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***guiBathy*: A Graphical User Interface to Estimate Nearshore Bathymetry from Hovering Unmanned Aerial System Imagery**

Brittany Bruder, Katherine Brodie, Tyler Hesser, Nicholas Spore,
Matthew Farthing, Matthew Geheran, and Alexander Renaud

February 2021

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Final report

Approved for public release; distribution is unlimited.

Prepared for US Army Corps of Engineers
Flood and Coastal Systems Research and Development Program
Vicksburg, MS 39180

Under Funding Account Code U4363305; AMSCO Code 031398; Unmanned Aircraft
Systems Support to Flood Risk Management

Abstract

This US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, technical report details *guiBathy*, a graphical user interface to estimate nearshore bathymetry from imagery collected via a hovering Unmanned Aerial System (UAS). *guiBathy* provides an end-to-end solution for non-subject-matter-experts to utilize commercial-off-the-shelf UAS to collect quantitative imagery of the nearshore by packaging robust photogrammetric and signal-processing algorithms into an easy-to-use software interface. This report begins by providing brief background on coastal imaging and the photogrammetry and bathymetric inversion algorithms *guiBathy* utilizes, as well as UAS data collection requirements. The report then describes *guiBathy* software specifications, features, and workflow. Example *guiBathy* applications conclude the report with UAS bathymetry measurements taken during the 2020 Atlantic Hurricane Season, which compare favorably (root mean square error = 0.44 to 0.72 m; bias = -0.35 to -0.11 m) with in situ survey measurements. *guiBathy* is a standalone executable software for Windows 10 platforms and will be freely available at www.github.com/erdc.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE), Flood and Coastal Systems Research and Development Program under the Unmanned Aircraft Systems Support to Flood Risk Management work unit; Funding Account Code U4363305; AMSCO Code 031398. The USACE Flood and Coastal Systems Research and Development Program Manager at the time of publication of this report was Dr. Brandon M. Boyd, and the Technical Director was Dr. Julie D. Rosati.

The work was performed by Coastal Observation Analysis, Coastal Processes, and Hydraulic Systems Branches of the Flood and Coastal Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Dr. Jeffrey Waters was Chief, Coastal Observation Analysis Branch; Ms. Kiara Pazan was Acting Chief, Coastal Processes Branch; Dr. Pearce Cheng was Chief, Hydraulic Systems Branch; and Dr. Cary Talbot was Chief, Flood and Coastal Division. The Acting Deputy Director of ERDC-CHL was Ms. Ashley Frey, and the Director was Dr. Ty V. Wamsley.

COL Teresa A. Schlosser was the Commander of ERDC, and the Director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Many hydrodynamic processes in the nearshore environment have optical signatures. For example, white foam cascading down a blue wave face indicates wave breaking, and alternating shadowed and brighter *lines* moving along the water surface indicate traveling and shoaling waves (Figure 1-1). While our eyes can qualitatively interpret these cues, they cannot provide quantitative estimates of length scales or physical processes (momentum transfer, etc.). However, with photogrammetry, researchers can georectify oblique imagery of the nearshore to obtain measurements of shoreline position, wave breaking patterns, currents, and wave parameters (length, period, celerity) (e.g., Lippmann and Holman 1989; Holland et al. 2001; Alexander and Holman 2004; Plant et al. 2007; Plant et al. 2008; Harley et al. 2011; Power et al. 2011; Almar et al. 2017; and many others). Furthermore, using physics-based relationships with these optical measurements, researchers have estimated downstream parameters such as depth and energy dissipation (e.g., Aarninkhof et al. 2005; van Dongeren et al. 2008; Holman et al. 2013; Bergsma and Almar 2018).

One example of these algorithms is cBathy, a bathymetric-inversion algorithm that measures wave speed, c , from long dwell ($\sim 15 \text{ min}^1$) georectified imagery and calculates water depth (Holman et al. 2013). cBathy performs a cross-spectral analysis between adjacent pixel intensity time series from a series of georectified video frames ($\geq 1 \text{ Hz}$) of the nearshore to estimate wave length L ($\therefore$ wave number, k), period T ($\therefore$ frequency, ω), and therefore celerity c (ω/k) for subsets of the domain. Using linear wave theory, these parameters can be entered in Equation (1) to determine depth, h , where g is gravity. Because cBathy analyzes in the frequency domain, wave speeds can be extracted from multiple frequency waves. Eigenvalue analysis is utilized to identify the top-four frequency waves observed by the video imagery at each location, and a non-linear

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¹ For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

solver is then used to determine the optimum depth (h) to satisfy Equation (1) for the four frequency-wave number pairs at each solve point. This approach allows uncertainty to be estimated as a function of fit quality to Equation (1), for each depth. cBathy can be applied when linear theory is valid (Dean and Dalrymple 2001) and where depth influences wave speed (intermediate to shallow water waves; $h < L/2$).

$$c = \sqrt{\frac{g}{k} \tanh kh} \quad (1)$$

As wave height increases and significant breaking occurs throughout the surf-zone, linear wave theory can become invalid, and cBathy speed estimates can be incorrect (Brodie et al. 2018). During these conditions, a simplified estimate of the probable shape of the nearshore bathymetric profile can be extracted from video imagery for use as a bottom boundary condition in nearshore numerical modeling. Bathymetry results from this approach, however, should not be used to estimate profile volumetric changes. This simplified approach, referred to here as the Parametric Beach Tool (PBT), involves fitting a parametric model with sandbar shapes to input parameters derived from the video imagery and climatologically known for your location (Holman et al. 2014, 2016).

In the PBT algorithm, the coordinates of the shoreline and sandbar are identified in time-averaged georectified video frames (≥ 1 Hz) taken over an extended period (at least 10 min). Concentrated white pixels in the surfzone are assumed to be areas of frequent wave breaking and therefore a proxy for sandbar location, and the average location of the tan/blue interface of sand and water is assumed to be an approximation of the shoreline position during the collection. Using these positions, and estimates of the onshore/offshore slopes and depths, a barred equilibrium beach profile is estimated across the domain utilizing empirically derived coefficients and assumed universal skewed Gaussian sandbar shapes derived by Ruessink et al. (2003). This approach allows for approximate bathymetry estimation in conditions where cBathy has high uncertainty.

1.2 Objective

Coastal and riverine shorelines are dynamic landscapes that change continually in response to environmental forcing. A cost-efficient technology and methodology that allows for accurate, detailed, and timely monitoring of the coastal zone is critical for US Army Corps of Engineers

(USACE) construction and monitoring projects in support of flood risk management actions. For example, USACE is presently limited by a lack of up-to-date observations on the state of the coastal zone immediately prior to storm events. This forces predictions of inundation and storm damage to use outdated data (often years out of date), which greatly reduces skill and increases uncertainty in predictions and makes accurate determination of impacts from single storms difficult.

Figure 1-1. A) Example small hovering unmanned aerial system (UAS) and B) UAS imagery at 60 m elevation for nearshore bathymetric estimation.

