

A Simple and Empirical Refraction Correction Method for UAV-Based Shallow-Water Photogrammetry

I GD Yudha Partama, A. Kanno, Y. Akamatsu, R. Inui, M. Goto, M. Sekine

Abstract—The aerial photogrammetry of shallow water bottoms has the potential to be an efficient high-resolution survey technique for shallow water topography, thanks to the advent of convenient UAV and automatic image processing techniques Structure-from-Motion (SfM) and Multi-View Stereo (MVS)). However, it suffers from the systematic overestimation of the bottom elevation, due to the light refraction at the air-water interface. In this study, we present an empirical method to correct for the effect of refraction after the usual SfM-MVS processing, using common software. The presented method utilizes the empirical relation between the measured true depth and the estimated apparent depth to generate an empirical correction factor. Furthermore, this correction factor was utilized to convert the apparent water depth into a refraction-corrected (real-scale) water depth. To examine its effectiveness, we applied the method to two river sites, and compared the RMS errors in the corrected bottom elevations with those obtained by three existing methods. The result shows that the presented method is more effective than the two existing methods: The method without applying correction factor and the method utilizes the refractive index of water (1.34) as correction factor. In comparison with the remaining existing method, which used the additive terms (offset) after calculating correction factor, the presented method performs well in Site 2 and worse in Site 1. However, we found this linear regression method to be unstable when the training data used for calibration are limited. It also suffers from a large negative bias in the correction factor when the apparent water depth estimated is affected by noise, according to our numerical experiment. Overall, the good accuracy of refraction correction method depends on various factors such as the locations, image acquisition, and GPS measurement conditions. The most effective method can be selected by using statistical selection (e.g. leave-one-out cross validation).

Keywords—Bottom elevation, multi-view stereo, river, structure-from-motion.

I. INTRODUCTION

MEASUREMENT of fluvial topographic data plays an important role in various management and research works such as the identification of river hydro-morphological features [1], investigation of bed deformation and bank erosion [2], assessment of river habitat quality [3], etc. These data are generally obtained by conventional on-site surveying, based on transverse profiles at locations selected to capture prominent features of the topography [4]. However, most of these methods require considerable labor and cost, and there is a limit to the

spatial and temporal resolutions of such monitoring.

In order to improve the reliability of the various operations, more frequent and high-density surveying is indispensable. Aerial photogrammetry based on stereo views is a technique for surveying with a wide field of view, and it has been employed to provide high spatial resolution topographic modeling, based on high density point cloud generation. However, this technique is limited in application because it requires expensive equipment (i.e. an aircraft and a sensor) and specialized user expertise to process the data.

In recent years, development of the SfM-MVS method, which is an automatic image-processing-based computer vision technology, has provided the opportunity for low-cost three-dimensional data acquisition. This method greatly reduces the level of expertise and ability required to extract high resolution and accurate spatial data, using cheap consumer-grade digital cameras mounted on UAVs (e.g. drones). Monitoring of both exposed and submerged terrain in river channels using this method is increasingly in demand for the creation of highly accurate terrain maps. The suitability of the method for exposed topographies has already been demonstrated and it has become clear that the UAV-SfM method has high accuracy and precision in dry areas [5]. In contrast, Digital Elevation Model (DEM) accuracy and precision are slightly poorer in submerged areas, due to the refraction of light at the air-water interface, as observed in studies using digital photogrammetry [5]-[7]. The submerged areas record shallower water depths than the reality due to this effect. Therefore, a refraction correction procedure is required.

A simple refraction correction procedure has been developed by [8]. This procedure proposes using the refractive index of water (1.34) as the correction factor (CF) to convert the apparent water depth into real water depth. This CF is the minimum possible value that can be used when the refraction effect is very low (i.e. camera position at the nadir of the target points). It can be shown geometrically that this CF is not always the optimal one, as revealed in the case of two cameras by [9]. According to [9], the CF varies depending on the position of the two cameras relative to the target points. However, in real underwater photogrammetry, it is not feasible to calculate the geometrical CF for two reasons: 1. No researcher has derived the geometrical CF for cases with more than two views. 2. Common photogrammetry software does not output the information on which camera was used for estimating the coordinates of each point (in the dense point cloud), which is required for calculating the geometrical CF.

In this study, we present an empirical approach that estimates a reasonable CF for a specific flight by minimizing the RMSE

I GD Yudha Partama is with the Graduate School of Science and Engineering, Yamaguchi University, Japan (e-mail: benzenoid_boyot@yahoo.co.id).

A. Kanno, Y. Akamatsu, R. Inui, M.Goto, and M. Sekine are with the Graduate School of Sciences and Technology for Innovation, Yamaguchi University, Japan (e-mail: kanno@yamaguchi-u.ac.jp, yakamats@yamaguchi-u.ac.jp, inuiyutei@gmail.com, gotou510gokobe@yahoo.co.jp, ms@yamaguchi-u.ac.jp).

