BATHYMETRIC MAPPING OF SHALLOW WATERS IN LIAN, BATANGAS USING UNMANNED AERIAL VEHICLE (UAV)

Katelene Panlilio, Salvacion Mae Pedido, Roseanne Ramos, Ayin Tamondong

Department of Geodetic Engineering, University of the Philippines, Diliman, Quezon City, 1101, Philippines
Email: katkatpanlilio@gmail.com; sgpedido@gmail.com; rvramos@up.edu.ph; amtamondong@up.edu.ph

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ABSTRACT: The Philippines, being an archipelagic country, entails bathymetric mapping of its shallow waters. Traditional vessel-based bathymetric surveys usually do not permit mapping of shallow waters since doing so damages both the equipment, the bottom surface and existing marine habitats. Hence, this research is conducted to test the potential of an Unmanned Aerial Vehicle (UAV) in determining bathymetry of a beach area in Lian, Batangas, Philippines. Various flight parameter settings such as 10 to 30 degrees camera tilt and 40 to 60 meters flying height are employed on bathymetric surveys using a quadcopter UAV at shallow waters with depth less than 2 meters. Ground controls were established offshore and approximately 10 meters away from the shoreline using GNSS observations and total station measurements. A refraction correction algorithm was applied on the UAV-derived apparent bottom elevations to estimate the actual bottom elevations. A corrector surface, obtained through Least Squares Adjustment (LSA) method, was also carried out to determine the adjusted depths. Depths extracted by subtracting bottom surface elevations from water surface elevations were utilized to generate bathymetric maps. In-situ depth measurements were compared with and used to validate the UAV-derived depths. Root mean square error (RMSE) and standard deviation (SD) were calculated to assess the accuracy of the bathymetry derived from UAV images. Refraction correction results show smaller errors for the second flight (RMSE = 26.9 cm, SD =12.5 cm) compared with the first flight (RMSE = 45.2 cm, SD = 28.5 cm). Errors were reduced for both the second flight (RMSE = 6 cm, SD = 5.9 cm) and first flight (RMSE = 6.4 cm, SD = 5.9 cm) using the LSA-based corrector surface. These results demonstrate that UAV, supplemented by other surveying methods, has a large potential in mapping shallow water bathymetry of beaches and coastal areas. The techniques presented in this study can also be helpful for easier and safer navigation, post-storm monitoring and management of the dynamic shallow waters.

1. INTRODUCTION

The Philippines is an archipelagic country in Southeast Asia confined by numerous deep waters such as the Pacific Ocean to its East, Celebes Sea to its South, and West Philippine Sea to its West. With the huge number of island count and approximately 36,000kilometer-long coastline, municipalities lying on coastal areas tend to become reliant mainly on its coastal waters for resources such as food, oil, gas, mineral salt, clean air and water, and livelihood. Rich ecosystems like beaches, mangroves, seagrass beds and coral reefs provide shelter and breeding areas for various organisms. The importance of these natural resources entails bathymetric mapping of its shallow waters as these are mostly found near the coast.

Emerging technologies such as ship-borne echosounder have been used conventionally to determine bathymetry of shallow water; however, the process is usually expensive, difficult, time-consuming and tedious. Depths at deep water are usually obtained with the use of an echosounder, a type of Sound Navigation and Ranging (SONAR) attached in a large vessel or a survey boat. The challenge is that vessel-based bathymetry cannot be performed safely on shallow portions of water since the boats will damage the bottom surface and the marine habitats living in shallow waters. The presence and significance of these marine habitats drive the researchers to propose an alternative way of mapping shallow-water bathymetry with the use of aerial photogrammetry, specifically using an Unmanned Aerial Vehicle (UAV), to complement the limitations of the traditional vessel-based method. The growth of inhabitants and the continuous damage of coastal areas demand an effort to better monitor, preserve and protect shallow water biodiversity. This study shall provide an alternative way of approximating bathymetry that is faster, more efficient and safer as compared to vessel-based bathymetry. The output bathymetry will aid in monitoring the shores, for managing the coastal resources and for better planning and decision-making in coastal communities.

