A Photogrammetric Correction Procedure for Light Refraction Effects at a Two-Medium Boundary

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A Photogrammetric Correction Procedure for Light Refraction Effects at a Two-Medium Boundary

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Abstract

We report on a correction procedure for light refraction effects at a two-medium boundary, based on the stereo view of underwater objects, to estimate underwater topography using photogrammetry. Because theoretically, no solution exists for photogrammetrically observed positions when the incident angles of light rays from an underwater object of interest to two cameras are different; approximation in solving the positions is needed. We show the feasibility of the approximation theoretically by examining the horizontal differences between the observed and true positions when objects are in line along an airplane track or when the incident angles are identical. We applied the procedure to bathymetric mapping of Shiraho Reef, southwest Japan, using a stereo-pair of aerial photographs. Comparison of the corrected depths with measured depths at 658 points showed a mean error and standard deviation of −0.06 m and 0.36 m, respectively, for measured depth range of −3.4 m to −0.2 m.

Introduction

Photogrammetry is an effective tool in mapping detailed surface morphology, and resulting elevation data based on stereo-pairs of aerial photographs have been used for efficient analyses of surface and geomorphic features (e.g., Collins and Chisholm, 1991; Chandler, 1999; Lane *et al.*, 2000; Lin and Oguchi, 2002). While satellite- or laser-based precise topographic mapping techniques have emerged recently (e.g., Ackermann, 1999; Toutin, 2004), photogrammetry is advantageous in that it can be applied to historical aerial photographs to elucidate three-dimensional surface changes over a decadal timescale (Brown and Arbogast, 1999; Suzuki *et al.*, 2001). Recent advances in computer technology have provided the use of digital photogrammetry to construct digital elevation models (DEM), which performs the photogrammetric workflow in a completely digital environment through a digital photogrammetry workstation (DPW).

Underwater topography, such as riverbeds and coastal seafloors, can also be measured using photogrammetric techniques. Such techniques could be an alternative to satellite- or laser-based bathymetric mapping techniques in clear, optically shallow water (e.g., Mason *et al.*, 1995; Irish and Lillycrop, 1999; Stumpf *et al.*, 2003; Huguenin *et al.*, 2004; Nadaoka *et al.*, 2004). This approach may also allow for analyses of decadal-scale volumetric change. However, precise mapping of underwater topography using the photogrammetric method requires correction for the effect of light refraction at the air/water boundary, by which observed depths are smaller than true depths. Conventional correction of the refraction effect has been performed to convert photogrammetrically observed depths to true depths by using correction factors calculated based on the theory of light refraction at the air/water interface (e.g., Estes and Thorley, 1983, p. 1441).

A fundamental problem in the photogrammetry of underwater objects is that no solution exists for photogrammetrically observed positions if the incident angles of light rays from an underwater object of interest to two cameras are different (Fryer, 1983; explained in detail in the next section), and thus approximation in solving the positions is needed. Existing procedures, however, considered the refraction correction factors based on one side view (Westaway *et al.*, 2000 and 2001; Butler *et al.*, 2002), calculated the factors by assuming existence of the solution for the stereo view without quantitative examination of the validity (Tewinkel, 1963; Meijer, 1964; Harris and Umbach, 1972; Estes and Thorley,

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1983, p. 1441), or lacked theoretical and quantitative examination of the approximation even if the evidence of no solutions for the stereo view was indicated (Fryer, 1983; Fryer and Kniest, 1985; Butler *et al.*, 2002). Accordingly, the lack of theoretical and quantitative examination of the approximation in solving the positions made the feasibility assessment of photogrammetry for bathymetric mapping impossible, though generation of bathymetric maps using stereo-pairs of aerial photographs by using refraction correction procedures based on one side view (Westaway *et al.*, 2000 and 2001) or by assuming existence of the solution for the stereo view (Harris and Umbach, 1972; Warner *et al.*, 2000) has been achieved. In this study, we report on development of a refraction correction procedure that allows theoretical and quantitative assessment of the approximation of the photogrammetrically observed positions by calculating horizontal difference between photogrammetrically observed and true positions. The calculation serves as guidelines on the feasibility of photogrammetry in bathymetric mapping. We then apply the procedure to coral-reef bathymetric mapping to show the effectiveness of photogrammetry and the correction procedure to generate bathymetric maps in clear, optically shallow water.