(Root Mean Square Error) in the corrected bottom elevation. We also test its effectiveness through its application to two river sites. The RMSE and ME (Mean Error) values in the corrected bottom elevation were compared with those from the three other existing methods: the no correction approach ($CF = 1$), the conventional method using $CF = 1.34$, and a method using an empirical linear regression between measured and estimated water depth [10].

II. METHOD

A. Study Site

In this study, the two test sites (Sites 1 and 2) were located at the main section of Saba River, Yamaguchi Prefecture, Japan. Site 1 is located about 8.5 km from Saba River Estuary, and Site 2 is located about 1.7 km upstream of Site 1. Fig. 1 shows the extents of Site 1 and Site 2.

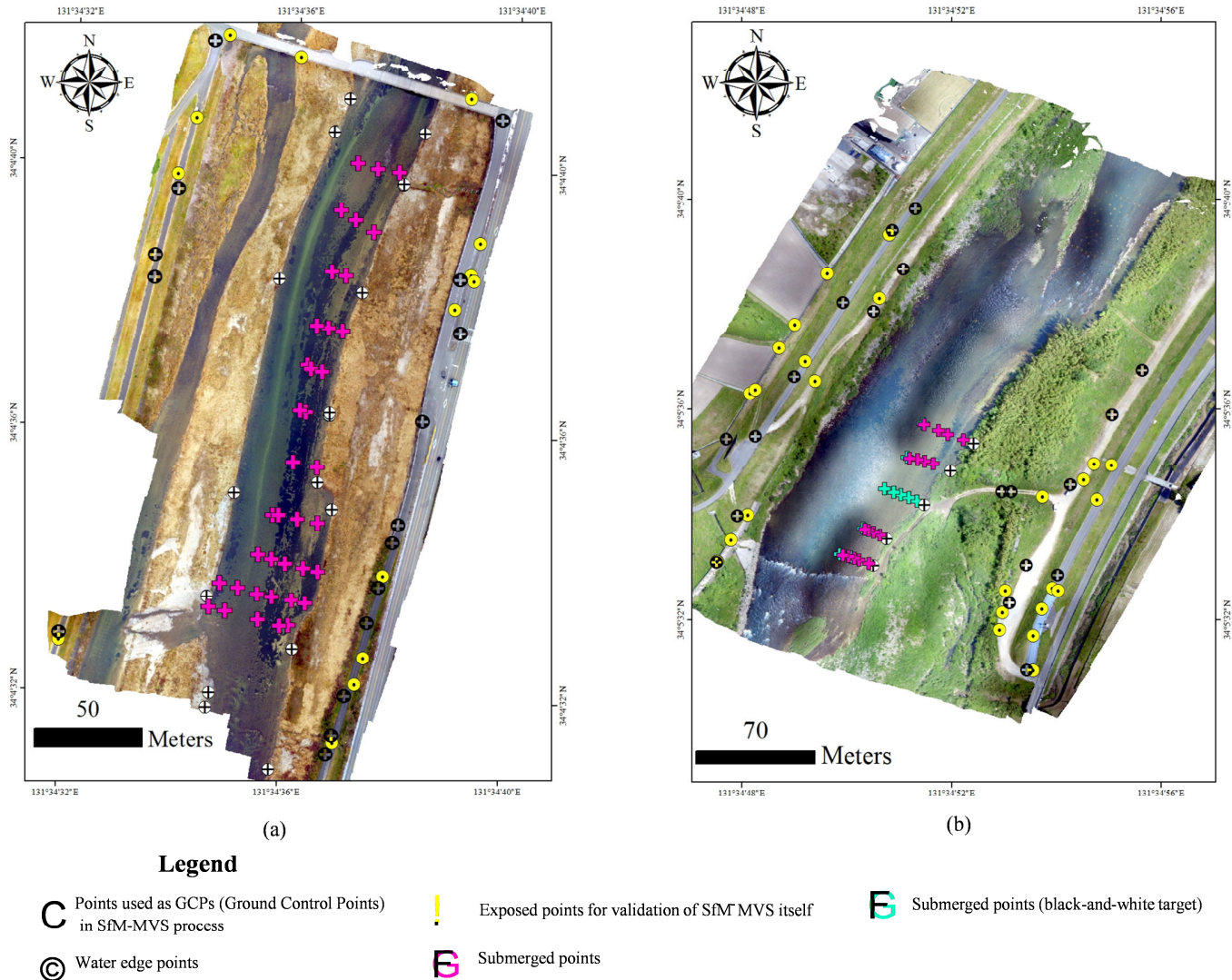


Fig. 1 The study sites and spatial distribution of the points measured by RTK-GPS in site 1 (a) and site 2 (b)

B. Image Acquisition and Image Selection

Aerial photos were collected using a 4K digital camera attached to a small, lightweight (1.28 kg), quad-copter UAV (a DJI Phantom 3 Professional). The UAV was flown at 25–30 m above ground level to give approximately 1 cm spatial resolution imagery of both sites. The resulting image footprint size was approximately 64 m × 48 m. Images were collected with a high level of overlap ($> 80\%$) to allow subsequent image matching during SfM processing. The total numbers of images collected at Sites 1 and 2 were 240 and 424, respectively. During each field survey, the position of the camera was set to

acquire imagery at the nadir (looking vertically downwards), to reduce the undesirable effects of reflection from the water surface on the acquired images. Finally, we checked all of the images and removed several images with blurring effects.