The region of interest is an irregular area approximately 28,000 square meters located along the coast of Lian, Batangas, Philippines and is bounded by the yellow polygon shown in Figure 1. The shallow portions consist of clear water wherein bottom surface can be seen clearly overhead and waves are minimal. Shallow water depth value adopted in this research is based on the defined depth less than 2 meters by Dietrich (2016). Validation data is acquired through traditional topographic surveys and random samples are obtained within the duration of the UAV flights.

Tidal corrections applied are based on an open-source prediction program that provides tide data within the drone flight times.

Figure 1. Study site located at Lian, Batangas, Philippines.

2. UAV AND AERIAL PHOTOGRAMMETRY FOR MAPPING BATHYMETRY

UAVs or drones are mostly utilized in the past to deliver strategies for wars, for disaster relief operations, for wildlife monitoring and even for filmmaking. Recently, the use of drones has become widely used for coastal monitoring (Aarnink, 2017). Images from a drone for mapping hydraulic and hydrologic variables are more preferred compared to satellite monitoring because UAV images ensure high spatial resolution, repeatability of flight missions and good tracking of the water bodies (Bandini, et.al., 2019). Ground or in-situ measurements are commonly used but they pose limitations such as insufficient monitoring gauge stations or networks, time gaps in records and differences in data processing and quality control algorithms (Bandini, 2017).

The primary steps in obtaining bathymetric data from UAV images are (1) generation of two-dimensional (2D) coordinates, (2) rectification stabilization, which translates the 2D coordinates to XYZ coordinates, and (3) depth computation (Aarnink, 2017). The acquisition and processing of these drone images are based on the concept of Structure from Motion (SfM), which can be utilized in bathymetric mapping. Overlapping images captured from multiple different views are processed to determine the geometry of the object or scene of interest (Micheletti, et.al., 2015), which is a faster and inexpensive method compared to traditional surveys and satellite remote sensing techniques. However, the main challenge to accurately map bathymetry using photogrammetry is correcting for the refraction of light as it passes between two different media (i.e. air and water), which causes water depths to appear shallower than they are (Dietrich, 2016). Photogrammetry-derived water depth is subject to correction based on the index of refraction, angle of observation, and the depth of the water itself (Tewinkel, 1963). Water is particularly sensitive to the sun–target–sensor geometry and water pixels look very different when observed at different times of the day or from different angles (Marcus and Fonstad, 2008). There can also be effects of glare on the images taken at high tilt or angle and images may contain reflected features from near-channel objects such as trees and low-altitude clouds.

UAV+SfM method is mostly used in inland waters such as monitoring of stream and river habitats (Klein Hentz, et.al., 2018), rehabilitation of rivers (Bagheri, et.al., 2015) and optical bathymetric modeling of inundated areas (Javernick, et.al., 2014). This approach is also applicable to coastal environments provided that shallow depths are found in these areas that are similar to small river systems. SfM photogrammetry involves a process that automatically finds and matches a limited number of common features between images which are then used to establish both camera interior and exterior orientation parameters (Micheletti, et.al., 2015). The resulting high resolution and color-coded point cloud become the main input for the succeeding processes. Dietrich (2016) developed an iterative approach in calculating refraction corrections for every point or camera combination in an SfM point cloud which is meant to address shortcomings of other correction techniques. In his study, the refraction correction from multiple cameras produced bathymetric datasets with accuracies of ~0.02% of the flying height and precisions of ~0.1% of the flying height. However, this methodology is also limited by ideal conditions such as clear water and minimal surface waves.

3. MATERIALS AND METHODS

The general workflow in this research is shown in Figure 2. Bathymetry in shallow portions was derived on aerial images captured using a quadcopter drone and compared with in-situ depth measurements acquired from topographic surveys. The detailed processes are discussed in section 3.2.