Theory and Correction Procedure

We assumed a stereo-pair of sequential aerial photographs taken by a metric camera (Figure 1) and set the geometry similar to that shown by Tewinkel (1963), Fryer and Kniest (1985), and Butler *et al.* (2002) (Figure 2). Rays of incident light originating from underwater point P with water depth of h are refracted at the air/water interface at P_1 and P_2 prior to arriving at camera stations S_1 and S_2, respectively, which are set at height of H from the water surface (Figure 2).

As with other conventional procedures (e.g., Estes and Thorley, 1983, p. 1441), our procedure is designed to correct photogrammetrically observed depths into true depths using correction factors based on the theory of light refraction at the boundary of two mediums. The basic procedure was similar to that of Tewinkel (1963) and Meijer (1964), who calculated correction factors based on a stereo-pair of photographs. However, as Fryer (1983), Fryer and Kniest (1985), and Butler *et al.* (2002) indicated, theoretically, no solution exists for photogrammetrically observed positions if the incident angles of light rays from an underwater object of interest to two cameras are different (Figure 2), and thus an approximation is needed to assume the photogrammetrically observed positions. In order to achieve theoretical and quantitative assessment of the approximation, we divided the procedure into three cases, according to the position of submerged features relative to the cameras (Figure 1) and assumed that the air/water interface was horizontal and planar. In *Case 1*, the points were situated in the line along the airplane track, and in *Case 2*, the points were situated in the perpendicular bisector of the airplane track. *Case 3* represented other situations in which no solution existed for photogrammetrically observed positions. Here, *Case 1* (Figure 3) and *Case 2* (Figure 4) have solutions for the observed positions, and these solutions could help in approximations in cases in which the incident angles are different. In addition, *Case 1* (Figure 3) is helpful to understand the "no solution problem" described in Figure 2. If we set a vertical line (A-A') in Figure 3, which intersects with the underwater object P, and fold the figure along the line, then Figure 2, which has no solution for the photogrammetrically observed point, is produced.

The basics of light refraction according to Snell's law are

$$i_1 = \sin^{-1}\left(\frac{\sin r_1}{n}\right), \quad (1)$$

$$i_2 = \sin^{-1}\left(\frac{\sin r_2}{n}\right), \quad (2)$$

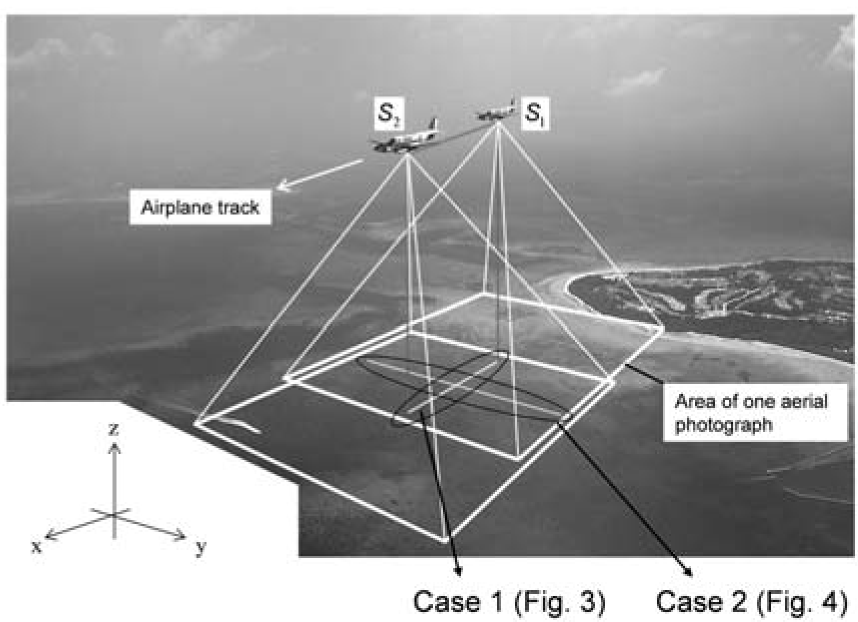

Figure 1. Procedure for taking a stereo-pair of aerial photographs. Definition of the coordinates for Figures 2, 3, and 5 are indicated. S_1 and S_2 are the positions of the cameras. Detailed photogrammetric geometry for underwater objects is shown in Figure 2.