C. RTK-GPS Measurements

We performed RTK-GPS measurements at both exposed and submerged (underwater) points, as shown in Fig. 1. Exposed points were landmarks recognizable in the aerial photos: stones, pins, and the black-and-white targets that we installed. They were distributed to cover the whole area as much as possible: on

both banks of the river, and a bridge in Site 1. Some of them were used as Ground Control Points (GCPs) in the SfM-MVS procedure, and the others were used for validation of the SfM-MVS itself.

Submerged points were of two types. The first type includes the 10 black-and-white targets only used in Site 2. The second includes the points distributed to cover various depths and bottom types.

D. Generation of an Apparent Elevation Map of the Water Bottom by SfM-MVS

We generated the apparent elevation map of the water bottom at both sites using a commercial software, Agisoft PhotoScan Professional version 1.2.6. First, SfM was performed to estimate the camera's extrinsic and intrinsic parameters, as well as the coordinates of the sparse point clouds. GCPs were used to give the world coordinates and to adjust some intrinsic parameters of the camera. Second, Multi-View Stereovision was performed to obtain the dense point clouds. Finally, the orthophoto and Digital Surface Model (DSM) were generated. The submerged area was manually extracted for further analysis.

E. Spatial Interpolation of the Water Surface Elevation (WSE)

We constructed the estimated water surface elevation (WSE) model using a different method for each site. In Site 1, we created the WSE model by extracting water edge points from the orthophoto and DSM. We extracted the water edge points where the water's edge was clearly visible in the orthophoto. Thus, we applied a trend interpolation technique to build a two-dimensional model of the estimated WSE. In Site 2, where the water's edge cannot be accurately detected visually using the orthophoto (due to overhanging vegetation), we used a conventional in situ technique with measurement devices (i.e. RTK-GPS) to measure the WSE at water edge points and we applied a linear interpolation technique to build a one-dimensional model of estimated WSE along the river channel. Fig. 1 shows the distribution of measured water edge points at both sites.

F. Application of the Empirical Refraction Correction

We tried four refraction correction approaches to compare their performances. In fact, Method 1 corresponds to a no-correction case: the apparent elevation estimated by the SfM-MVS process is regarded as the refraction-corrected elevation. Methods 2 and 4 are the existing methods, and Method 3 is our method. In these methods, the refraction correction is based on (1):

$$h_R = p.h_A \quad (1)$$

where p is the gain of the refraction-CF, h_R and h_A are the real-scale, and apparent water depths are estimated as

$$\hat{h}_R \equiv \hat{z}_{sfc} - z_{R,btm} \quad (2)$$

$$\hat{h}_A \equiv \hat{z}_{sfc} - \hat{z}_{A,btm} \quad (3)$$

Here, \hat{z}_{sfc} is the water-surface elevation estimated by spatial interpolation of the elevations of water edge points (read from orthophotos or measured in situ), $z_{R,btm}$ is the real water bottom elevation measured by RTK-GPS, and $\hat{z}_{A,btm}$ is the estimated apparent water bottom from SfM-MVS. If we define the biases (mean errors) in \hat{h}_R and \hat{h}_A as $\bar{\epsilon}_R$ and $\bar{\epsilon}_A$, (1) can be rewritten as

$$\hat{h}_R = p.\hat{h}_A + \beta \quad (4)$$

where $\beta \equiv p.\bar{\epsilon}_A - \bar{\epsilon}_R$. (4) is the correction formula for water surface refraction.

Method 1 corresponds to using $p=1$ and $\beta=0$ in (4). Method 2, proposed by [8] and conventionally used by others [5], uses $p=1.34$ and $\beta=0$, where the value 1.34 is the relative index of refraction for the air-water interface. In Method 4, proposed by [10], p and β are estimated by linear regression between \hat{h}_R and \hat{h}_A . In Method 3, only p is estimated, and $\beta=0$ is assumed.

G. Calculation of the Refraction-Corrected Bottom Elevation

To build the estimated refraction-corrected elevation map of the water bottom, we followed a procedure from an existing method [8]. The first step of this method is generating the estimated apparent water depth map by subtracting the apparent elevation map of the water bottom from the WSE map. Next, we multiplied the apparent water depth map by the empirical refraction-CF to produce the refraction-corrected water depth map. Finally, to produce the refraction-corrected elevation map of the water bottom, we subtracted the refraction-corrected water depth map from the estimated WSE map.