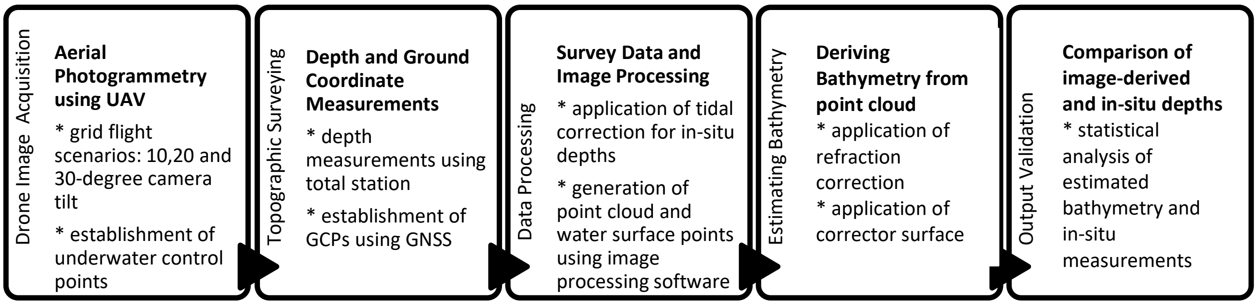

Figure 2. Research Workflow

3.1 Survey Equipment and Software

Aerial imaging surveys were conducted using a DJI Phantom 4 Pro quadcopter drone (refer to Figure 3) with an optical RGB camera of 24 mm equivalent focal length and aperture ranging from f/2.8 to f/11. This type of drone has a mechanical shutter that provides high-quality images with minimal distortions when capturing fast-moving objects. The hover accuracy ranges for vertical and horizontal positioning are ±0.5 m and ±1.5 m, respectively. Prior to drone flights, 20x20 cm grid targets (also shown in Figure 3) are deployed underwater. The grids were made using tarpaulins painted with black. These were later fastened with a rope and a colored plastic bottle at the end for quick retrieval of points. The deployed control points were positioned using four pieces of 2.5lb sinkers and rocks. Other materials include steel tape, scissors, and electrical tape. These targets serve as reference points in processing the aerial images.

(a) (b)

Figure 3. Imaging sensor (a) and materials in creating grid targets (b) in aerial mapping

Equipment used for the measurement of horizontal control coordinates and depths includes a total station, prism target and rods, and a survey-grade GNSS receiver (refer to Figure 4).

(a) (b)

Figure 4. Total station and prism target (a) and survey-grade GNSS receiver (b)

The software used for image acquisition and processing are Pix4DCapture and Pix4D Pro, respectively. Pix4DCapture is a free and downloadable mobile application used to easily generate and execute a flight plan. To connect to DJI drones, a plug-in called Ctrl+DJI is utilized. One advantage of using this application is that it easily defines and adjusts parameters such as the size of the subject area, image overlap, altitude of flight, camera angle. Also, it provides the user a live feed of the camera's view for monitoring purpose. Pix4D Pro is used to generate the 3D models and images of the coastal area.

Other software applications utilized in this research are WxTide and MS Excel (for applying tidal correction and processing of in-situ depths), Cloud Compare (for generating the 3D point cloud from stitched aerial images), Python 2.7 (for application of refraction correction algorithm) and QGIS (for viewing, editing and analysis of topographic and bathymetric points).

3.2 Detailed Methodology

Aerial photos were taken at an altitude of 50 meters above ground level and with camera angles equal to 10, 20, and 30 degrees. All flights were designed to capture images with 80% overlap. Ground control points were established using GNSS observations simultaneously with the drone flights. Topographic surveys were executed at a 2-meter interval at portions parallel to the shoreline (refer to Figure 5). Water surface and bottom elevations were measured to estimate actual depths and later corrected with tidal data.

(a) (b)

Figure 5. Drone flights (a) and topographic surveys (b) for estimating water depths

Processing of drone images includes photo alignment and generation of dense point cloud using Pix4D Pro. The dense point cloud is used to generate water surface elevations and apparent bottom surface elevations of the shallow region of interest in this study. These conversions were done in CloudCompare using functions Point List Picking Tool, creation of Delaunay Mesh, Subsampling tool, Cloud to Mesh distance and Filter by Value tool. The computation of the apparent depth is shown in steps summarized in Figure 6.