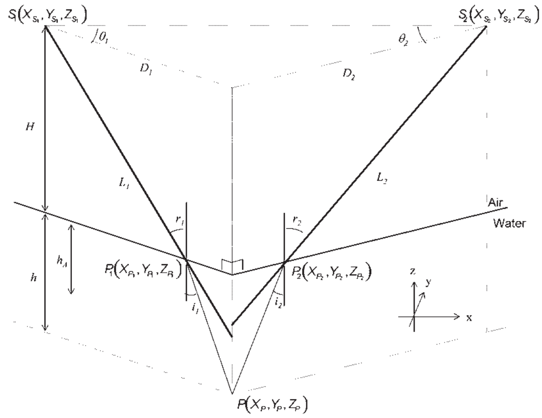

Figure 2. Geometry of two-medium photogrammetry after that by Fryer and Kniest (1985). *h* is the true depth of the underwater object of interest to be calculated from other variables. S_1 and S_2 are the positions of the cameras, *P* is the true position of the underwater object of interest, and P_1 and P_2 are refraction point-of-light rays to the cameras. *H* is the height of the airplane and camera, and h_A is the photogrammetrically observed depth of the underwater object of interest.

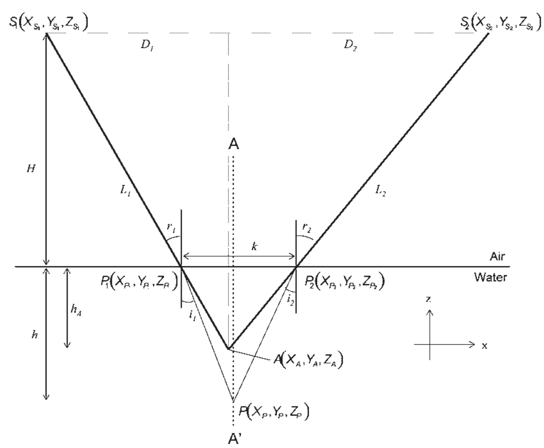

Figure 3. Geometry in the case that the observed points are on the line along the airplane track (*Case 1* of Figure 1).

where i_1 and i_2 are angles of incidence to the left and right, respectively; r_1 and r_2 are angles of light refraction at the left and right, respectively; and *n* is the refractive index for seawater (1.340; Jerlov, 1976).

Case 1: Points in the Line along the Airplane Track (Figure 3)

The photogrammetrically observed position is located at point *A* (X_A, Y_A, Z_A), and the true position is located at *P* (X_P, Y_P, Z_P). Here, $Y_P = Y_A$.

If *k* is the distance $P_1 P_2$,

$$k = (\tan r_1 + \tan r_2)\cdot h_A = (\tan i_1 + \tan i_2)\cdot h. \tag{3}$$

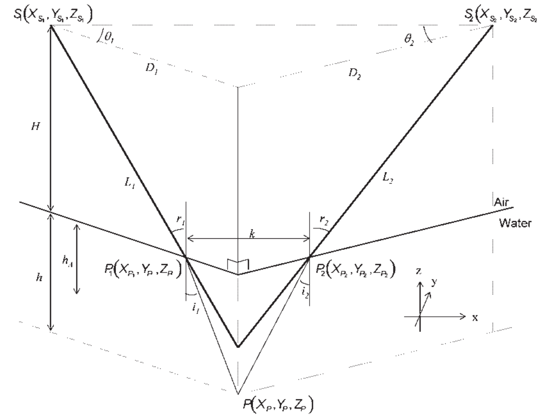

Figure 4. Geometry in the case that the observed points are on the perpendicular bisector of the airplane track (*Case 2* of Figure 1).