UAS offer an affordable solution from which to collect geospatial data of the coastal environment (Figure 1-1, A). While many efforts have focused on extracting topographic information from UAS imagery using structure-from-motion (SfM) photogrammetry, considerably less research exists on extracting bathymetry information, particularly in breaking-wave and turbid environments. However, algorithms have been developed to exploit tower-based imagery of the coastal zone. These algorithms can also be applied to UAS imagery (Figure 1-1, B) but typically require additional photogrammetric and signal processing expertise not traditionally taught in coastal engineering curriculums to employ. As part of the UAS Support to Flood Risk Management work unit within the USACE Flood and Coastal Systems Research and Development Program, the US Army Engineer Research and Development Center (ERDC) has developed software, called *guiBathy*, which synthesizes and packages an end-to-end solution to utilize commercial-off-the-shelf (COTS) UAS platforms to quantify nearshore bathymetry, making these techniques widely accessible to USACE district engineers and other coastal practitioners. The purpose of

this technical report is to document this software and record the results of significant technical milestones during this multiyear work unit.

1.3 Approach

These imaging algorithms have been primarily developed in research settings from fixed imaging towers such as the Argus Tower at ERDC Coastal and Hydraulics Laboratory (CHL), Field Research Facility at Duck, NC (Holman and Stanley 2007). The algorithms require wide and unobstructed views, typically provided by high towers or vantage points. Unfortunately, such towers are impractical to install for federal beach projects, and as a result, USACE district use of this video-based synoptic monitoring technology is restricted to locations with elevated buildings along the coast (e.g., mini-Argus) (Bruder et al. 2019a,b). However, with the advancement of COTS UAS technology, such as multi-rotor systems that can hover in one place, high vantage points are more rapidly accessible than ever. With a 15 min hovering flight overlooking the nearshore environment, districts can now perform rapid and high-frequency bathymetric estimates of federal beach projects to supplement more costly and time-consuming traditional boat-based surveys for better informed adaptive management techniques. Developed to accompany the transition of UAS hardware technology, *guiBathy* is a software package to perform photogrammetric georectification, cBathy, and PBT processing of UAS imagery without the need of subject matter experts.

1.4 Report layout

The presented report outlines the *guiBathy* software, UAS data collection requirements for *guiBathy* processing, and an example application. Chapter 2 discusses required UAS calibrations needed and optimal Concept of Operations (CONOPS) for *guiBathy* data collection. Chapter 3 outlines each step and feature in the *guiBathy* processing workflow. Chapter 4 concludes the report with an illustrative example of rapid storm response monitoring and bathymetry measurements during the 2020 Atlantic Hurricane Season at Duck, NC.

2 Data Collection Requirements

The following section highlights the necessary calibrations, information, and optimal CONOPS to estimate nearshore bathymetry from a hovering UAS using *guiBathy*.

2.1 UAS camera calibration

To produce georectified imagery, two pieces of information must be determined for a given UAS data collection: the camera *intrinsic* and the camera *extrinsic calibrations*. This section will describe how to and how often to perform each calibration, further summarized in Table 2-1.

Table 2-1. Types of UAS camera calibrations and rate of occurrence.

Type	Occurrence	Mechanism
Intrinsics	Once for each individual • UAS Platform • Sensor • Recording Mode • Focal Length (Zoom)	• Checkerboard Calibration or • SfM Topographic Survey
Extrinsics	Every flight	Surveyed GCPs (RTK or PPK)

2.1.1 Intrinsics

The camera intrinsic coefficients define the projective matrix to scale image pixels to real-world space as well as correct for lens distortion, such as is easily visible in a fisheye lens. Traditionally, this calibration is performed by recording video or taking images of a checkerboard pattern (with known dimensions) using the camera and same recording mode used in the data collection. Multiple third-party software tools (Cal-tech Camera Calibration Toolbox, MATLAB Image Processing Toolbox) can calculate intrinsic coefficients from the checkerboard images. Intrinsic coefficients can also be calibrated in SfM software frequently used for UAS topographic point cloud generation. If utilizing the SfM method, however, it is important to ensure the following: (1) the analysis is optimized with accurate ground control; (2) the recording mode is the same for the SfM and bathymetry collection; and (3) all pixels in the images are utilized (i.e., images should not contain large portions of water).

Intrinsic camera calibration needs to occur once for each camera and each recording mode, on an individual UAS unit regardless if the camera has a

low-distortion lens or if that same make and model camera had been calibrated on another unit. *guiBathy* does not perform intrinsic calibrations but can ingest information from third party software if using a radial and tangential distortion model (Brown 1971). Table 2-2 highlights the necessary intrinsic coefficient format needed for *guiBathy* and conversion factors from common software distortion models referred to as either *frame* or *perspective*. *guiBathy* currently cannot support skew calibrations or *fisheye* distortion models. Note, if a coefficient is not listed, make sure in the third-party software (Metashape, etc.) these values are not solved for.

Table 2-2. Conversion of intrinsic calibration coefficients from common software to *guiBathy* input. Note: all values should be in pixels (not millimeters) unless specified.

guiBathy	Photoscan/ MetaShape (Camera Calibration Parameters)	Cal-Tech Camera Calibration Toolbox (.mat file variables)	Pix4D (Camera Model Internal Parameters)	Bentley Context Capture (Exported Camera Model .opt file) Note: do not use EXIF values
NU	Width	nx	Image Width	Width
NV	Height	ny	Image Height	Height
cUo	Width/2+cx	cc(1)	Principle Point X	PrinciplePoint X
cVo	Height/2+cy	cc(2)	Principle Point Y	PrinciplePoint Y
Fx	b1+f	fc(1)	Focal Length	FocalLength*Width/ Sensor Size
Fy	f	fc(2)	Focal Length (does not account for Fy)	AspectRatio* Focal Length(mm)*Width/ SensorSize (mm)
d1	k1	kc(1)	R1	K1
d2	k2	kc(2)	R2	K2
d3	k3	kc(5)	R3	K3
t1	p2	kc(3)	T1	P2
t2	p1	kc(4)	T2	P1

2.1.2 Extrinsic

Camera extrinsics describe the exact position (XYZ) and orientation (azimuth, tilt, swing) of the camera sensor throughout the data collection. These data form the translation/rotation component of the camera projective matrix. Required precision and pose accuracy (<1 cm, <0.1°) necessary for accurate georectification cannot be provided by standard

COTS UAS platforms, even if supplied with Real-Time-Kinematic (RTK) or Post-Processed-Kinematic Global Position System corrections and high-end Inertial Measurement Units due to heading drift in stationary flight and camera gimbal movement. Thus, extrinsic calibration is performed by placing surveyed Ground Control Points (GCPs) and Stabilization Control Points (SCPs) in the UAS collection field of view (FOV) during the entirety of the collection (Holman et al. 2017).

GCPs are typically large (0.3 – 1 m) flat squares with an Iron Cross pattern (exaggerated in Figure 2-1), whose survey point (the center of the cross) can be easily identifiable in UAS imagery. Targets can be constructed from fabric, wood, or plastic, or purchased. Other fixed items can also be used (signposts, etc.) if easily surveyed and identifiable and continuously visible in the imagery. Each GCP must remain stationary during the entire collection and be surveyed with RTK or PPK precision (1 – 3 cm). SCPs are easily recognizable points that do not have to be surveyed, but an estimate of the elevation must be known (<1 m). SCPs must significantly differ in brightness or darkness as compared to their immediate surroundings and not be too close to the edge of the image frame. Iron Cross GCPs serve well as SCPs; however, SCPs do not have to be a GCP. *guiBathy* can ingest GCP/SCP coordinates for georectification and stabilization, respectively, and use this information to perform extrinsic calibration for each frame collected during the flight.

guiBathy requires at least four GCPs and SCPs each for extrinsic calibration (a GCP can also serve as an SCP). Extrinsic calibration must be performed correctly to enable properly estimated bathymetry. For example, incorrect azimuth determination may place data at improper horizontal locations, or incorrect tilts may lead to bathymetric profiles with too shallow or steep slopes. Proper extrinsic calibration results from optimum GCP/SCP placement (Figure 2-1), which features distributed GCPs/SCPs across the image FOV at different elevations (beach, dune, and pier) and not aligned along a single dimension. Note that coastal structures such as piers can be used to increase GCP/SCP placement in the offshore portion the imagery but are not required. For environments without a pier, angling the camera azimuth slightly with respect to the shoreline can increase ground coverage across the image in both image dimensions and thus enable increased spread of GCPs. More discussion of optimum flight paths and FOV are described in Flight CONOPS Section 2.2, following.