H. Error Evaluation and Comparison

We compared the RMSE and ME in the corrected bottom elevations from the four methods at each site. In order to evaluate the RMSE and ME for Methods 3 and 4, we performed a cross validation. The cross validation consisted of 1000 calibration/prediction trials. In each trial, the available underwater points with GPS measurements were randomly split into training and test data. The correction formula was calibrated for p and β (in Method 4) using the training data, and then used to predict the h_R of the test data. The RMSEs of the prediction errors for the 1000 trials were evaluated for each site and method. Because using many underwater GPS measurements for the calibration will not be desirable in practical applications, we performed the cross validation for various numbers of training data.

III. RESULTS AND DISCUSSION

A. Validity of SfM-MVS in Exposed Areas

Fig. 2 (a) shows the apparent elevation map generated by the usual SfM-MVS procedure in Site 1, as an example. Table I lists the RMSE in the estimated X, Y, and Z coordinates of the GPS-measurement points not used as GCPs (Fig. 1). For the

exposed area, the RMSE for each axis was about 0.03 m on average for each site. It is of the same order as the general error in RTK-GPS measurements and demonstrates the success of our SfM-MVS procedure.

B. The Necessity of Refraction Correction

Table I also lists the RMSE in the apparent bottom elevation obtained by the SfM-MVS procedure for 10 submerged black-and-white targets in Site 2. We can observe that the

RMSE value for each of the X, Y, and Z coordinates is larger than that for the exposed area. Specifically, the RMSE values for the horizontal (X and Y) directions increased by a factor of only 1.6. On the other hand, in the vertical (Z) direction, the RMSE increased by a factor of more than 3.4. This shows that the refraction effect increases the errors mainly in the vertical (Z) direction, and indicates the importance of the correction method in that direction, which is the topic of this paper.

