. For wave models, the bathymetry boundary condition dictates wave shoaling, refracting, and breaking, all of which must be resolved for the wave model to be effective. In nearshore flow models, bathymetry often dictates rip current formation. For nearshore morphology modeling, the input bathymetry is a critical initial condition for the model, and the evolution of this bathymetry will necessarily be dictated by the accompanying wave and flow components. However, the ability to accurately describe the input bathymetry is limited by the methods used to acquire it. Generally, bathymetry is measured by surveying discrete spatial locations, and the number of discrete samples taken is limited by the duration required to survey the locations (Plant et al. 2009). Surveying is often expensive, not only in dollar cost but also in equipment and manpower requirements, and is further constrained by the weather and equipment maintenance schedules. As a consequence, bathymetry data are generally sparse, both spatially and temporally. For example, at the CHL FRF, bathymetry surveys are typically performed monthly by acquiring a series of survey lines. These lines are densely sampled in the cross-shore on the order of 1 meter (m) (O 1 m) but far sparser in the alongshore (O 50 m – 200 m).

Irrespective of the model used, the bathymetry data must be interpolated onto a grid to fully populate the model domain (Plant et al. 2009). The need to interpolate the survey data introduces two types of error to the model that are often unaccounted for. The first is the aliasing of small-scale features when interpolating from an under-sampled survey (Plant et al. 2002). In the example of the CHL FRF data, small-scale alongshore features such as beach cusps (O 10 m – 30 m) are not adequately resolved by the wide spacing of the transects. Consequently, either the surveys will pass through a cusp, in which case the shoreline location in the cusp will be incorrectly aliased to the adjacent bathymetry nodes during the interpolation, or the survey will fail to observe the cusps entirely. The second error is related to the spatial scales that the model is capable of addressing. Continuing with the beach cusp example, many phase-averaged nearshore models do not resolve swash flow and other fine-scale dynamics that are critical to the formation of beach cusps (Plant et al. 2002, 2009). As a result, these models are not able to address beach cusp features and may return inaccurate results if the input bathymetry contains them. The model results are shown to improve if those small-scale features are filtered out (Plant et al. 2009). Optimal model performance is realized when the bathymetric features are smoothed enough to be treated by the underlying model physics but not overly smoothed such that treatable bathymetric features are filtered out. Note that, as pointed out in Plant et al. (2009), it is possible for coupled wave and flow models to be optimized at different smoothing scales.

Additionally, model domains frequently exceed the bounds of the most recent surveys, particularly those that require uniform or periodic alongshore boundary conditions (and thus must have extents sufficiently large to either reasonably meet those requirements or such that any

deficiencies do not impact the model results). As a result, model domains are frequently comprised of an older or composite background bathymetry, with the most recent survey data incorporated where available. These new surveys must be carefully incorporated into the background bathymetry such that the transition between the previous and current data is continuous and any discontinuities are smoothed out.

This CHETN describes the integrated bathymetry product generated from surveys conducted at the CHL FRF for use across various models employed in the CMTB. New bathymetry surveys are interpolated onto a survey grid using the scale-controlled interpolation routine of Plant et al. (2002, 2009) and fused into the most recent integrated bathymetry from the previous survey using a cubic basis spline, or “b-spline” (Ooyama 1987), to generate an up-to-date integrated bathymetry. These integrated bathymetries are archived as netCDF4 files on a publicly accessible THREDDS server. The process described herein is designed to be flexible enough to accommodate various types of elevation data integration, such as the topography measured by the dune-mounted lidar system (Brodie et al. 2015) on an hourly basis, or remotely sensed bathymetry estimates (e.g., cBathy from Argus Camera data [Holman and Stanley 2007; Holman et al. 2013]).

DOMAIN OF INTEREST: The purpose of the integrated bathymetry product is to serve as the baseline bathymetry for the CMTB’s suite of models. The cross-shore extents for the integrated bathymetry product were selected to range from the 0 in the FRF cross-shore coordinate system to the cross-shore position of the 11m Acoustic Wave and Current Meter (AWAC) wave and current gauge rounded up to the nearest cross-shore grid-spacing (5 m in n this case). The alongshore extents range from -200 m to 5,000 m in the FRF alongshore coordinate system. The principal reasons for the large extents of this domain are (1) numerical models often recommend the alongshore numerical domain be at least three times the size of the alongshore zone of interest to remove lateral boundary issues (Plant et al. 2009) and (2) bathymetry data are sometimes collected north of the CHL FRF property (which ends at alongshore position = 1000 m) and should be made available for any future modeling efforts. The large alongshore extents will prove particularly valuable given the recent beach nourishment conducted north of the FRF property. Any future morphology modeling will need to constrain the newly placed sediment in the domain and will, therefore, require the domain extents to exceed the alongshore bounds of the beach nourishment. The grid spacing is 5 m in both the alongshore and cross-shore directions. Figure 1 shows an example integrated bathymetry product generated from a July 2014 survey.