Figure 2-1. Example GCP placements for UAS hovering CONOPS.

2.2 Flight CONOPS

The previous section outlined necessary data needed for accurate georectification and therefore cBathy and PBT bathymetry estimation. Additional CONOPS considerations such as flight height and azimuth can maximize algorithm accuracy. First, a general CONOPS will be outlined for optimal data collection for georectification. Then, CONOPS particular to each algorithm, cBathy, and PBT will be described. Both general and specific CONOPS are summarized in tabular form at the end of the section. Note that these recommendations should be considered in addition to (but not as a replacement for) all USACE Aviation Headquarters and Federal Aviation Administration Part 107 protocols.

2.2.1 General CONOPS

The following section outlines the general CONOPS to collect hovering UAS data for estimating bathymetry. When preparing for data collection, it is beneficial to conduct one to two test flights prior to collection to evaluate different elevations, view angles, and GCP placement. During these flights, users should take example videos in the anticipated recording mode with a few GCPs (non-surveyed) placed. This allows adjustment of data collection CONOPS on the ground, in lieu of in flight, which would expend battery life and reduce data collection time.

When choosing a view angle, elevation, and position, there are multiple considerations to balance. Higher elevations provide increased FOVs and more data coverage; however, higher elevations also reduce pixel resolution, making GCP identification difficult. Offshore look angles and hover locations closer to the shoreline can limit land coverage in the image and provides maximum ocean data; however, reduced land coverage may constrain or limit GCP placement. During test flights, all of these considerations should be evaluated. Figure 2-2 shows suggested FOVs for cBathy and PBT. Typically, flights at 60 – 70 m Above Ground Level

(AGL), 100 – 125 m landward of the shoreline, and with a tilt of 60° – 70° degrees up from nadir (straight down) allow for (1) substantial coverage of the nearshore (500 m offshore and alongshore); (2) sufficient resolution for GCP (0.3–1 m square) identification; and (3) adequate SCP/GCP distribution and extrinsic calibration on land.

Figure 2-2. Example FOVs and environmental conditions for optimum A) cBathy and B) PBT data collection.

Once a FOV and flight parameters have been decided, GCPs should be placed, secured, and surveyed. Pilots may then commence data collection flights. A data collection flight consists of flying to the appropriate position determined in test flights, remaining hovering in place, and recording imagery. *guiBathy* requires video imagery, not snapshots or frames. For adequate pixel resolution, it is suggested to use 30 Hz 4K HD video, standard on most commercial multi-rotor UAS. Other video modes can be used, but frame rate must be at a minimum of 1 Hz. The UAS should hover in place and record for as long as safely possible considering battery life. Useable video of incoming waves should be at least 10 min, but longer time series are suggested for environments with longer-period waves (e.g., > 10 s). Users should also manually record UAS position, Camera Pose, and time at the start of the collection in their log book; this information is required to provide an initial estimate for *guiBathy* processing. The UAS heads-up display typically shows this information. After collection and

UAS landing, users should collect GCPs and note if any have moved; if so, they are no longer applicable for use.

2.2.2 cBathy specific CONOPS and limitations

For cBathy to estimate depths, waves at the time of the collection must be in the shallow to intermediate depth regime ($h < L/2$); otherwise, Equation (1) becomes ($c = g\omega^{-1}$) and wave speed is thus independent of depth. Previous surveys (for h), wave information from nearby buoys (for f), and Equation (1) ($k \propto L$) can help estimate the valid solve region for a given time.

Many publications have discussed additional limitations and sources of error of the cBathy algorithm (Holman et al. 2013; see Brodie et al. 2018 for a review). cBathy depth retrieval errors typically increase with increasing wave non-linearity (when linear theory becomes less valid) and increasing wave-breaking within the domain (when how a camera sees waves changes). Errors due to the presence of non-linear waves will be on the order of 40% of the depth (assuming a 15% to 20% faster wave speed than linear shallow water theory).

In addition, generally, if the approximate depth of the sandbar crest is known, when offshore wave height exceeds more than half of the sandbar depth, breaking wave interference in the cBathy algorithm is likely to occur (Brodie et al. 2018). For example, if the depth at the crest of the sandbar is 3 m, when offshore wave heights exceed 1.5 m, errors due to wave breaking are likely. In these cases, the algorithm can misinterpret the sudden appearance of white pixels as rapid wave progression and celerity. These anomalously high wave speeds can sometimes result in a severe overestimate of depths (i.e., cBathy-measured wave speeds can reach twice linear theory, depending on conditions, resulting in depths up to four times too deep) at the onset of breaking (Brodie et al. 2018).

Thus, it is ideal to collect cBathy data during times of little to no wave breaking, but with visible waves (Figure 2-2, A). For many sites, this typically occurs during high tide during quiescent conditions. Finally, prior research suggests the optimal view angle for cBathy occurs with views that are parallel to the direction of wave propagation (i.e., looking into the face of approaching waves), due to light refraction properties (Perugini et al. 2019). Balancing land/GCP coverage, this typically results

in views with azimuths $\pm 10^\circ - 15^\circ$ off cross-shore, signage depending on wave direction (Figure 2-2, A).

2.2.3 PBT specific CONOPS and limitations

The PBT can be used to approximate bathymetry during larger wave conditions when the user can accurately identify the shoreline and sandbar from time-averaged UAS imagery. Thus, ideal wave conditions for this algorithm occur when waves are large enough to consistently break over the sandbar (Figure 2-2, B) but not so large that the surf zone is saturated and breaking is persistent throughout the domain. This occurs typically with small to moderate wave heights at low tide. Because the algorithm solves where a shoreline/sandbar can be defined, ideal azimuths are aligned along the shoreline ($+15^\circ$) to maximize the solution domain while retaining GCP/SCP coverage.

Note that the PBT utilizes theoretical and empirical formulations to produce an estimated profile. PBT assumes that the nearshore profile follows a concave-up parametric shape where nearshore slopes are steeper than offshore slopes; if a concave-up parametric shape cannot be fit, a linear profile is used. In addition, the tool makes assumptions about the shape and spacing of sandbars based on empirical fits to bathymetric data from Ruessink et al. (2003). No error estimates are provided with the final profile (in contrast to cBathy), and the final profile shape may be sensitive to the accuracy of the background inputs. When possible, PBT should be tuned using a recent prior survey of the region to ensure that background parameters are adequately set for your location; Chapter 3 includes guidance on the selection of these parameters. The PBT has not been as widely evaluated as the cBathy algorithm and should only be utilized as a bathymetry approximation tool when conditions are not valid for cBathy. In some cases, PBT output may also be directly combined with cBathy to locally improve bathymetric estimates where cBathy has high error. PBT output should never be used to estimate nearshore volume changes but may be useful in generating reasonable modeling grids in the absence of survey data for initial design studies or for tracking general changes and trends in sandbar cross-shore position.