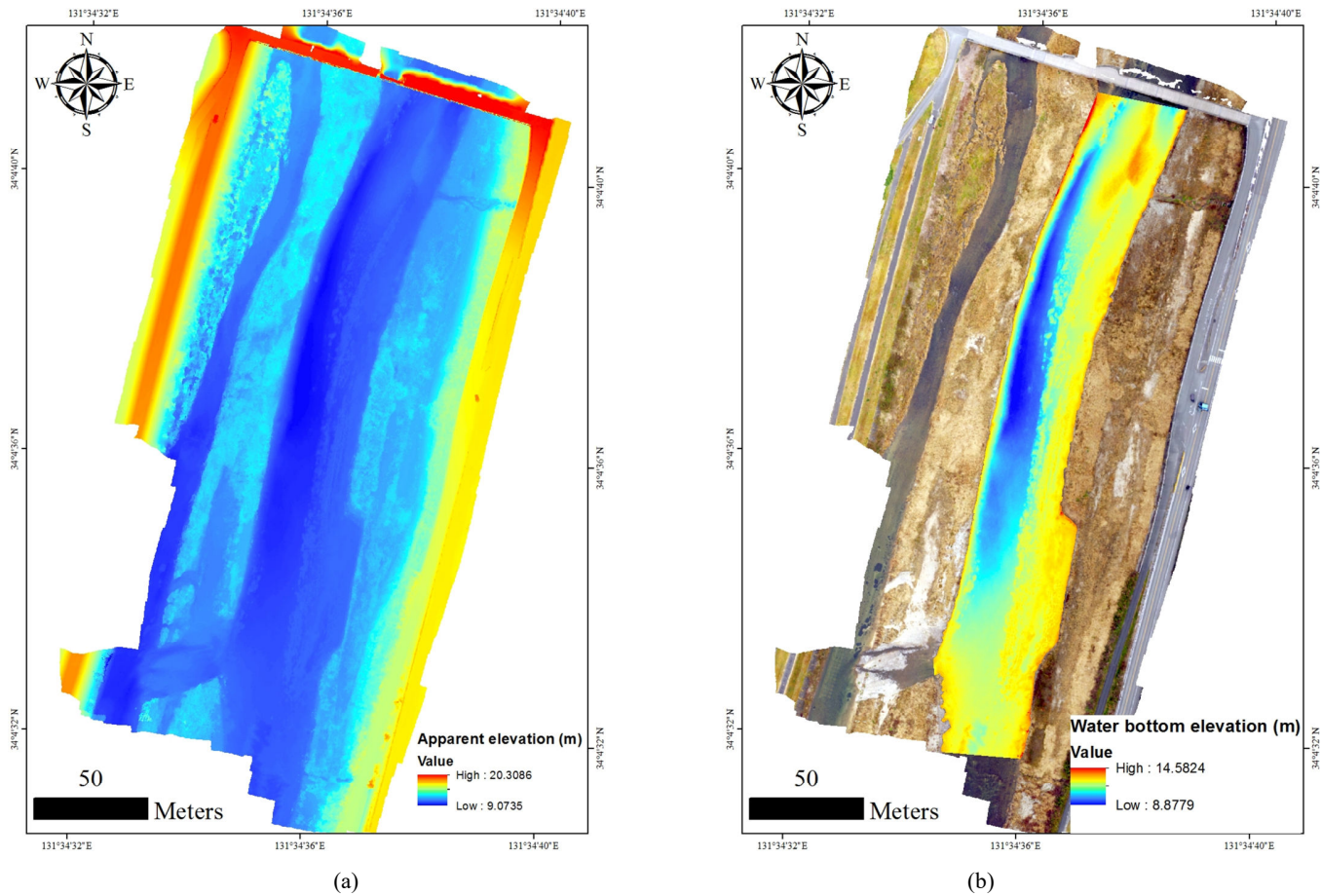


Fig. 2 Example of the resultant maps in Site 1. (a) the apparent elevation map generated by the SfM-MVS procedure (b) the water-bottom elevation map corrected for refraction by the proposed Method 3

TABLE I
 ROOT MEAN SQUARE ERRORS IN THE ESTIMATED X, Y, AND Z COORDINATES OF THE GPS-MEASUREMENT POINTS NOT USED AS GCPS

Site	Point type	RMSE (m)		
		X	Y	Z
1	exposed	0.0331	0.0192	0.0407
2	exposed	0.0306	0.0319	0.0371
2	submerged	0.0512	0.0505	0.1253

C. Error Statistics for Four the Correction Methods

Fig. 2(b) demonstrates the corrected bottom elevation map for Site 1 and Method 3. Figs. 3 (a) and (b) shows the RMSE and ME evaluated for each method and site. They were evaluated by the cross validation described in section II for Methods 3 and 4. For a visual understanding of the behavior of each method, Figs. 4 and 5 show the scatter plots of the

corrected against measured bottom elevations for Sites 1 and 2. Based on Fig. 3, overall, Method 1 resulted in the largest values of RMSE and ME (except for the case where Method 4 was calibrated with just two training data) due to the systematic overestimation (reflected in a large positive ME) introduced by neglecting the refraction effect. This result proves the necessity of a refraction correction.

As a result of the simple refraction correction, Method 2 resulted in RMSE and ME values about 40% smaller than Method 1, but it still suffered from a significant systematic overestimation (i.e. a large positive ME). This demonstrates the geometrical fact, described in the Introduction, that a CF of 1.34 is the minimum possible value and is not enough in a real application.

Methods 3 and 4 outperformed Methods 1 and 2, except

when the training data used for calibration were very few. For these methods, the RMSE and the ME increased as the number of training data decreased, and the increase was more significant for Method 4. This is statistically natural: the more degrees of freedom a regression model has, the more unstable are the estimates of the coefficients, and the model requires more training data to function well. As a result, Method 4, which has two degrees of freedom in the correction formula, yielded extremely large errors when the number of training data was two (the minimum possible number). On the other hand, Method 4 gave smaller magnitudes of RMSE and ME than Method 3 in Site 1 when the number of the training data was three or more.

Excluding the case where the training data numbered only two, Method 4 was superior (in terms of RMSE) in Site 1, and Method 3 was superior in Site 2, regardless of the number of

training data (Figs. 3 (a) and (b)). ME also showed a similar tendency. Therefore, we need to conclude that the best method depends not only on the number of training data but also on many other factors. Because the two methods are different only in the existence of the intercept β in (4), the best method depends on the true magnitude of β . As β depends on the errors in estimating the apparent elevations of the water surface and bottom, the best method may change depending on the site, image acquisition conditions, GPS measurement conditions, and so on. Because it is impossible to know the true value of β , we present statistically selecting the best method in each situation. One recommended selection method is the leave-one-out cross-validation, a cross-validation that uses only 1 test datum in each trial, and thereby can simulate the prediction errors when all the available GPS measurements are used for the calibration.