Figure 1. Integrated bathymetry product produced from the 24 July 2014 survey at the CHL FRF.

REGIONAL DIGITAL ELEVATION MODEL (DEM): The regional bathymetry used as an *initial condition* (background) for areas bereft of CHL FRF survey data was taken from Blanton (2008). The Blanton (2008) report was written in part to develop a state-of-the-art DEM of coastal North Carolina. As a part of the Blanton (2008) effort, the local DEM was revised to remove several non-physical features south of the FRF property (Figure 2A). The bathymetry was further updated to include four additional datasets, specifically the three profile surveys spanning the upper beach to approximately 10 m water depth collected by USACE (Figure 2B colored transects) and one swath survey collected by U.S. Geological Survey (USGS) (Figure 2B blue contours). These datasets were included to fill the *Duck Hole* (noted by Blanton [2008], a large region off the coast of Duck, NC, void of National Ocean Service sounding data), to incorporate more up-to-date nearshore bathymetry and to better define some of the nearshore shore-oblique bars as documented by McNinch (2004).

Data were converted from original datums and interpolated into a gridded product using the Interactive Visualization System three-dimensional Fledermaus software. All datasets were interpolated to a 10 m cell resolution using a weighted moving average algorithm. The search weight diameter for the weighted moving average was 9 for the initial bathymetry data and 3-5 for the update datasets. The search weight diameter governs the number of cells the algorithm will use in the weighted average — the higher the search weight, the greater the smoothing of the elevation data. The coordinate systems for the final regional DEM are given in State Plane, North Carolina, FIPS=37055, in meters, and vertical datum NAVD88 (meters).

Figure 2. (A) Non-physical features (orange rectangle) in the original DEM presented in Blanton (2008). (B) Datasets used to update the original DEM of Blanton (2008): (1) Town of Duck, NC, Erosion Study (purple lines), (2) Dare County, NC, Beach Profiles (green lines), (3) CHL FRF Survey Data (blue lines), and (4) USGS Offshore Bathymetry (blue contours).

TIME-AVERAGED LOCAL DIGITAL ELEVATION MODEL: Following the suggestion of Plant et al. (2009), the initial bathymetry that serves as the *starting point* for the integrated bathymetry product is a weighted average surface consisting of the local regional DEM averaged with all surveys conducted since the beginning of January 2008 (note the implicit assumption that more recent data-rich time periods will be modeled more frequently in the CMTB, but this date range is easily amended). The weights for each new survey are generated from the interpolation errors output by the scale-controlled interpolation routine, discussed subsequently. Thus, in areas with no new survey data available, the regional DEM elevation will be returned, and in areas with one or more surveys, the elevation will be modulated to reflect the localized averaged surface. The averaged surface is run through the scale-C interpolation (Plant et al. 2002) routine to smooth out any discontinuities and filter the resulting spatial features to the user-defined alongshore and cross-shore length scales.

This weighted average surface procedure is used to update the local background bathymetry to be more congruous with the new survey bathymetries and avoid excessively large discontinuities during individual survey integration. Figure 3 illustrates the distinction between the original local regional DEM and the time-averaged background surface. Note that the time-averaged bathymetry

is generally shallower in the region updated with the most recent surveys (FRFx-position, 0 m to 900 m; -y-position, -200 m to 3,500 m), and the trough in the vicinity of the CHL FRF pier is better defined (FRF y-position $\approx$ 515 m). This also highlights the need to update the bathymetry when attempting to resolve nearshore physical processes.

Figure 3. (A) The original local Regional DEM bathymetry. (B) The time-averaged local bathymetry. (C) The elevation difference between them (time-mean minus Regional DEM). The position of the 8 m array at the CHL FRF is plotted with a red square for reference.