2.2.4 CONOPS summaries

Table 2-3 provides a summary of the general and algorithm specific CONOPS described in Sections 2.2.1 – 2.2.3.

Table 2-3. Suggested CONOPS for *guiBathy* processing.

Value	cBathy	PBT
Elevation	60 — 0 m AGL	
Azimuth	Balance between 10° – 15° from cross-shore direction for GCP placement and looking into dominant wave direction for cBathy	10° – 15° from alongshore direction
Tilt	60° – 70° up from nadir; (20° – 30° down from horizontal)	
Position	100 – 125 m onshore of shoreline, though may depend on shape of coast	
Duration	As long as safely possible, 10 min minimum; longer for longer period waves >10 s.	
Timing	Higher tides for more water coverage and less wave breaking.	Lower tides for more wave breaking over sandbars.
	Avoidance of low angle sun glare close to sunrise or sunset (depending on coast). Consistently clear or overcast skies, partly cloudy skies can disrupt stabilization algorithm.	
Wave Conditions	Minimal breaking waves, shallow to intermediate wave regime ($h/L < 1/2$)	Wave breaking, but not completely saturated surfzone (need to be able to delineate sand bar from inner surf)
Recording Mode	Recommend 4K HD Video, 30 Hz, minimum 1Hz	

3 *guiBathy* Overview

3.1 Software and data requirements

guiBathy is a standalone GUI that was developed in MATLAB v. 2019b with the Statistics and Machine Learning and Image Processing Toolboxes. Once compiled, the software can be run on any Windows 10 operating system without MATLAB or toolbox licenses with an installation of the MATLAB run-time environment, which is included in the *guiBathy* installer. The executable software will be available at www.github.com/erdc; the open-source development code (which does require MATLAB licenses) will be available at <https://github.com/Coastal-Imaging-Research-Network/>. *guiBathy* utilizes two existing code repositories at <https://github.com/Coastal-Imaging-Research-Network/> for back-end processing: *The CIRN Introduction to Quantitative Coastal Imaging Toolbox v1.0* for georectification (Bruder and Brodie 2020) and *cBathy Toolbox v2.0* (Holman et al. 2013) for cBathy bathymetric estimates. Code for the PBT is based off of Holman et al. (2016), developed for this graphical user interface (GUI) and not independently released yet.

The data required to successfully run *guiBathy* are outlined in Table 3-1. Most data and information are discussed in Chapter 2.

Table 3-1. Data and metadata requirements to run *guiBathy*.

Value	
UAS Videos	Raw videos with approximate timing of video start within 30 min
GCP Coordinates	Minimum of four GCPs with surveyed coordinates (RTK or PPK Accuracy) in desired output projected coordinate system.
SCP Elevations	Minimum of four SCPs with estimated elevations (can be GCPs)
Initial UAS Camera Position/Pose	Initial guess of UAS Camera Position/pose with 10m/10° accuracy. Obtained from autopilot or logbook.
Tidal Elevation Estimate	Estimate of tidal elevation during flight, relative to MTL.
Elevation of MTL	Elevation of Mean Tidal Level (MTL) in desired output coordinate system.
Intrinsic Calibration	Intrinsic Calibration for specific UAS unit, sensor, and recording mode used in flight. Calibration must be radial/tangential Distortion Model (Brown 1971).

Note, Table 3-1 does require a tidal elevation estimate during the time of collection relative to MTL as well as the elevation of MTL in the desired output coordinate system (e.g., NAVD88). This information is necessary for accurate georectification and depth offsets. Nearby tidal and MTL information can be found at <https://tidesandcurrents.noaa.gov/>.

3.2 Software workflow

guiBathy processing is outlined in Figure 3-1 for both cBathy (blue) and PBT (yellow) workflows (arrows). The workflow is organized into a linear set of tabs (listed in Figure 3-1 and pictured in Figure 3-2); data and metadata from each intermediate step are saved in a standardized project directory created by the GUI (output listed in Figure 3-1 and directories shown in Figure 3-2). Each instance or *project* in *guiBathy* is designed to process one flight. Files with commonalities between flights such as grid parameters can be copied into other project directories to use for other flights. Both the cBathy and PBT workflows require georectification processing (green blocks) to occur first.

Users can then process and export cBathy or PBT bathymetry estimates independently of each other (i.e., you do not need to run cBathy to run PBT and vice versa). However, users also have the option for PBT to ingest cBathy to better estimate parameters or merge PBT and cBathy results by copying bathymetry estimates between project directories.

The following sub-sections go through each processing tab and subtab according to the workflows outlined in Figure 3-1, following the same progression as a user with a new flight to process would. Saving locations of intermediate output is listed in Figure 3-1. In addition to feature descriptions, these subsections outline suggested analysis parameters.

Figure 3-1. *guiBathy* workflow.

3.2.1 Project initiation tab

Figure 3-2 shows the first tab (Project Initiation) and sub-tab (Create/Load Project) in *guiBathy*. Here, the user can either initiate a new project, specifying a name and saving location, or open an existing project directory. Upon creating a new project, a standardized project directory is created with sub-folders (Figure 3-2, left). While the project directory can be moved or name changed, the sub-folder names cannot and must be left as is. Then the user is asked to “Load Videos,” which copies raw video imagery (mp4, avi) into the project directory. Since UAS platforms typically split long video collections into multiple smaller videos, multiple videos can be selected and loaded. Upon completion of loading or opening, as in all processes in the GUI, lamps will highlight green indicating completion (Figure 3-2).

Figure 3-2. Example opening screen of *guiBathy* (left) and project directory (right).

After opening a project, the user can click on any tab they had previously completed. For new projects, after *Create/Load Project* is complete, the user continues to *Generate Frames* tab. Here, users can select the order of

the videos, specify an initial timestamp, and generate individual non-compressed jpg frames at a specified frame rate. Once complete, the user continues to *Load Intrinsic* tab. Here, the user can load an intrinsic (.mat) file from the Cal-Tech Camera Calibration toolbox or manually enter coefficients if known (Table 2-2) for the camera and recording mode corresponding to the loaded videos. If loaded into *guiBathy* for a previous flight with the same calibration, the user can also drag a *guiBathy* intrinsic .mat file into the *intrinsic* folder in the project directory.

3.2.2 GCPs tab

Figure 3-3 highlights the next tab, *Click GCPs*. The user clicks to add and delete GCPs seen in the first frame of the imagery. Users can zoom into imagery to highlight small GCPs and make precise clicks. Once saved, users continue to the *Assign GCP Coordinate* Tab. Here GCPs are automatically presented similarly to the frame in Figure 3-3.

Figure 3-3. Example GCP clicking mechanisms of *guiBathy*.

Users must enter coordinates of the GCPs in the projected coordinate system desired for orthophoto grids and bathymetric output and save the file. If multiple coordinate systems are to be output, the user can create

multiple GCP coordinate files and repeat the entire *Extrinsics* tab for each. Users can specify horizontal and vertical descriptions of GCP coordinate systems, which will continue to be used for extrinsic solutions and grid generations. If the user desires to use the same grid between projects and flights, these GCP datum descriptions must be the same between projects.