Thus,

$$h = \frac{\tan r_1 + \tan r_2}{\tan i_1 + \tan i_2}\cdot h_A. \tag{4}$$

From Figure 3 and Equations 1 and 2,

$$\tan r_1 = \frac{D_1}{H + h_A} \tag{5}$$

$$\tan r_2 = \frac{D_2}{H + h_A} \tag{6}$$

$$\tan i_1 = \tan\left(\sin^{-1}\left(\frac{\sin r_1}{n}\right)\right) = \tan\left(\sin^{-1}\left(\frac{D_1/L_1}{n}\right)\right) \tag{7}$$

$$\tan i_2 = \tan\left(\sin^{-1}\left(\frac{\sin r_2}{n}\right)\right) = \tan\left(\sin^{-1}\left(\frac{D_2/L_2}{n}\right)\right). \tag{8}$$

Further consideration is made for *x* values of the true position:

$$X_P = X_{P_1} + h\cdot\tan i_1 = X_A - h_A\cdot\tan r_1 + h\cdot\tan i_1. \tag{9}$$

Substituting Equation 4 into Equation 9 gives

$$X_P = X_A + \frac{\tan i_1\cdot\tan r_2 - \tan i_2\cdot\tan r_1}{\tan i_1 + \tan i_2}. \tag{10}$$

Therefore, the *x* values for the observed and true positions are different, and the difference can be obtained by substituting Equations 5 through 8 into Equation 10. The resultant difference may help to examine the feasibility of photogrammetry in bathymetric mapping, because the large difference in comparison with the spatial resolution of the image may lead to incorrect stereo matching.

Figure 5 shows the difference in *x* values between the observed and true positions in the case in which the airplane altitude is 3,000 m and the distance of the central points of the paired photographs is 1,000 m, as in our validation work described in the subsequent section. Water depths of the observed points were set at 1 and 30 m because 30 m is the approximate limit for seeing the bottom features (e.g., Maritorena *et al.*, 1994).

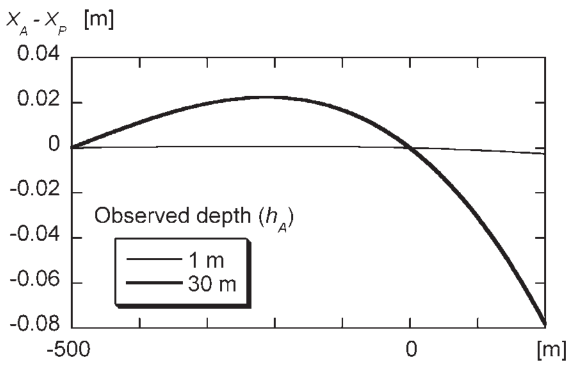

Figure 5. Difference in x values of observed and true positions (X_A and X_P) for *Case 1* as a function of distance from the foot of a perpendicular line from one camera station. The height of the airplane was set at 3,000 m. Water depths of the observed points were set at 1 and 30 m.

Case 2: Points on the Perpendicular Bisector of the Airplane Track (Figure 4)

As with *Case 1*, the photogrammetrically observed position was located at point A (X_A, Y_A, Z_A), and the true position was located at P (X_P, Y_P, Z_P). Because the incident angles were identical for the two cameras, $i_1 = i_2$, $r_1 = r_2$, $X_A = X_P$, and $Y_A = Y_P$.

Thus,

$$h = \frac{\tan r_1}{\tan i_1} \cdot h_A = \frac{\tan r_2}{\tan i_2} \cdot h_A. \quad (11)$$

Substituting Equations 5 through 8 into Equation 11 gives the h value.

Case 3: Others

The feasibility of photogrammetry in bathymetric mapping depends on whether approximation of the positions could be possible for this case, because theoretically there will be no solution for the photogrammetrically observed position (Figure 2).

As estimated from *Case 1* and *Case 2*, the horizontal difference between photogrammetrically observed and true positions is small (Figure 5) in the case in which the airplane altitude is 3,000 m and the distance of the central points of the paired photographs is 1,000 m, and in that case we could neglect the difference shown by Fryer (1983), Fryer and Kniest (1985), and Butler *et al.* (2002) (see Figure 2). Based on this assumption, we set the same geometry as in Figure 4, although i_1 and i_2 were different. This is the case shown by Tewinkel (1963), and we followed his procedure.