UPDATING BATHYMETRY: To generate the integrated bathymetry product, recent surveys are interpolated onto a sub-grid based on the spatial extents of the newly collected survey data. The resulting sub-grid is smoothed and splined to be seamlessly integrated into the surrounding background grid using a cubic B-spline routine (Ooyama 1987). The resulting composite bathymetry is explicitly generated via Equation 1 (Plant et al. 2009).

$$Z_n(x_i, y_i, t_i) = Z_{bg}(x_i, y_i) + K_b(x_i, y_i, t_i) \{Z_s(x_i, y_i, t_i) - Z_{bg}(x_i, y_i)\} \quad (1)$$

In Equation 1, Z_n is the updated composite bathymetry, Z_{bg} is the background bathymetry, K_b are the weights computed from the errors output by the scale-controlled interpolation, and Z_s is the survey grid generated by the scale-controlled interpolation routine. If no archived integrated bathymetry exists, the time-averaged local digital elevation model is used as the initial background grid in which to integrate the new survey sub-grids. Otherwise, the routine uses the most recent integrated bathymetry prior to the date of the current survey to be assimilated. The integrated bathymetries at each survey date are archived as monthly netCDF4-files arranged in yearly folders. This results in a time-indexed series of gridded bathymetries at the CHL FRF updated with the latest bathymetric survey at the specified time-index. The basic workflow for generating the integrated bathymetry product is defined in Figure 4. This workflow is capable of assimilating other data types (DEMs and surveys) regardless of the data source.

Figure 4. Workflow for the script to generate the integrated bathymetry product.

Scale-Controlled Interpolation. The scale-controlled interpolation scheme employed for this evaluation is based on the work of Plant et al. (2002, 2009) and uses the quadratic loess interpolation scheme (Schlax and Chelton 1992), containing filter properties that are used as smoothing factors. Without these factors, interpolation schemes can produce small-scale features (related to aliasing) that may not be present in the physical surface the procedure aims to reproduce. The quadratic loess interpolation method removes some small-scale variability to provide a more robust, albeit smoother, interpolation. The cross-shore and alongshore smoothing factor used in this execution are 40 and 100 m, respectively, as recommended by Plant et al. (2002, 2009). One key advantage to using the scale-controlled interpolation routine is that the scheme yields error estimates from the interpolation and the ability to include measurement errors (see Plant et al. [2002] for more information). Interpolating the perturbations from the original background bathymetry facilitates integration to a background value by forcing the perturbations to zero at the intersection of the new sub-grid and the original bathymetry. Consequently, it is critical to stress that this methodology works with perturbations from the background, as explained in the Splining section.

To determine the cross-shore (x-) and alongshore (y-) direction extents of the sub-grid generated from survey data by the interpolation routine, the script first determines the alongshore spacing between each profile line in the survey. The alongshore position of each profile line is calculated as the average alongshore position of every point in the profile line. Only the largest continuous block of three or more survey lines with alongshore spacing less than or equal to 249 m is retained in the survey. All lines outside of this block are discarded. If the maximum alongshore spacing of the remaining profile lines exceeds one-half of the alongshore smoothing factor, then the alongshore smoothing factor for that survey is automatically changed to be equal to twice the

maximum alongshore spacing (rounded to the nearest background DEM alongshore grid spacing). This step is performed to avoid the distance between survey lines exceeding the alongshore smoothing factor, which causes the scale-C interpolation to return a non-physical surface between the two survey lines. Increasing the smoothing factor avoids this concern, though it may result in an over-smoothed surface. The allowable survey spacing of 249 m is enforced to avoid over-smoothing the bathymetry.

The maximum alongshore (y-direction) extent of the new sub-grid is the y-position of the profile line with the largest average y-position. The minimum alongshore extent is similarly defined as the y-position of the profile line with the smallest (or most negative) average y-position. The maximum cross-shore (x-direction) extent of the new sub-grid is specified to be 1.5 times the median of the maximum (offshore) cross-shore FRF-positions of each profile line (not to exceed the maximum cross-shore position measured in the survey). The offshore extent is capped at the position of the 11 m AWAC, rounded to the nearest cross-shore grid spacing (1290 m in this case). The minimum cross-shore (x-direction) extent of the new sub-grid is defined as the median of the minimum (onshore) x-positions of each profile line. The median is used to select the extents in the cross-shore direction to avoid biasing the offshore extents chosen sub-grid by the relatively few but substantially longer profile lines (see Figure 5). The resulting sub-grid is always rectangular in FRF coordinates.