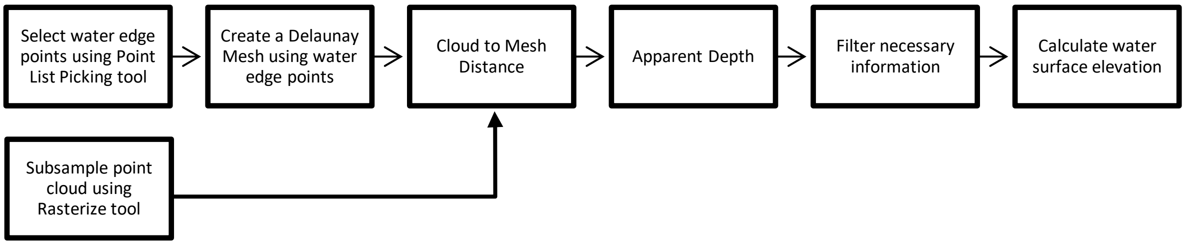

Figure 6. Depth determination from point cloud

The refraction correction algorithm, based on the study of Dietrich (2016), is applied on the point cloud file containing values XYZ_oZ_i (i.e. easting, northing, bottom surface elevation and water surface elevation). Other required files are the camera orientation file containing the drone camera position information (i.e. easting, northing, altitude, pitch, roll and yaw) and the camera parameters focal length and sensor dimension in millimeters. The refraction angle (r), as illustrated in Figure 7, can be computed based on the relationship of the camera position (X_c Y_c Z_c) and target position (X_a Y_a Z_a). The actual position of the targets is at point X_p Y_p Z_p.

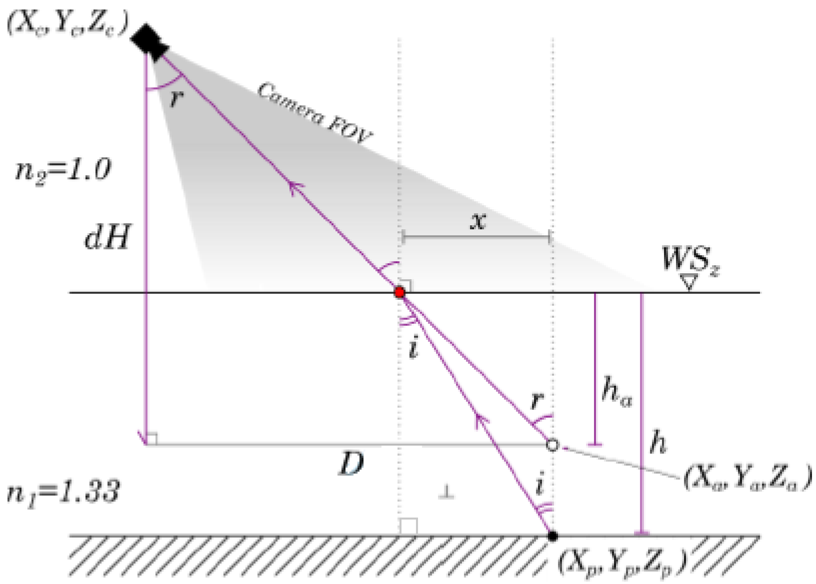

Figure 7. Refraction correction illustration (Dietrich, 2016)

The Euclidian distance D between the camera and target is computed using Equation 1:

$$r = tan^{-1}(\frac{D}{dH}) \tag{1}$$

where r = camera rotation angle, D = Euclidian distance and dH = point elevation relative to camera position.

Using Snell's Law, the refraction angle is computed using Equation 2:

$$n_1 \sin(i) = n_2 \sin(r) \tag{2}$$

where n_1 = water refraction index, n_2 =air refraction index and i = incidence angle and r = refraction angle.

The apparent depths are then computed using Equations 3 and 4:

$$x = h_a * \tan(r) \tag{3}$$

$$h = \frac{x}{\tan(i)} \quad (4)$$

where x = Euclidian distance between incident water surface (WS) point and actual bottom surface point, h_a = apparent depth, h = actual depth.

The bottom surface elevations from these computations were compared with in-situ measurements from topographic surveys. Root Mean Square Error (RMSE) and Standard Deviation (SD) quantify the uncertainty in the estimation of depths from the drone images and is calculated using Equations 5 and 6:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(D_{UAV} - D_{topo}\right)^2}{N}} \quad (5)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(D_{UAV} - \overline{D_{UAV}})^2}{N-1}} \quad (6)$$

where D_{UAV} = bottom elevation derived from UAV images, D_{topo} = bottom elevation derived from topographic survey and N = number of points compared.