If k is the distance $P_1 P_2$,

$$k = (\tan r_1 \cdot \cos \theta_1 + \tan r_2 \cdot \cos \theta_2) \cdot h_A = (\tan i_1 \cdot \cos \theta_1 + \tan i_2 \cdot \cos \theta_2) \cdot h. \quad (12)$$

Thus,

$$h = \frac{\tan r_1 \cdot \cos \theta_1 + \tan r_2 \cdot \cos \theta_2}{\tan i_1 \cdot \cos \theta_1 + \tan i_2 \cdot \cos \theta_2} \cdot h_A. \quad (13)$$

Here,

$$\cos \theta_1 = \frac{X_A - X_{S_1}}{D_1} \quad (14)$$

$$\cos \theta_2 = \frac{X_{S_2} - X_A}{D_2}. \quad (15)$$

Substituting Equations 5 through 8, 14, and 15 into Equation 13 gives the h value.

Collectively, implementing these three cases into refraction correction of DEMs generated from aerial photographs could ensure precise bathymetric mapping.

Application to Coral-Reef Bathymetric Mapping

Study Site and Data

We examined Shiraho Reef on the east coast of Ishigaki Island, southwest Japan (24° 22′ N, 124° 15′ E), where clear waters have permitted detailed mapping of submerged features based on aerial photographs and satellite images (Nakamori *et al.*, 1992; Hasegawa, 1998; Andréfouët *et al.*, 2003; Nadaoka *et al.*, 2004). In addition to their clear waters, reefs provide a calm environment in the backreef area that is protected from breaking ocean swells by the reef edge (Roberts *et al.*, 1975). Thus, waves that cause changes in light rays (Rinner, 1969) are minor in backreef areas. Figure 6 is an aerial photograph of Shiraho Reef, illustrating the well developed fringing reef and distinct topographical zonation from land to ocean, backreef moat, and reef crest. Semidiurnal tides are dominant with the maximal range at spring tide is approximately 1.7 m (Nakamori *et al.*, 1992). In middle to low tides, most part of the reef crest and southern part of the sand flat are sub-aerially exposed. The topographic data were obtained in 1997 using a staff with a mirror and a laser distance meter along 36 transects that were set from west to east across the reef (Figure 6)

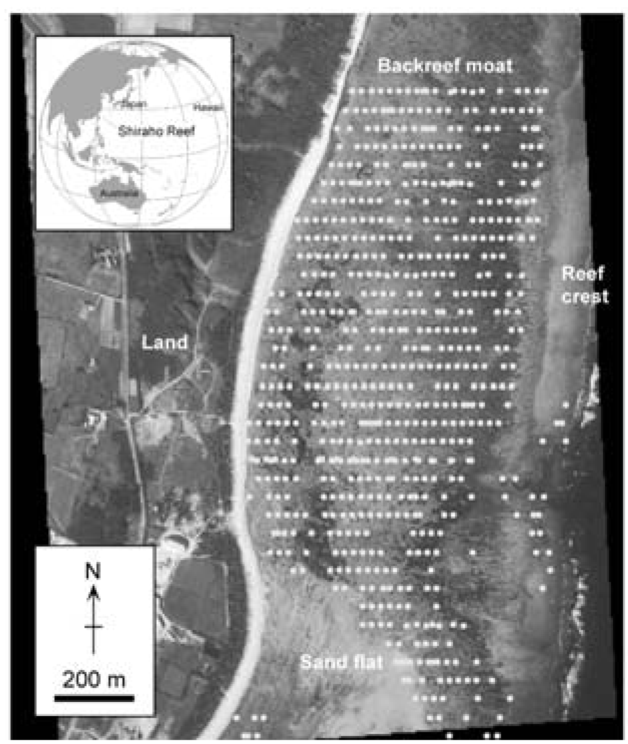

Figure 6. Location and aerial view of Shiraho Reef, southwest Japan (24° 22′ N, 124° 15′ E), and points with measured depths. Note the dark seagrass and coral patches in the backreef moat.