3.2.3 Extrinsics tab

The next tab *Initial Solution*, Figure 3-4, performs the initial extrinsic calibration. Here, the user selects a generated frame set, intrinsic file, and GCP file (with associated coordinates) from lists the GUI automatically prepopulates based on files in the project directory. The user must input an initial guess of the camera position and pose; this can be identified from notes taken during collection or from autopilot records. The position must be in the same projected coordinate system of the GCPs and have 10 m accuracy (i.e., no need to convert between geodetic coordinate systems). User pose estimates can have 10° accuracy; the user can find definitions and sign conventions by clicking the “Help” button.

Figure 3-4. Example initial extrinsics solution in *guiBathy*. Poor solution shown to highlight different GCP Projections.

ERDC prelsias

Project Initiation | GCPs | Extrinsics | Georeferencing | cBathy | Parametric Beach Tool

Initial Solution | GCP Selection | Stabilization

Select Frame Set
prelsias_2Hz

Select Intrinsic File
ANAP1_A_KK.mat

Select GCPs File
prelsias_2Hz_GCPsUVWXYZ.mat

Coordinate System
Horizontal: NCSP
Vertical: NAVD88
Units: degrees, m

Select Frame Set, intrinsic and GCPs file and continue to 'Initial Guess'

Initial Guess
Enter guess of UAS position/look angle, continue to 'Select GCPs'
Click check box directly below variable to fix

E [m]	N [m]	Z [m]	Azimuth [deg]	Tilt [deg]	Roll [deg]
601725	274606	70	89	50	0

Select GCPs
Enter GCP numbers (on left) to use, separate by commas
GCP Numbers: 1,2,3,4,6,5

Solution Metrics

Variable	Value	Uncertainty (m)	GCP	E Error [m]	N Error [m]
E [m]	8.0175e+05	9.0396	1	0.2730	-5.0
N [m]	2.7464e+05	7.5762	2	45.0703	-3.9
Z [m]	70	0	3	01.9314	4.7
Azimuth [deg]	71.7594	0.2095	4	178.2598	26.0
Tilt [deg]	60.0000	0	5	-4.2719e+05	6.2720e
Roll [deg]	8.5201	6.0363	6	0.3374	70.0

Saving Solution
Filename: prelsias_2Hz_initEO
No Spaces
Save

When Saved, go to 'GCP Selection' tab

1 Can select different GCP clicks/datums
2 Can 'freeze' initial guess to narrow solution
3 Can select different GCPs to utilize
4 Solution Reprojection
5 Solution Uncertainty /Error

After entering an initial solution, the user can click “Solve.” If a solution can be found, the Solve lamp will highlight green. If a solution cannot be found, it will highlight red, and the user must either enter a more accurate initial guess or make sure GCP coordinates were entered correctly. The accuracy of the solution can be assessed by the reprojection of the GCPs in the oblique imagery (Figure 3-4) as well as the solution metrics. An accurate solution should have the reprojected GCPs (green X, Figure 3-4) directly on top of the Used/Clicked GCPs (yellow circles, Figure 3-4) and have GCP errors < 20 cm (Solution Metric table, Figure 3-4). If a good solution cannot be found, the user can reduce the number of GCPs to use (useful if a particular GCP survey is not accurate). In addition, the user can *freeze* known initial extrinsic guess parameters to help refine other parameter initial guesses and solutions. Once satisfied, the user saves the output and continues to SCP Selection (Figure 3-5)

Figure 3-5. Examples of good and poor SCP parameter specification in *guiBathy*.

Next, the user identifies SCPs for subsequent image stabilization through extrinsic calibration of the remaining frames in *Click SCPs*. The clicking mechanism is the same as in *Click GCPs*: however, with each SCP click, the user must enter additional information for the stabilization algorithm (Figure 3-5): the *Search Radius* and *Intensity Threshold*. *guiBathy* calculates extrinsics for each subsequent frame by first selecting an area (defined by the *Search Radius*) around the last known position of the SCP in the prior frame. *guiBathy* applies an *Intensity Threshold* to the pixel intensities, depending if a Bright (Dark) SCP is specified. Pixels below (above) this threshold are considered bad (blue) and good (yellow) if above (below) the threshold for Bright (Dark) SCPs. The algorithm then calculates the center of area of *good* pixels; this is considered the location of the SCP. Optimum threshold parameters will consistently pick the same feature regardless of slight camera movement. Figure 3-5 highlights poor and good SCP parameter definition.

Once the user saves SCP clicks, the extrinsic calibration is then completed in the *Stabilization* tab for every frame (Figure 3-6). Here, the user picks a frame set, initial solution, and SCP file. The user must then enter an elevation estimate (within 1 m) for each SCP clicked, which will be displayed and labeled in the oblique imagery. Once the user clicks *Solve*, *guiBathy* will solve the extrinsics for each frame, displaying the solution and frame in real time. The *guiBathy* stabilization algorithm uses the SCP threshold method to automatically find the SCP locations in each frame, and the extrinsics are solved similarly to the *Initial Solution* tab automatically. Only the elevation is needed from the user for the SCPs because the calibrated initial solution from the surveyed GCPs is used to estimate their horizontal position. Thus, the GUI plots both the autodetected and reprojected points in real time so the user can assess the accuracy of the auto detection and solution accuracy. Once completed, the GUI will output a plot of the change in extrinsics over the time of the collection. Good stabilizations, on non-windy days, should see position changes no larger than 2 m and pose changes less than 1°. If change is larger than these values, the user should double check original video to see if such UAS movement did occur or retry stabilization with different SCP parameters. Once saved, extrinsic calibration is complete.

Figure 3-6. Example SCP stabilization tab (top) and in-flight camera extrinsic output (bottom) by guiBathy.

- 1 Can select different initial solutions and SCP combinations
- 2 Can enter different SCP elevations
- 3 Tracking/Solution Reprojection
- 4 Solution Uncertainty

3.2.4 Georectification tab

In the *Grid Generation* tab, the user can observe the rectification of the first frame as well as define the local rotated coordinate system (Figure 3-7). Local rotated coordinate systems are necessary for both the operation of cBathy and PBT.

Figure 3-7. Example grid specification in *guiBathy*.

A correctly defined local rotated coordinate system has positive X directed offshore and Y alongshore. For east-facing beaches, this requires a rotation angle of -90° to 90° counterclockwise (CCW) from east. For west-facing beaches, this requires a rotation angle of 90° to 180° CCW from east. The origin can be clicked or entered manually. Limits of the grid are defined by alongshore and cross-shore extents. The user can also enter the desired resolution of the grid for the output georectified imagery; increased grid spacing (defined in the GUI as resolution) results in less detail but faster processing times. Typically, 1 – 2 m grid spacing produces adequate feature resolution and processing times for most coastal imagery applications (~ 1 hr). Here, the user also enters the elevation of MTL in the output geographical coordinate system. Once the grid is saved, it can be

copied and used in other project directories for solutions in the same coordinate system. This allows multiple flights in the same area to be rectified to the exact same grid.

After Grid Generation, the user can create georectifications (orthophotos) for each frame and statistical ensemble timex and bright products in the *Orthophoto Generation* tab (Figure 3-8). The user selects the frame, extrinsics calibration, and grid file as well as enters the estimated tidal elevation relative to MTL. The GUI will then create an orthophoto for each frame and save it as a jpg. Ultimately, the GUI will save four copies of each frame, with each type in its own folder: orthophotos are saved in both geographical and local coordinates (these images, where each pixel represents a unit grid spacing, are used in subsequent *guiBathy* analysis); the other two copies are simply labeled plots of the orthophotos in geographical and local coordinates (e.g., Figure 3-8; note pixels in these images do not correspond to length but rather length scales are indicated by the plot axes; these images can be used for presentation/reports, and in the *Orthophoto Movie* tab).