After refraction correction, least squares method was then applied to minimize the square of the residuals – the difference between the observed values and the predicted value. The best-fit plane resulting from this process is a corrector surface. Randomly selected points from the topographic surveys were used as inputs in generating the corrector surface and the remaining set of points were used for validation. Corrector surfaces are developed with the objective of providing an optimal transformation between ellipsoidal heights h from GPS and orthometric heights H with respect to a given leveling datum (Fotopoulos, 2003). This model is necessary to account for the inconsistencies and systematic distortions between different datums and types of height data (You, 2006).

4. RESULTS AND DISCUSSION

4.1 Established control points and validation points

Control points were established for georeferencing the point cloud derived from UAV images and for validating depth measurements. Grid targets are placed underwater at random points within the region of interest (shown in Figure 8). Positions of these targets are referred from the ground controls established onshore using GNSS observations. The ground controls were used for obtaining in-situ depths using topographic surveying method.

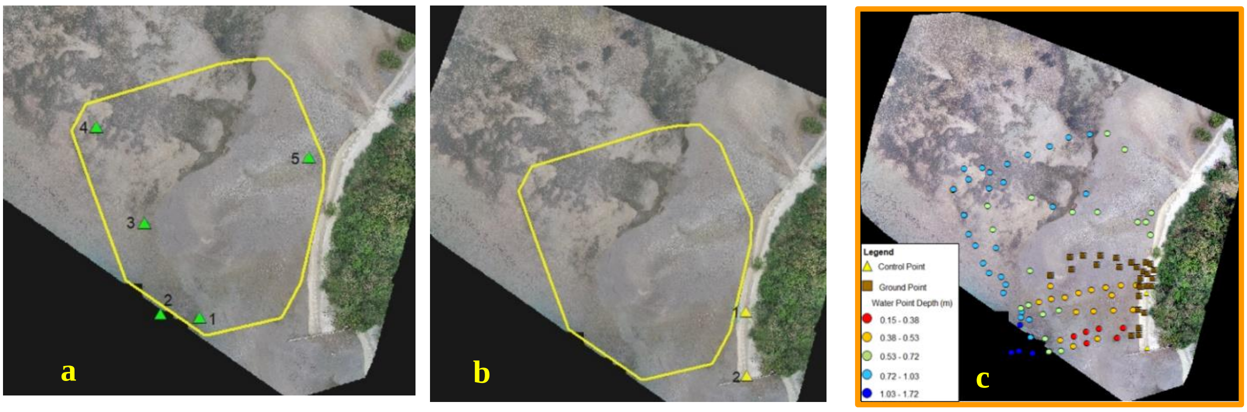

Figure 8. Underwater targets deployed (a), ground controls established (b) and in-situ depths obtained from topographic surveys within the study site

4.2 Point cloud derived from UAV images

The point cloud generated from calibrated UAV images for two different flights, flight 1 at 10-degree camera tilt and flight 2 at 20-degree camera tilt, are shown in Figure 9. A total of 228 calibrated images (82% of captured images) and 220 calibrated images (70% of captured images) from first and second flights, respectively, were utilized for depth computations.

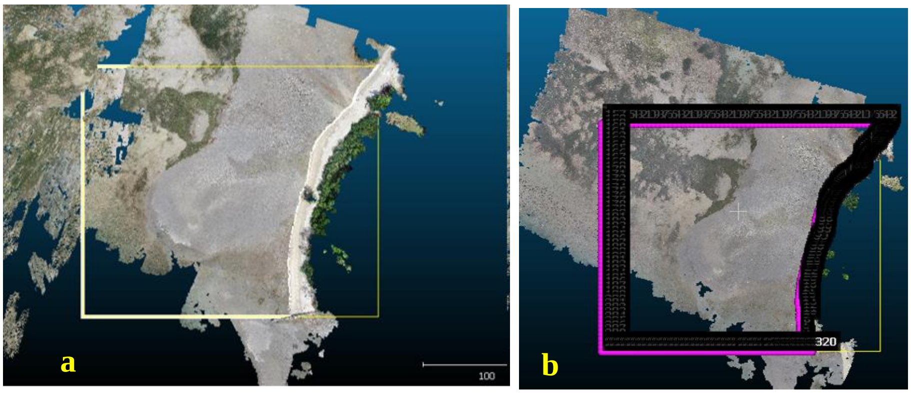

Figure 9. Point cloud derived from calibrated images of flight 1 (a) and flight 2 (b)