(Kayanne *et al.*, 2000). The base of each transect was set in reference to established survey benchmarks, and thus the positional errors of the topographic data were minimal. The depth ranged generally from −2.0 to −0.5 m relative to mean sea level in the backreef area with maximum and minimum of −3.4 m and −0.2 m, respectively. The reef crest was shallow, having less than −0.5 m depth relative to mean sea level. We used 658 data points for the validation (Figure 6).

DEM Generation

Aerial photographs of Shiraho Reef were taken on 11 January 1995 at an altitude of ~3,000 m. The scale of the photographs was approximately 1:10 000. We scanned one stereo-pair of the positive film of the photographs at a resolution of 1,200 dpi, which resulted in a pixel size of the image at approximately 20 cm. The estimated water level at the photograph acquisition time was 39 cm above mean sea level. At this water level, the reef crest would have been submerged, and the water level would have been uniform in the sea area, including at the coral reef; sub-aerial exposure of the reef crest and ponding (i.e., a higher water level than that in the outer ocean) in a backreef moat were observed during low tides (Nakamori *et al.*, 1992; Kayanne *et al.*, 1995). Because the difference in timing between the taking of topographic measurements (1997) and photographs (1995) was small, little topographic modification was expected to have occurred.

Fieldwork to collect ground-control points (GCPs) was conducted in September 2002. We searched roads and other benchmarks that appeared to have suffered no change since 1995. We collected GCPs on the island using an auto level and a total station by referencing two bench marks set by the Geographical Survey Institute of Japan. The scanned photographs were processed based on the lens parameters of the metric camera and the GCPs using DPW with the SOCET SET® software (Leica Geosystems AG, Heerbrugg, Switzerland). Accordingly, the initial DEM without refraction correction was produced. We then applied the correction to the underwater DEM, following the procedure with the three cases specified in the previous section. We adopted the approximation shown in *Case 3* because the estimated difference of the *x* values (Figure 5) was smaller than the size of the image pixels (~20 cm).

Error Assessment

To evaluate the effectiveness of the correction procedure, errors in the DEM were assessed by comparing the observed and corrected DEMs with measured depths. Both the mean error (ME) and standard deviation (SD) relative to measured depths were calculated to examine the DEM accuracy and precision. In addition, we checked whether the accuracy of the corrected depths could be affected by their location relative to the camera and the true depth. We did this by plotting the difference in corrected depths and measured depths as functions of the distance from the point of interest to the middle point of the foots of the perpendicular lines from the camera stations and the true water depth of the point of interest.

Figure 7 shows the photogrammetrically observed depths and corrected depths plotted against the measured depths by Kayanne *et al.* (2000). The depths photogrammetrically observed were systematically shallower than the measured depths, with the ME and SD being +0.62 m and 0.79 m, respectively, which indicate the need for refraction correction. However, the corrected depths agreed well with the measured depths, with −0.06 m for the ME and 0.36 m for the SD. The small ME value after the correction indicates the high accuracy of the DEM. Both the ME and SD were stable, irrespective of the positions of the pixels (Figure 8), suggesting the global effectiveness of our correction procedure for the entire image. Our SD after the correction is much smaller than that found for terrestrial coastal dunes with high relief (5.74 m and 9.23 m by Brown and Arbogast, 1999) and similar to that for a barrier island with low relief (0.31 m by Judge and Overton, 1999). This indicates that a DEM for coastal submerged areas can be produced with reasonable accuracy, similar to that for terrestrial areas. However, our error values are larger than those of studies that quantitatively evaluated underwater DEMs for gravel-bed rivers by Westaway *et al.* (2000 and 2001). The study sites of Westaway *et al.* (2001) had depths less than 1.1 m, with most depths being less than 0.6 m; this difference in depths could explain our larger errors in depth estimation compared to those of Westaway *et al.* (2001).