Figure 3-8. Example Orthophoto output in *guiBathy*. Left: Statistical brightest image in geographical coordinates. Middle: Statistical timex image in local coordinates. Right: Example individual frame in geographical coordinates.

As frames are generated, ensemble statistical products (timex and bright) are *built* and displayed in real time. While timex is the average pixel intensity throughout the collection, bright is the brightest pixel intensity (Figure 3-8). Brightest images are useful for measurement of the maximum swash run up and display where any wave breaking occurred during the collection (e.g., maximum surf-zone extent or white-capping). Orthophoto generation is one of the longer processing steps, taking 1 – 2 hr, but this methodology saves processing time in downstream steps that require more

iterative processing attempts. After completion, users can make compressed .avi movies, played at various playback speeds of each type of orthorectified image in the *Orthophoto Movie* tab.

3.2.5 cBathy tab

Once frames are georectified, downstream bathymetric analysis such as cBathy and PBT can start. Users that want to use cBathy as a final product or as an input to PBT can next click on the *cBathy* and *Timestack Generation* Tab (Figure 3-9).

Figure 3-9. Example timestack generation in *guiBathy*.

The *Timestack Generation* tab downsamples and formats the frame orthophoto images for cBathy. Users should downsample the data in space to reduce computational processing time and memory demands.

Ultimately a resolution should be selected so waves are still discernable in the live updated imagery and there are at least 5 grid nodes per wavelength in the most inshore region (Plant et al. 2008). Grids of 5 m × 5 m are suitable in most nearshore applications. To help increase wave visibility,

the user can also enhance image contrast. Note that too much enhanced contrast can also emphasize short period wind waves and induce error. Once parameters are selected, users can build and save timestacks and continue to the *Run cBathy* tab (Figure 3-10).

Figure 3-10. Example cBathy parameter specification in *guiBathy*.

On the *Run cBathy* tab, users can specify cBathy parameters (Table 3-2) such as Solution Points and Analysis Area. Solution points are the points where cBathy will estimate depth; increased solution resolution significantly increases processing times. The analysis area is the region of image data cBathy will analyze around each solution point. The analysis areas are typically two to four times the solution resolution. Typically, offshore points have longer wave lengths and require larger analysis areas. This is accounted for by the user-defined alongshore smoothing factor. Example inshore and offshore Analysis Areas (green) for one Solution Point (center green point) and nearby Solution Points (red) to indicate overlap are displayed in the imagery. Usually, the alongshore resolution is set larger than the cross-shore resolution since bathymetric variability is typically less in the alongshore direction than cross-shore direction. The user can alter the suggested solution frequencies; however, this is not

suggested for novice users for most nearshore environments. This option is more suitable for inland bodies of water with shorter period waves. Once cBathy processing is started, a progress bar will appear and indicate solution completion. Once cBathy is complete, users can continue to the *Solution Exploration* tab to graphically display data (Figure 3-11).

Table 3-2. Suggested cBathy parameters for hovering UAS flights.

Parameter	Suggested Value
Cross-shore Resolution	5 m (~15 ft)
Alongshore Resolution	x2 Cross-shore resolution
Analysis Areas	x4 Resolutions in both dimensions. Large enough to cover one to two wavelengths at most inshore points
Offshore Smoothing Factor	Large enough to cover one to two wavelengths at most offshore points
Total Domain Limits	Cover entirety of subaqueous areas and swash
Estimated Depths	GUI requires depths entered as positive values

Figure 3-11. Example cBathy data viewer.

In the *Solution Exploration* tab, users can extract and plot cross-shore profiles, overlay cBathy estimates on top of orthophoto statistical image products, and visualize error estimates. At the given profile, there is a deep estimated hole. The profile and plot show this area has high error. The overlay on the timex shows this area is right at the onset of breaking, congruent with cBathy limitations. If satisfied with cBathy output, the user can continue to the *Export Bathymetry* tab (Figure 3-12). If not, the user can reprocess with different cBathy parameters or continue to the *Parametric Beach Tool* tab to blend with PBT estimates.

Figure 3-12. Example cBathy data viewer and export options in *guiBathy*.

The *Export Bathymetry* tab has similar visualizations as the *Solution Exploration* tab but can also filter the data based on error estimates and smooth data estimates in both the alongshore and cross-shore dimensions (Figure 3-12). Resultant bathymetry profiles and plots are displayed as parameters are changed in real time. It is suggested to filter (remove) data with errors greater than 0.5 m. Note that this error estimation typically underestimates the true error since it is calculated as a 95% confidence limit; the true error is typically two to three times the provided error. cBathy

can only resolve bathymetric features greater than 10 times the water depth; this can serve as a starting point for suggested smoothing lengths. Once exported, *guiBathy* will provide the following filtered data for both local and geographical coordinates: an XYZ file of bathymetric elevations, a .mat file of bathymetric elevations, and a .jpg and .fig of the filtered bathymetry contour plot displayed in the GUI. Note that all bathymetric products are exported in the vertical datum specified in the *Assign GCP Coordinates* tab (not relative to MWL or current tidal elevation).

3.2.6 Parametric Beach Tool (PBT) tab

The user can begin the PBT tab either immediately after georectification or after cBathy analysis (Figure 3-13). Here, the user can select an orthophoto set, and the corresponding timex image will appear. The user can then click on the shoreline and sandbar. If optimum CONOPS is not available as shown in Figure 2-2, the user can extend shoreline and sandbar extents to approximate these values along the domain if the beach is assumed alongshore uniform. The user should click the shoreline at the onshore edge of the swash and click the sandbar on the offshore edge of wave breaking for accurate results.

Figure 3-13. Example PBT parameter specification in *guiBathy*.

ERDC/CHL TR-21-3

PBTTest_3

Select Orthophoto Set

Use Flight 2Hz_Orthos
Use Flight 2Hz_OrthosTN
Use Flight 2Hz_Orthos_navigate

Select cBathy File (Optional)

Use Flight 2Hz_OrthosTN
Use Flight 2Hz_OrthosTN_Timexstack_cBathy_pr
Use Flight 2Hz_OrthosTN_Timexstack_cBathy_pr

After selecting Timex and cBathy (optional) files, continue to 'Feature Identification'

Feature Identification

Click features below, do not zoom or change transparency when clicking

Shoreline Estimate (Pink)

Start Clicking Shoreline
Stop Clicking Shoreline
Reset Shoreline

Sandbar Estimate (Green)

Start Clicking Sandbar
Stop Clicking Sandbar
Reset Sandbar

Extrapolation Extents (Optional)

400 Y min [m] 1000 Y max [m] Extrapolate Features

After selecting shoreline and sandbar continue to 'Parameter Estimates'

Parameter Estimates

Enter parameters manually below, in same units as grid

Depth of Closure [m]	X Dist of DoC [m]	Offshore Slope [m/m]	Onshore Slope [m/m]	# Bars (1-5)
7.7000	717	0.0056	0.0032	1

After all 4 parameters are entered, continue to 'Desired Resolution'

Desired Resolution

X [m] Y [m]

5 10

Then continue to 'Run Parametric Beach Tool'

Run Parametric Beach Tool

Start PB Tool

At completion continue to 'Saving Bathymetry'

Saving Bathymetry

File name: Use Flight 2Hz_Orthos_ne
No Spaces

Save Bathymetry

When saved continue to 'Solution Exploration' Tab

1 Click shoreline + sandbar on timex

2 Can extrapolate features past FOV

3 Can overlay cBathy results if minimal wave breaking

After clicking the shoreline and sandbar position, the PBT requires estimates of nearshore parameters such as climatological offshore/onshore slope, depth (and position) of closure, and number of bars. The implementation of the PBT in *guiBathy* has been modified from the formulations discussed in Holman et al. (2016) to reduce the number of inputs and place more weight on the UAS observations. Specifically, instead of asking the user to define the maximum offshore depth of the sandbar for a given location, *guiBathy's* implementation instead asks the user to define the number of sandbars (from visual inspection of the timex image) instead of using assumed sandbar length scales, and iteratively solves for the sandbar locations by minimizing error between the sandbar *clicks* and PBT solution. In addition, tidal input has been added so that the shoreline is located appropriately based on the time of the UAS data collection.