4.3 Bathymetry from UAV images and topographic surveys

Elevation values of point clouds generated from UAV flights and topographic survey points are shown in Figure 10. The elevation differences range from 0.010 to 0.720 m for flight 1 and 0.009 to 0.729 m for flight 2. These large differences in the elevation values are accounted for in the refraction correction algorithm and corrector surface computations.

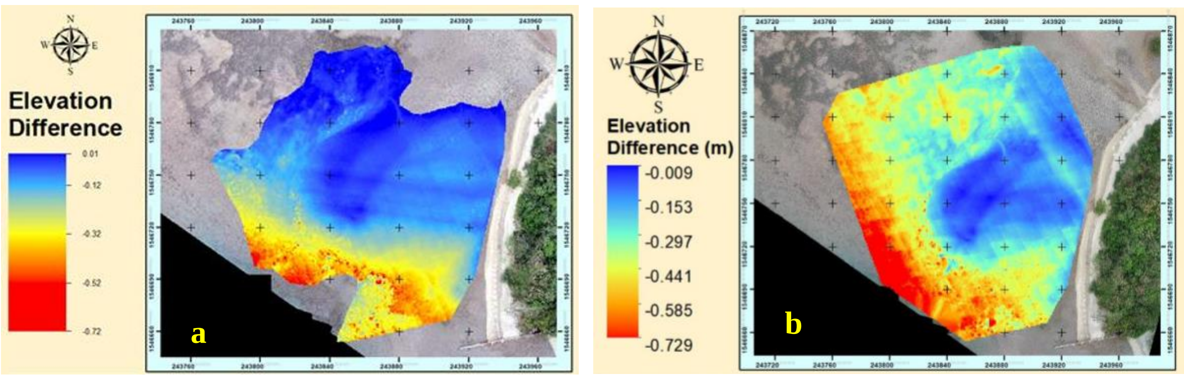

Figure 10. Elevation difference between refraction-corrected elevation and apparent elevation for flight 1 (a) and flight (2)

The results of these adjustments are the bathymetry from both flights, validated against the in-situ data from topographic surveys. Figure 11 shows the bathymetric surfaces from flights 1 and 2 compared with the surfaces generated from the topographic data.