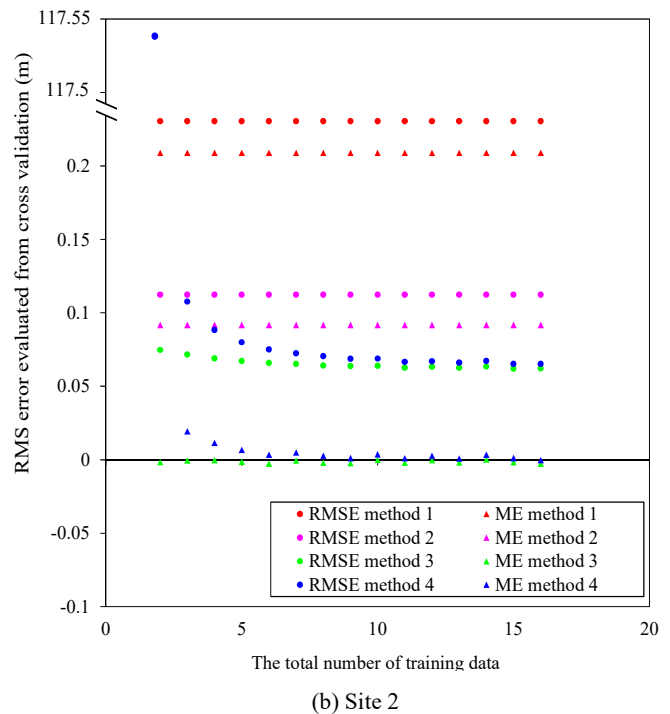
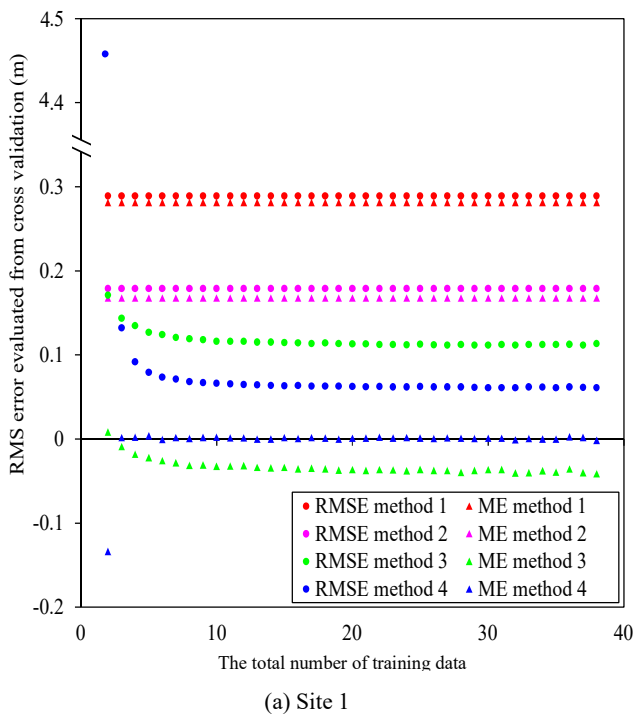


Fig. 3 RMSE and ME evaluated for each method and site, by cross validation for Methods 3 and 4, for different numbers of training data

D. Unrealistically Small Correction Factor (CF) in Site 1

Our method (Method 3) produced realistic CF values in both Site 1 and Site 2, as listed in Table II. On the other hand, the correction coefficient produced by Method 4 was unrealistically small in Site 1. This might be due to the large noise contained in h_A . This is likely because, in Site 1, the WSEs at the water edges were read from the orthophoto, and thus contain errors resulting from unclear edge readings as well as the photogrammetry itself.

TABLE II
 THE CORRECTION COEFFICIENTS FOR EACH METHOD AND SITE

Method	Correction Factor p		Offset β (m)	
	Site 1	Site 2	Site 1	Site 2
1 (no correction)	1.000		0.0000	
2 (conventional)	1.340		0.0000	
3 (proposed)	1.722	1.603	0.0000	0.0000
4 (linear regression)	1.200	1.566	1.0703	0.0264

For methods 3 and 4, the coefficients were calculated using all the available underwater GPS measurements.