Diagrams of these parameters can be seen in the Help button; values are highly dependent on the local environment, so suggestions are not provided. Depth of closure estimates for the US coastline are found as a layer in the Sediment Mobility Tool on the Navigation Portal (<https://navigation.usace.army.mil/SEM/SedimentMobility>), which were calculated using empirical relationships (Brutsché et al. 2016; McFall et al. 2018) with wave conditions from the Wave Information Study stations, which can be found at <http://wis.usace.army.mil/>. It is advised to utilize the depth of closure depth in combination with a recent (< 10 yr old) survey to provide input parameters of offshore slope and distance to the depth of closure, as well as onshore slope if possible. The user can define the resolution of the PBT output; typically it is defined at a similar resolution to cBathy Solution Points (5–10 m). Once the PBT tool is initiated, depending on domain size, the solution takes 1–10 min. Once PBT processing is complete, the user can visualize the results in the *Solution Exploration Tool*, which is similar to that seen in Figure 3-11 for cBathy. PBT error estimates are not provided, since it is merely a bathymetry approximation tool; however, the user can compare results with selected cBathy results.

In the final *Export Bathymetry* tab, the user can either export PBT results directly (the same products output as in the cBathy *Export Bathymetry* tab) or blend PBT and cBathy results (Figure 3-14). To do this, the GUI employs a Bayesian updating strategy to blend the PBT and cBathy bathymetries. In broad terms, the strategy treats the PBT as a prior estimate with a spatial correlation structure described by a Gaussian

covariance function. The cBathy results are treated as independent observations with a uniform measurement error. The two fields are then combined via Bayes' rule to produce a blended, posterior (final) estimate for bathymetry (Asch et al. 2016). The user can provide correlation length scales to smooth the data, remove cBathy estimates over a given error threshold, as well as assign relative credence of the PBT and cBathy Solutions. A PBT Solution Weighting Value of 100% will provide raw PBT results whereas a value of 0% will just fill missing cBathy values with PBT values. The resultant blended bathymetry is updated as in the cBathy *Export Bathymetry* tab.

Figure 3-14. Example *guiBathy* Bayesian blender specification.

4 Example Application and Conclusions

4.1 Example *guiBathy* application

Traditional boat-based survey project monitoring methods can be costly and time/personnel consuming. As a result, few are budgeted for during a federal project's lifespan. With limited surveys, it is difficult to isolate natural bathymetric evolution versus project/event driven change. Brodie et al. (2019) highlights the USACE need for increased survey capability, particularly after storm events, to better allocate recovery resources. UAS and *guiBathy* can assist in this need. To exemplify this, researchers at the ERDC Field Research Facility in Duck, NC, performed two UAS hover surveys during the 2020 Atlantic Hurricane Season to demonstrate use of both cBathy, PBT, and blending the two results. This section will outline the field efforts and results.

4.1.1 Flight and processing descriptions

ERDC-CHL personnel performed 15 min UAS hover flights on July 31, 2020 (pre-Hurricane activity), and September 15, 2020 (mid-Hurricane activity), at the ERDC-CHL Field Research Facility in Duck, NC. During this period, there were two significant wave events ($H_s > 2$ m) on August 4 (Hurricane Isaias) and September 18 – 23 (Hurricane Teddy). Each data collection effort required two personnel and took 60 – 90 min, including GCP placement. The first collection occurred during small wave conditions with minimal breaking (tide = -0.05 m NAVD88; $H_s = 0.44$ m; FOV Figure 2, A) while the second collection occurred during persistent wave breaking (tide = -0.054 m NAVD88; $H_s = 1.94$ m; FOV Figure 2, B). H_s estimated from National Buoy Data Center, Buoy 44056. Propeller Aeropoints self-recording GCPs were used as GCPs and SCPs. In situ bathymetric sonar surveys were completed by a Lighter Amphibious Resupply Cargo vessel (LARC) (Birkemeier and Forte 2019) for each flight (+/-10 days).

Both flights are processed and bathymetries are estimated with *guiBathy* cBathy using the following parameters: cross/alongshore resolution 5 – 10 m; analysis area x4 resolution, alongshore smoothing factor of 3, and one contrast enhancement. In post-processing, the first and second flight have a cross/alongshore smoothing factor of 100 m and 100 m, respectively. For both flights, points with estimated errors greater than

0.5 m are removed. Data were able to be processed within 1 day of their collection, using *guiBathy*.

The second flight was collected during conditions with increased wave breaking and thus likely poor cBathy performance. As a result, this survey is also processed using the PBT with an offshore slope of 0.006, onshore slope of 0.032, Depth of Closure of 7.7 m at $x = 717$ m, and 1 bar specified. Parameters are estimated from boat-based survey data taken on July 21, 2020. The PBT and raw cBathy results were blended using a cBathy error limit of 0.2 m, cross/alongshore scaling factors of 30/30 m, and weighting factor of 60% (Figure 3-14).

4.1.2 First flight (July 31, pre-hurricane activity) results

Figure 4-1, A highlights *guiBathy* cBathy estimates from the first July UAS flight at the beginning of the 2020 Hurricane Activity at Duck, NC. cBathy results capture the main bathymetric features measured with the LARC (Figure 4-1, B) such as the cross-shore position and depth of the sandbar as well as the deeper scouring on the southern half of the FOV. Figure 4-1, C shows a slight bias on either side of the pier due to non-linear wave structure interaction and FOV obstruction. There is good agreement with LARC measured depths in Figure 4-1, C (RSME = 0.72 m, bias = -0.35 m).

Figure 4-1. *guiBathy* UAS bathymetry estimates compared to LARC survey data for July 31 pre-hurricane activity flight. In difference plots, red (blue) indicates under (over) estimate of depth by *guiBathy*. Colored and dashed lines correspond to profiles presented in Figure 4-2. Solid black line represents location of pier. Coordinates in North Carolina State Plane and NAVD-88.

Figure 4-2 shows example cross-shore profiles of *cBathy* and LARC bathymetry. The alongshore local coordinates the profile is $Y = 460$ m; the corresponding geographic coordinates are plotted in Figure 4-1. Y increases positively to the northwest direction. Figure 4-2 highlights the accuracy of *cBathy* when data are collected during ideal conditions with shoaling waves and minimal wave breaking. The LARC and UAS *cBathy* profiles match extremely well: trough and sandbar depth magnitudes and cross-shore locations are correctly resolved as well as the onshore slope.