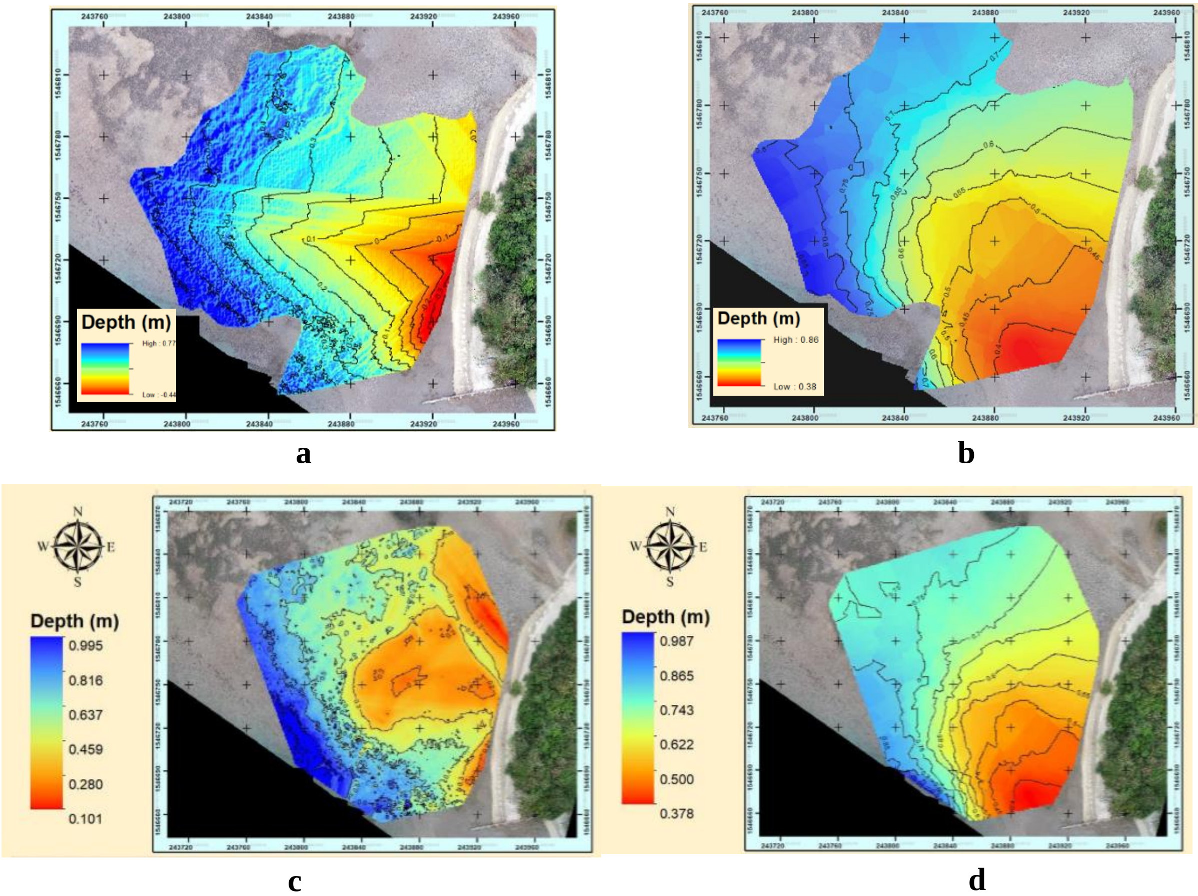

Figure 11. Bathymetric surface derived from UAV images for flight 1 and 2 (a,c) and bathymetric surface for flights 1 and 2 derived from topographic surveys (b,d)

4.4 Error analysis of bathymetric data

Statistical results show that UAV images for both flights can provide depth computations at sub-meter to centimeter accuracies. Table 1 summarizes the uncertainties in the output depths resulting from the refraction correction algorithm and application of a surface corrector. RMSEs range from 0.06 to 0.452 m and SDs range from 0.059 m to 0.285 m. The results indicate that the corrections applied in the apparent depths determined from the UAV images are significant in reducing these uncertainties.

Table 1. Statistical errors in estimating bathymetry from UAV images

Flight 1 (10-degree tilt)	RMSE (m)	SD (m)
With refraction correction	0.452	0.285
With surface corrector	0.064	0.060
Flight 2 (20-degree tilt)		
With refraction correction	0.269	0.125
With surface corrector	0.060	0.059

Possible sources of these errors are due to the presence of sun glint on some images as shown in Figure 12. The overall poor correlation of the UAV-derived depths and depths measured using a total-station may be attributed to these glinted images used in the computations.