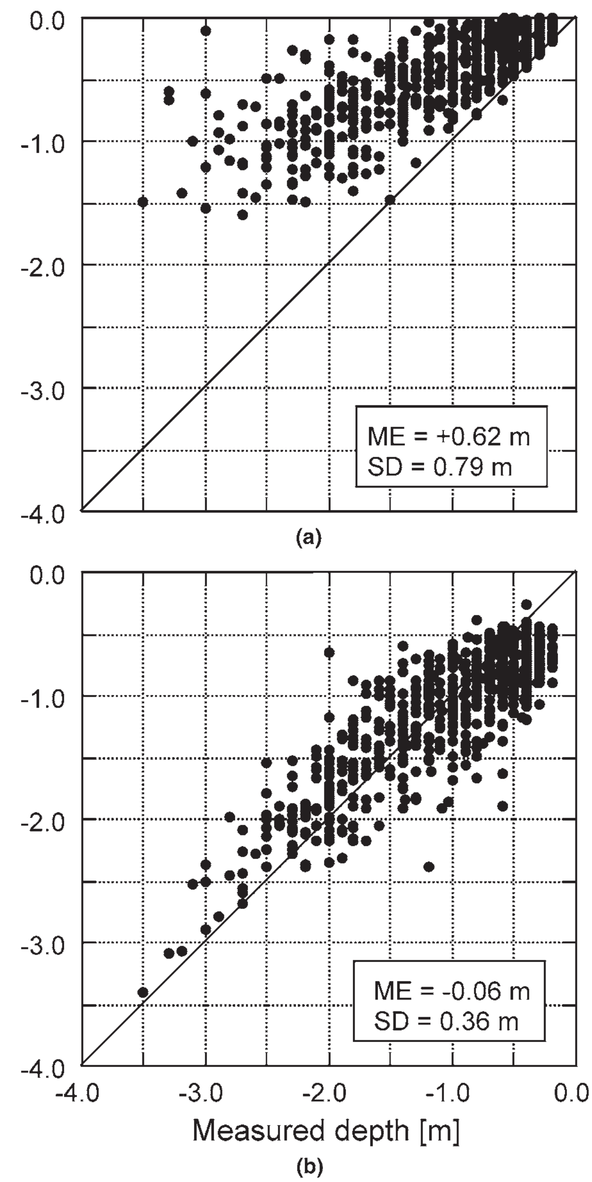

Figure 7. (a) observed, and (b) corrected depths plotted against measured, true depths. Depths are described relative to the mean sea level.

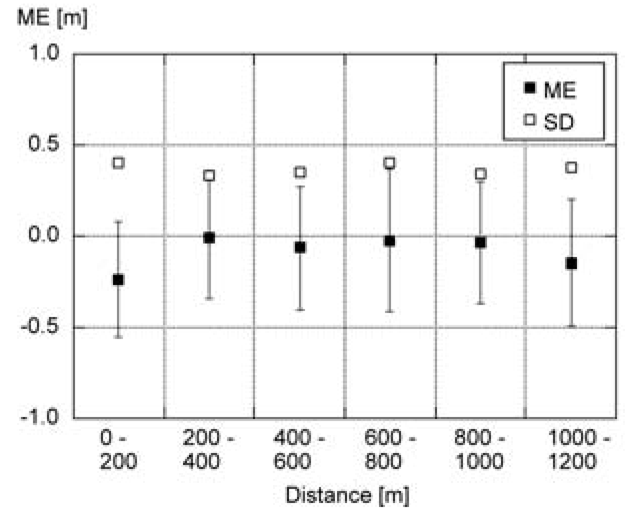

Figure 8. The relationships between the average ME ($\pm 1\ \sigma$) and SD and the distance from the point of interest to middle points of the feet of the perpendicular lines from the camera stations. Plus values for the ME indicate that the corrected position was shallower than the measured position.

Distribution of the ME showed that deeper and shallower depths were observed for shallower (0.0 to -1.0 m) and deeper (-1.0 to -3.5 m) waters, respectively, while the SD showed stable values (Figure 9). Coral reefs have a highly patchy structure, with numerous coral colonies (note the many coral patches in Figure 6); some have heights of 1 m and nearly reach the sea level (e.g., Scoffin and Stoddart, 1978), which could make the DEM quality sensitive to horizontal errors of georegistration. Horizontal misregistration in shallow areas of coral colonies could cause the resultant depth to be deeper, and the misregistration in deep areas near coral colonies could cause the resultant depth to be shallower. The more patchy structure of coral reefs compared to that of gravel riverbeds could also explain why our depth estimations had larger errors compared to those by Westaway *et al.* (2000 and 2001).