Figure 4-2. Cross-shore profiles for July 31 pre-hurricane activity flight compared with corresponding LARC measurements. Local alongshore coordinate is $Y=460$ m. Geographic location is represented in Figure 4-1.

4.1.3 Second flight (September 15, mid-hurricane activity) results

Figure 4-3 highlights *guiBathy* *cBathy* and PBT estimates from the second September UAS flight during 2020 mid-hurricane activity. The *cBathy* estimate (Figure 4-3, B) compares poorly with the LARC measurements (Figure 4-3, A) due to extensive wave breaking. *cBathy* results overestimate the depth offshore of the bar and underestimate the depth in the trough (Figure 4-3, C), suggesting the sandbar is placed too far onshore, consistent with the findings of Brodie et al. (2018) during breaking wave conditions. In addition, raw *cBathy* estimate (Figure 3-14) has poor coverage due to the non-linearities introduced by breaking waves and is highly smoothed removing smaller scale features. As a result, there is poor agreement between the *cBathy* and LARC measurements with a root mean square error (RMSE) of 1.26 m and bias of -0.54 m.

Figure 4-3. *guiBathy* UAS bathymetry estimates compared to LARC survey data for September 15 mid-hurricane activity flight. In difference plots, red (blue) indicates under (over) estimate of depth by *guiBathy*. Colored and dashed lines correspond to profiles presented in Figure 4-4. Solid black line represents location of pier. Coordinates in North Carolina State Plane and NAVD-88.

The PBT estimate (Figure 4-3, D) correctly approximates the slope of the foreshore and cross-shore position of the bar; however, it overestimates the depths of the entire domain resulting in a overestimated trough depths and underestimated bar height (Figure 4-3, E). Despite this, the PBT agreement with LARC measurements is an improvement over cBathy: the RMSE and bias are both reduced to 0.56 m and -0.26 m, respectively.

These results are highlighted in a profile comparison at $Y = 780$ m (Figure 4-4). Figure 4-4 shows the cBathy limitations during large wave breaking conditions. As expected, the cBathy profile overestimates the depths where the bar should be located near the onset of wave breaking. As a result, it appears there is a bar 100 m onshore of the true location. In contrast, the PBT profile correctly locates the cross-shore position of the bar, albeit slightly overestimating the depths of the trough and bar due to its theoretical limitations.

Figure 4-4. Cross-shore profiles for September 15 mid-hurricane activity flight compared with corresponding LARC measurements. Local alongshore coordinate is $Y=780$ m. Geographic location is represented in Figure 4-3.

Final bathymetry estimates are further improved by blending the PBT and cBathy estimate in Figure 4-3, F. The cbathy/PBT blend reduces overall error (RMSE and bias of 0.44 and -0.11 m, respectively) with a slight underestimation of depth along the foreshore (Figure 4-3, G). The blended data set results in a more accurate overall profile by better capturing the depth of the trough (Figure 4-4).

4.1.4 Storm impact (morphologic change) results

Comparing the bathymetries from the July cBathy result and the September merged result, the UAS measurements capture 75 m of offshore movement of the bar over the course of the initial 2020 Atlantic Hurricane season, as seen in Figure 4-5, B and C (and via profiles in Figures 4-2 and 4-4). This offshore sandbar migration observed in the UAS data is consistent with the bathymetric change quantified by the two LARC surveys, shown in Figure 4-5, A and C. Figure 4-5, B does indicate that the UAS-based observations suggest an increase in accretion in the forehore region relative to the LARC surveys during this same time period. This could be due to real changes that may have occurred between flights and surveys (10 days each) but could also be a result of algorithm error and failure to resolve smaller scale features. Regardless, the represented change can still be used to quantify offshore bar migration patterns and improve bottom boundary conditions for numerical modeling efforts. Note that this change occurred in less than 2 months, further emphasizing the need for frequent bathymetric measurements in coastal environments.

Figure 4-5. Difference maps between mid- and pre-hurricane activity flights using A) LARC measurements and B) *guiBathy* estimates. Red indicates accretion where blue indicates erosion. Coordinates in North Carolina State Plane and NAVD-88. Black lines indicate location of cross-shore profile plotted in C).

5 Conclusion

This report detailed *guiBathy*, a GUI to estimate nearshore bathymetry from hovering UAS imagery utilizing the cBathy and PBT algorithms. The report outlined the data collection requirements and algorithm assumptions, as well as operational use of the GUI. Software Application was demonstrated with UAS measurements during the 2020 Atlantic Hurricane Season at Duck, NC. UAS and *guiBathy* have the potential to transform federal beach project monitoring efforts, allowing for rapid and cost-effective bathymetric surveys to develop a holistic understanding of system behavior and response to better manage recovery resources.

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Acronyms and Abbreviations

AGL	Above Ground Level
CCW	counterclockwise
CHL	Coastal and Hydraulics Laboratory
CONOPS	Concept of Operations
COTS	commercial-off-the-shelf
ERDC	US Army Research and Development Center
FOV	field of view
GCP	Ground Control Point
GUI	graphical user interface
LARC	Lighter Amphibious Resupply Cargo
MTL	Mean Tidal Level
PBT	Parametric Beach Tool
PPK	Post-Processed-Kinematic
RMSE	root-mean-square-error
RTK	Real-Time-Kinematic
SCP	Stabilization Control Point
SfM	Structure from Motion
UAS	unmanned aerial system
USACE	US Army Corps of Engineers

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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1. REPORT DATE February 2021.		2. REPORT TYPE Final Report		3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE guiBathy: A Graphical User Interface to Estimate Nearshore Bathymetry from Hovering Unmanned Aerial System Imagery				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Brittany Bruder, Katherine Brodie, Tyler Hesser, Nicholas Spore, Matthew Farthing, Matthew Geheran, and Alexander Renaud				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Coastal and Hydraulics Laboratory US Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CHL TR-21-3		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Flood and Coastal Systems Research and Development Program Vicksburg, MS 39180				10. SPONSOR/MONITOR'S ACRONYM(S) USACE		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES Funding Account Code U4363305; AMSCO Code 031398; Unmanned Aircraft Systems Support to Flood Risk Management						
14. ABSTRACT This US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, technical report details <i>guiBathy</i> , a graphical user interface to estimate nearshore bathymetry from imagery collected via a hovering Unmanned Aerial System (UAS). <i>guiBathy</i> provides an end-to-end solution for non-subject-matter-experts to utilize commercial-off-the-shelf UAS to collect quantitative imagery of the nearshore by packaging robust photogrammetric and signal-processing algorithms into an easy-to-use software interface. This report begins by providing brief background on coastal imaging and the photogrammetry and bathymetric inversion algorithms <i>guiBathy</i> utilizes, as well as UAS data collection requirements. The report then describes <i>guiBathy</i> software specifications, features, and workflow. Example <i>guiBathy</i> applications conclude the report with UAS bathymetry measurements taken during the 2020 Atlantic Hurricane Season, which compare favorably (root mean square error = 0.44 to 0.72 m; bias = -0.35 to -0.11 m) with in situ survey measurements. <i>guiBathy</i> is a standalone executable software for Windows 10 platforms and will be freely available at www.github.com/erdc .						
15. SUBJECT TERMS Aerial photography, Drone aircraft, Hurricanes—Atlantic Ocean, Imaging systems—Computer programs, Shorelines--Monitoring						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 49	19a. NAME OF RESPONSIBLE PERSON Brittany Bruder	
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code) 252-261-3511, ext. 230	
Unclassified	Unclassified	Unclassified				