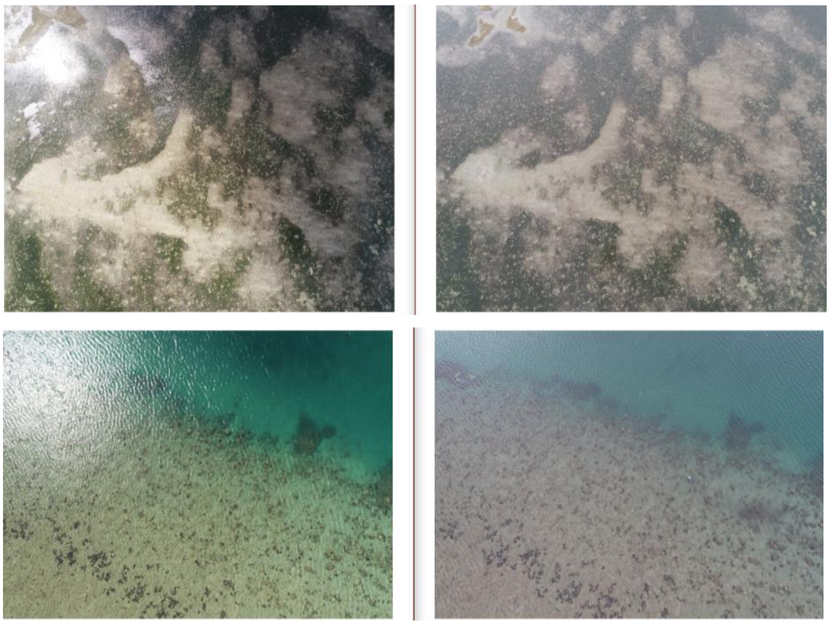

Figure 12. Sample images with glint from flight 1 (left) and flight 2 (right)

5. CONCLUSION AND RECOMMENDATIONS

The bathymetry of a small shallow region along the coast of Lian, Batangas is estimated using UAV images and validated against measurements from conventional topographic surveying method. The use of refraction correction algorithms and corrector surfaces were found to improve estimates at relatively low accuracies (i.e. sub-meter to centimeter level). The methodology and output bathymetry demonstrated in this study can be an initial step to better understand and enhance the potential of UAV in mapping shallow water bathymetry of beaches, which can be helpful for easier and safer navigation, for post-storm monitoring and for management of the dynamic shallow waters. For future studies, the researchers recommend performing similar set-ups taken at various dates within the same time frame to improve calculations and analysis of bathymetric data. Addition of control points and underwater targets is also recommended in creating highly accurate georeferenced images for the point cloud generation.

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REFERENCES

Aarnink, J.L., 2017. Bathymetry Mapping using Drone Imagery. MSc Thesis, Delft, Netherlands, Delft University of Technology.

Bagheri, O., Ghodsian, M., Saadatseresht, M., 2015. Reach scale application of UAV+ SFM method in shallow rivers hyperspatial bathymetry. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40(1), 77.

Bandini, F. 2017. Hydraulics and drones: observations of water level, bathymetry and water surface velocity from Unmanned Aerial Vehicles. Kgs. Lyngby: Department of Environmental Engineering, Technical University of Denmark (DTU).

Bandini, F., Luthi, B., Bauer-Gottwein, P., 2019. Unmanned Aerial Systems (UASS) for monitoring water surface elevation, bathymetry, surface velocity and discharge in streams. Hydrolink number 1/2019, pp. 10-12

Dietrich, J., 2016. Bathymetric Structure from Motion: Extracting shallow stream bathymetry from multi-view stereo photogrammetry. Earth Surface Processes and Landforms 42(2):355–364

Fotopoulos, G., Kotsakis, C., & Sideris, M. G. (2003). How accurately can we determine orthometric height differences from GPS and geoid data?. Journal of surveying engineering, 129(1), 1-10.

Javernick, L., Brasington, J., Caruso, B., 2014. Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry. Geomorphology, Volume 213, 15 May 2014, pp. 166-182.

Klein Hentz, Â. M., Kinder, P. J., Hubbart, J. A., Kellner, E., 2018. Accuracy and Optimal Altitude for Physical Habitat Assessment (PHA) of Stream Environments Using Unmanned Aerial Vehicles (UAV). Drones, 2(2), 20.

Marcus, W. A., Fonstad, M. A., 2008. Optical remote mapping of rivers at sub-meter resolutions and watershed extent. Earth Surface Processes and Landforms, 33, 4-24Micheletti, N., Chandler, J. H., & Lane, S. N., 2015. Structure from Motion (SfM) Photogrammetry. Geomorphological Techniques, Chapter 2, Sec. 2.2. (2015), British Society for Geomorphology.

Tewinkel, G. C. (1963). Water depths from aerial photographs. Photogrammetric Engineering, 29(6), 1037-1042.

You, R. J. (2006). Local geoid improvement using GPS and leveling data: Case study. Journal of surveying engineering, 132(3), 101-107.