Figure 5. Results of Scale-C Interpolation routine to generate gridded bathymetry from survey conducted on 29 April 2016 at the CHL FRF. The spatial position of each survey data point is plotted with a black circle on top of the resulting surface.

Splining. The sub-grid generated by the scale-C interpolation routine must be incorporated back into the larger background grid to ensure that the transition to the newly updated portion of the grid appears seamless to the CMTB models. This incorporation involves three steps. First, the

background grid is subtracted from the newly generated sub-grid in the overlapping region to create a differenced surface (perturbation surface) on which to perform the splining. Second, the differenced surface is run through a cubic b-spline (Ooyama 1987) filtering routine. The spline weights for each point in the sub-grid (representing the *confidence* the spline routine has in each point) are calculated from the estimated interpolation errors from the scale-C interpolation routine. Prior to implementing the cubic b-spline, the weights near the edges are smoothed to zero at the boundaries of the sub-grid by multiplying them by an edge filter generated using the outer product of two one-dimensional (1D) Tukey filters (Tukey 1967), one for the cross-shore and one for the alongshore boundaries. The default cross-shore and alongshore edge smoothing scales for the 1D Tukey filters are 100 m and 300 m, respectively. The edge smoothing allows the b-spline filtering routine to spline the edges of the differenced surface to match the background bathymetry. The modified differenced surface is added to the background grid (where it overlaps with the sub-grid) to obtain the final estimate of the bathymetry in the sub-grid region. Cross-shore and alongshore cross sections of the final estimate of the newly incorporated bathymetry in the sub-grid region are shown in Figure 6 (a) and (b), respectively.

Figure 6. Comparison among the background DEM (black dashes), original survey bathymetry obtained from Scale-C interpolation (red line), and splined bathymetry integrated into background (blue line). (a) Illustrates a cross-shore transect at FRF alongshore location $y \approx 630$ m, (b) illustrates an alongshore transect at FRF cross-shore location $x \approx 440$ m, approximately 150 m offshore of the sandbar. Note: the FRF pier trough at alongshore coordinate of approximately 500 m.

Note in Figure 6 that the original sub-grid bathymetry from the scale-C interpolation routine (red lines) deviates significantly from the background bathymetry (dashed black lines). However, once run through the spline routine, the final splined sub-grid bathymetry (blue line) ties back into the background bathymetry at the alongshore and cross-shore boundaries; elsewhere, it follows the original scale-C interpolation sub-grid bathymetry. Also note in Figure 6 (b) that the splined surface at $y \approx 0$ m ties back into the background surface over a relatively short distance (~ 100 m). To obtain a smoother gradient, the alongshore edge smoothing scale could be increased. The background bathymetry in the sub-grid region is replaced with the newly determined sub-grid bathymetry and each new bathymetry is saved into monthly netCDF4 for easy data access.

SUMMARY AND FUTURE DEVELOPMENT: The result of this process is a time-series of gridded bathymetries at the CHL FRF that are updated with the latest bathymetric survey and integrated into a continuously updated background grid to produce a consistent bathymetry domain. The survey data are interpolated onto a sub-grid using a scale-controlled interpolation routine that smooths the spatial features of the interpolated grid to the user-specified alongshore and cross-shore smoothing scales appropriate for (1) the given model in which the bathymetry will be used and (2) the survey technique used to acquire the survey data. This sub-grid is incorporated into the background bathymetry using a spline routine to ensure seamless integration, free of discontinuities at the boundaries of the updated sub-grid and the surrounding background elevations. The integrated bathymetry product is primarily intended for use in the CMTB's suite of nearshore hydrodynamic and morphologic models, but the information is publicly available for other purposes. This script used to generate these bathymetries is available in the MakeBathyInterp repository on Bitbucket (Bak 2018). These scripts will be accompanied by Sphinx-generated documentation in the very near future. These features make it straightforward for new users to generate their own bathymetries with settings tailored to specific situations. Future work may involve using the integrated bathymetry routine to incorporate bathymetric data generated by experimental remotely sensed techniques, such as cBathy098 from Argus Camera data (Holman and Stanley 2007; Holman et al. 2013). Model results generated from these experimentally derived bathymetries will be compared to those derived from traditional survey techniques to determine how the use of remotely sensed bathymetry impacts model performance.

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