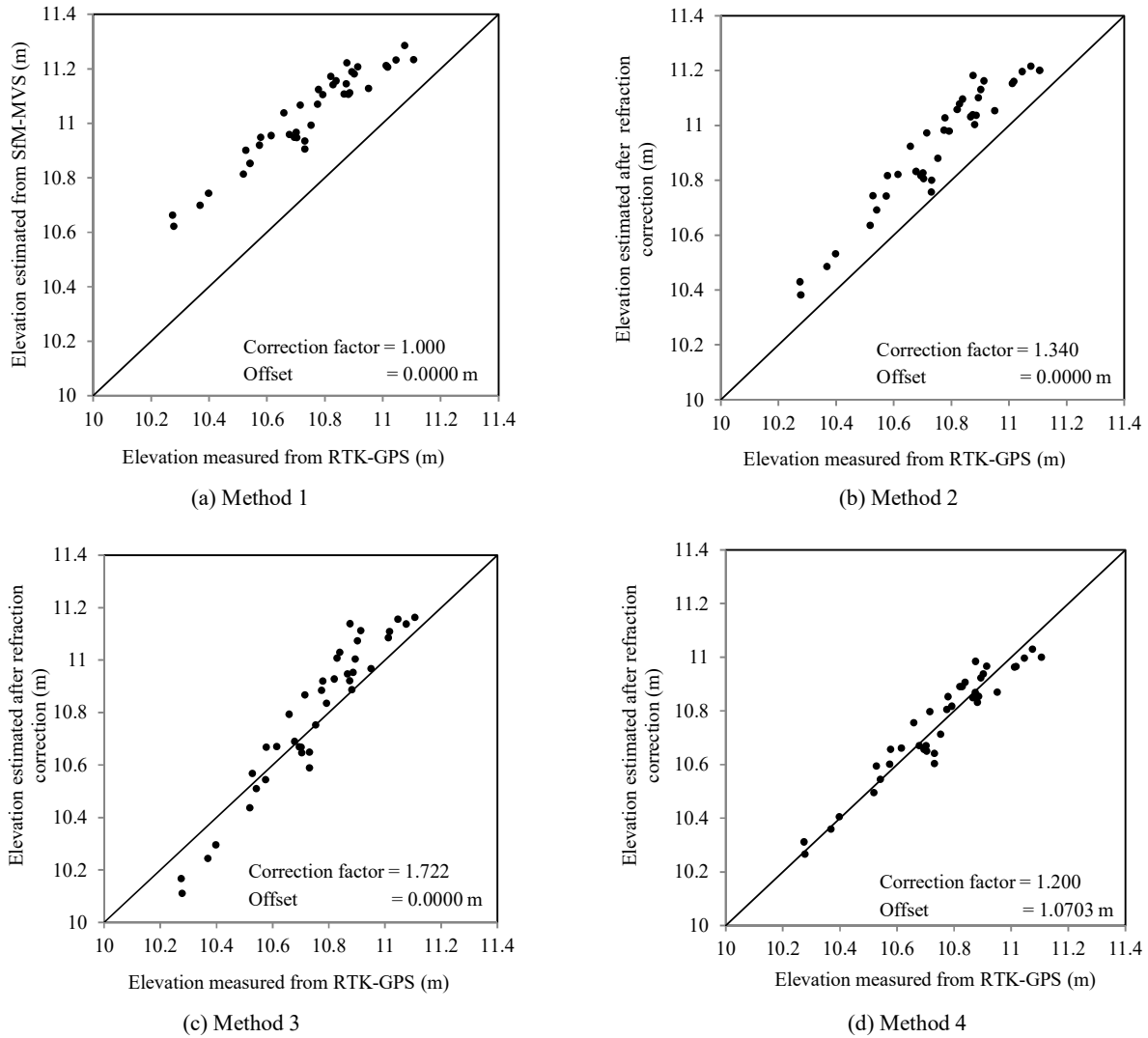


Fig. 4 Elevation estimated after correction, plotted against elevation measured from RTK-GPS, in Site 1 for (a) Method 1, (b) Method 2, (c) Method 3, (d) Method 4. For Methods 3 and 4, the figure shows the goodness of fit rather than prediction performance because all the plotted data were used to calibrate these methods

In order to examine this hypothesis, we performed another numerical experiment to observe the effect of the noise in h_A on the estimated CF. In this experiment, we added artificial normal noise with zero mean and various standard deviations to h_A , estimated the CF, and observed how it changes in response to the noise levels. Such estimation was done 1000 times for each method and for each site, using a same seed of random number generator. The result is summarized in Fig. 6.

We can observe that, for Method 4, the mean of the estimated CF significantly decreases as the noise level increases, supporting the hypothesis described in paragraph one. This means that Method 4 suffers from a large negative bias in the CF when h_A is noisy. On the other hand, the decrease for Method 3 is much less, showing the robustness of Method 3 against noise in h_A . This result indicates the superiority of Method 3 in terms of the geometric soundness of the estimated CF.

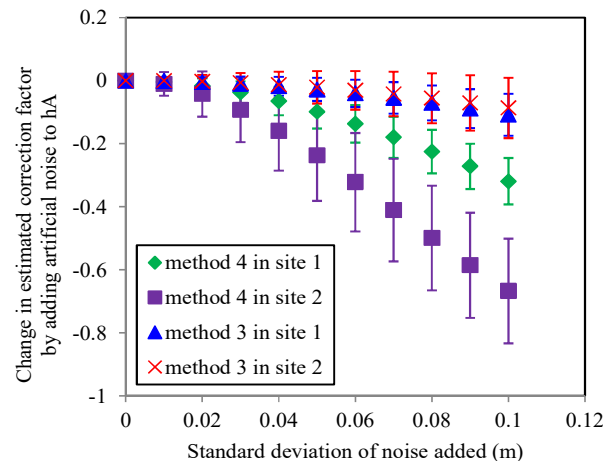


Fig. 6 The change in estimated CF when artificial normal noises were added to h_A . Points show the mean values, and error bars show the standard deviations, in 1000 trials