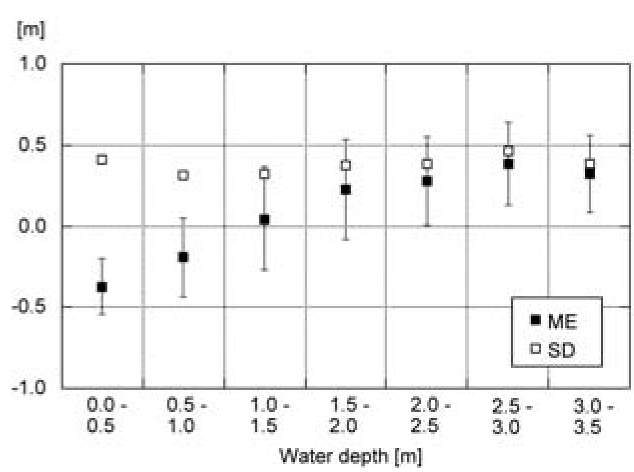

Figure 9. The relationships between the average ME ($\pm 1\ \sigma$) and SD and true water depth of the point of interest. Plus values of the ME indicate that the corrected position was shallower than the measured position.

Concluding Remarks

We have described development of a procedure for refraction correction at the boundary of two mediums to map underwater topography based on a stereo view of underwater objects. While previous works lacked theoretical and quantitative assessment of the "no solution problem," the advantage of our procedure was to theoretically calculate the difference by solving Equation 10, in assuming the solution of photogrammetrically observed positions, which allowed feasibility assessment of photogrammetry in bathymetric mapping. Application of the procedure to coral reef bathymetry produced a corrected DEM with favorable accuracy, indicating the effectiveness of our procedure. Our results may encourage bathymetric mapping, as for terrestrial areas (e.g., Toutin, 2004), using a stereo-pair of high-resolution satellite images such as Ikonos and QuickBird (the blue, green, and panchromatic bands allow observation of bottom features) in addition to aerial photographs.

The applicability of photogrammetry in bathymetric mapping could be estimated by solving Equation 10. When we used the procedure to map Shiraho Reef, we assumed that the horizontal difference of the corrected and observed positions was negligible, which could be true for our case where the airplane altitude was approximately 3,000 m (Figure 5). However, though theoretically possible, the applicability of our correction procedure to deeper areas (< -3.5 m) remained to be tested in the future, because the maximum depth of our study site was -3.4 m. The horizontal difference from Equation 10 could exceed the scale of the spatial resolution of the image according to incident angles or the water depth of the position, which may lead to incorrect stereo matching. This could be true when using wide-angle lenses. In that case, conventional correction procedures based on a single, one-side look (Westaway *et al.*, 2000 and 2001; Butler *et al.*, 2002) may be feasible. In addition, although minor in coral-reef backreef areas, waves could affect the photogrammetric results in other coastal areas, which should be examined further to achieve detailed bathymetric mapping (Rinner, 1969; Okamoto, 1982; Fryer and Kniest, 1985).

Coastal areas are dynamic; both long-term and short-term sediment transport and deposition at a vertical scale of up to several meters (e.g., van der Wal *et al.*, 2002) can alter coastlines (e.g., White and El Asmar, 1999) and seafloors. In coral reef areas, though normal reef accretion could not likely be detected because of a large error (0.36 m) in comparison with present-day reef accretion rates (0.3–0.6 m/100 years; Montaggioni, 2005), changes caused by cyclones or tsunamis, which can modify the seafloor at several meters vertically (e.g., Chavanich *et al.*, 2005), could be detected. Coastal areas often appear in aerial photographs, and historical photographs have been used to detect decadal changes (e.g., Yamano *et al.*, 2000; Cunha *et al.*, 2005), but these studies have mainly examined two-dimensional changes. Our results, along with those of Westaway *et al.* (2000 and 2001), encourage the use of digital photogrammetry in submerged areas, such as riverbeds and coastal seafloors, to detect and monitor volumetric changes over a decadal timescale.

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