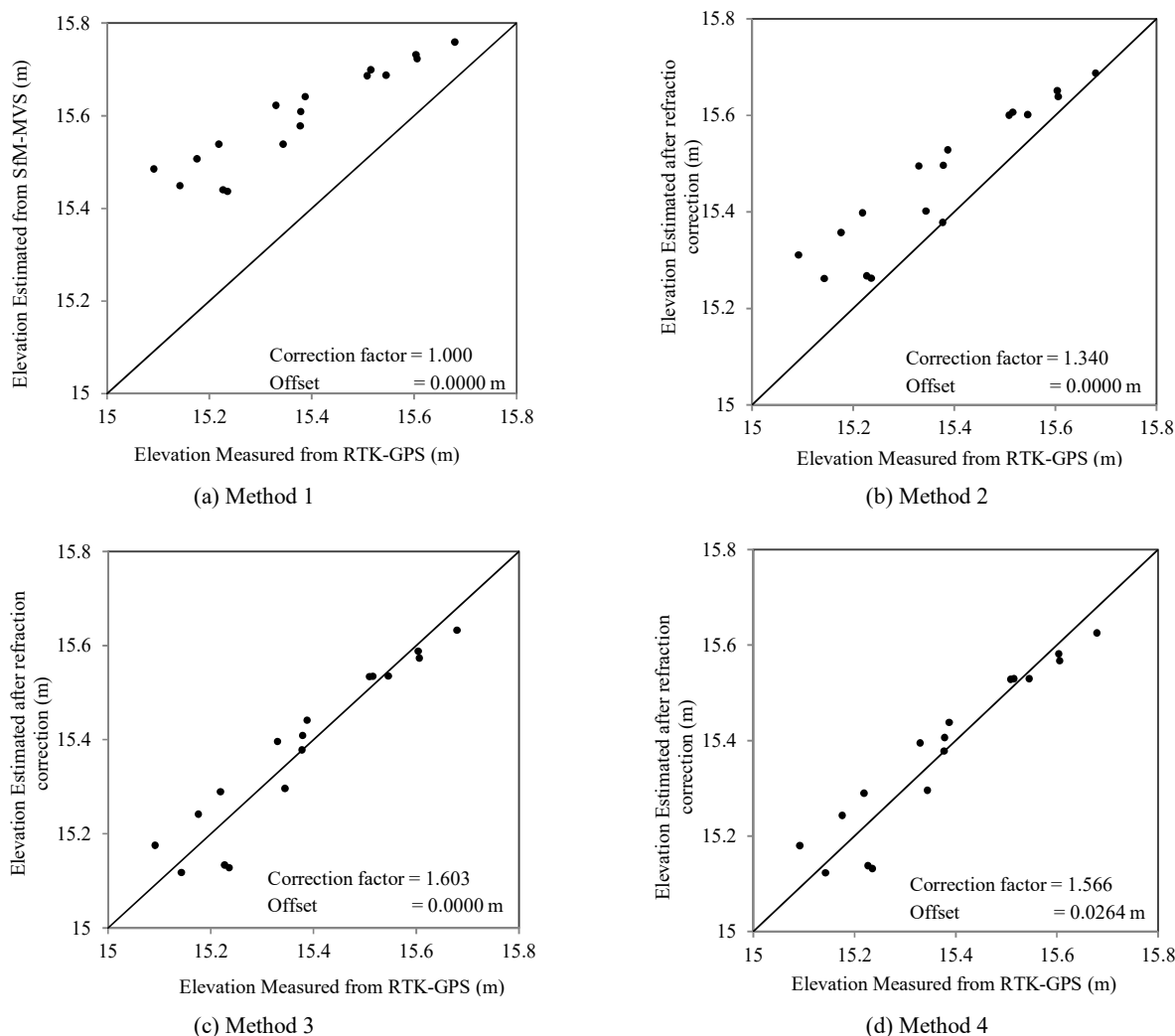


Fig. 5 Elevation estimated after correction, plotted against elevation measured from RTK-GPS, in Site 2 for (a) Method 1, (b) Method 2, (c) Method 3, (d) Method 4. For Methods 3 and 4, the figure shows the goodness of fit rather than prediction performance because all the plotted data were used to calibrate these methods

IV. CONCLUSION

This study presented and examined an empirical method to correct for the effect of refraction after the usual SfM-MVS procedure using common software. The presented method converts the apparent water depth into a refraction-corrected (real-scale) water depth by multiplying by an empirical CF. We examined its effectiveness by applying the method to two river sites, and comparing the RMSE and ME in the corrected bottom elevation with the three existing approaches. Overall, the presented method outperformed two of the existing methods: the no-correction approach (Method 1) and the method using the relative index of refraction (1.34) as the CF (Method 2). The remaining existing method (Method 4), which adds an empirical offset after multiplying by the empirical CF, was unstable when the training data for calibration were very few. Excluding such cases, Method 4 performed better in Site 1 and worse in Site 2 than the presented method. In addition, we found that the linear regression method (Method 4) suffers from a large negative bias in the CF when the apparent water depth

estimated is noisy. We conclude that the most accurate correction method in terms of the bottom elevation depends on many factors (e.g. site, image acquisition conditions, GPS measurement conditions), and should be statistically selected, for example by leave-one-out cross validation.

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