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New Approaches in Photo-Bathymetry

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Abstract

Stereo-Photogrammetric measurements under water with a camera placed outside the water requires modelling refraction. In the case of a wavy, non-stationary natural water surface, this spatio-temporal modelling may become rather complex. This paper will give a short overview on methods for instationary water surface consideration in photogrammetric approaches recently developed in a joint research project between TU Dresden and TU Wien. We first introduce a comprehensive and rigorous model which reconstructs the water surface with cubic splines and determines the underwater points in a simultaneous bundle block adjustment. In addition, we introduce an alternative approach to handle dynamic, wavy water surfaces based on image sequences. We show that by combining approximately 100 images taken at roughly the same position and orientation into a single image, the distortions of underwater objects caused by the wavy water surface can be largely mitigated. In the resulting image, the water surface appears smoothed, and the 3D reconstruction underwater can be performed as if the water surface were completely flat. The sequence-based approach can be formulated in image space and in object space. First results indicate a substantial accuracy increase of around an order of magnitude.

1. Introduction

Stereo-Photogrammetry is, together with Lidar-Bathymetry, an appealing method for 3D measurements from an airborne platform through water surfaces, for instance in hydro-ecology, monitoring of fluvial morpho-dynamics, habitat monitoring or coral reef change detection (Burns and Delparte, 2017; Mandlburger, 2022; Mandlburger et al., 2025). Applying photogrammetric techniques in environments with different optical media, the necessity of consideration of refraction according to Snell's law arises (Kotowski, 1988; Murase et al., 2008; Dietrich, 2016). This requires the existence of a suitable geometric model of the interface separating the optical media (Engelen et al., 2018). In the simplest case, this model may be a horizontal planar water surface. However, such a simple model is not valid under the presence of waves, which have a very significant influence on underwater point coordinate determination. In photogrammetric applications, where images are taken through a water surface with significant waves, spatial or spatio-temporal modelling of the instationary water surface needs to be integrated into the reconstruction process as a basis for strict consideration of refraction on the optical paths in stereo-photogrammetric 3D point coordinate determination (Engelen et al., 2018).

Photo-bathymetry, also referred to as Through-water photogrammetry (Mandlburger, 2019), is a technique to derive models of the water bottom from stereo imagery, provided limited water depth and low turbidity (Westaway, 2001; Hodul et al., 2018). While the observations vs. unknowns count in standard stereo photogrammetric forward intersection is trivial (two images taken from different viewpoints deliver four observations for the determination of the three coordinates of a point, with each additional image adding redundancy), it is much more complex in photo-bathymetry, where three additional unknowns (namely the water surface height and the two components of the local water surface normal vector) emerge for each image ray. Therefore, the system is inherently under-determined. This rank deficit is independent of the number of images used for 3D point determination, as each image ray will hit the water surface at a different location with a different (wave pattern dependent) surface height and normal. In many cases of aerial through-water photogrammetry, this problem is simply solved by the assumption of a planar horizontal water surface (i.e. setting the surface normal components to zero) with a known height. As a consequence, large errors occur in photo bathymetric water bottom determination if waves are present on the water surface (Okamoto, 1982). A brief estimate of the quantitative effects neglecting waves in geometric modelling shows that for a UAV flying at 10 meter above the water surface and a water depth of 3 meter, and a 5 degree tilt of the water surface at the air-water interface of one image ray leads to a depth error of approx. 25 cm at the water bottom – compared to sub-centimetre accuracy achievable in non-bathymetric UAV-based photogrammetric terrain surface determination (e.g., Eltner et al., 2018).

Therefore, our goal is to develop models that are capable of improving the accuracy potential of photo-bathymetry by at least one order of magnitude. In the following, we will first give an error assessment on the effect of waves on underwater point coordinates in photo-bathymetry. Then we will show two approaches to handle wave effects: The first approach focuses on strict geometric modelling of water bottom and water surface simultaneously. In addition, we will show an alternative approach based on processing short image sequences taken at each camera position rather than single images.

2. Error assessment

Simulated water surface and bottom data have been used to analyze the significance of errors introduced neglecting waves in photo-bathymetry. The simulation reproduces multiple images taken simultaneously, e.g. as acquired from multiple synchronized UAVs. For that purpose, synthetic images of an underwater object seen through a wavy water surface have been generated, applying pixel-wise ray tracing (Sardemann et al., 2024). For each pixel, its 3D image ray is calculated, refracted at the according water surface location (also considering the local surface inclination) and intersected with the underwater object. We then used the received image information to calculate object coordinates with the (false) assumption of a planar water surface.

Comparing those coordinates with the ground truth reveals the resulting error. We applied this workflow for varying camera configurations, water surfaces and water depths (Sardemann et al., 2024). As one can see in Figure 1 (top), through-water photogrammetry also comes with a smaller ray intersection angle, further affecting the depth coordinate accuracy (Maas, 2015). For the example shown in Figure 1 (bottom), where the water surface has rather gentle slopes, we observed errors in the order of 10% of the water depth. Sinusoidal water surfaces with steeper inclinations lead to errors of up to 50% of the water depth (Sardemann et al., 2024). The magnitude and distribution of errors in depth caused by the presence (and neglection) of waves on the water surface has also been examined in Fryer and Kniest (1985), who found depth errors to be in the order of 20% of the actual depth via computer simulations.

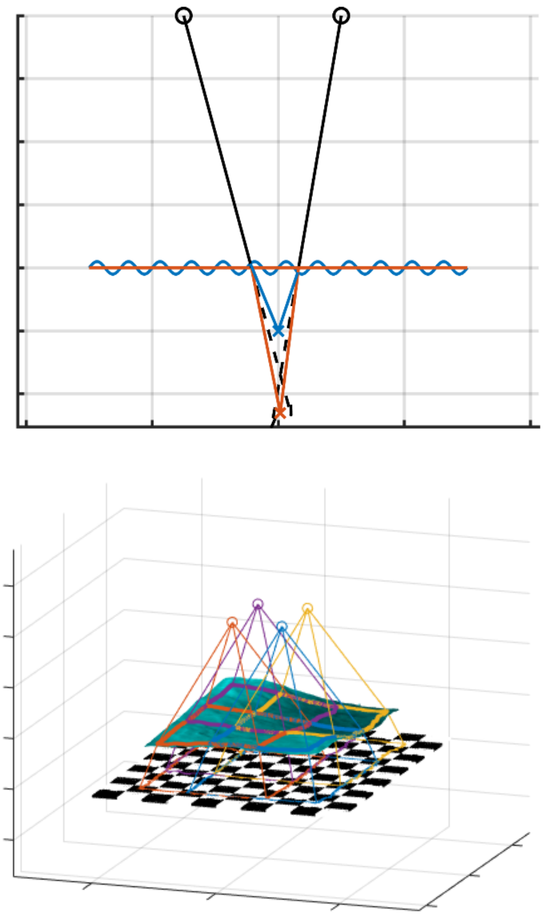

Figure 1. Simulation of water surface geometry on underwater object coordinates. Top: Location of a single object point assuming no water (black dashed), a planar water surface (orange) and a wavy water surface (blue). Bottom: Simulation of four cameras observing an underwater checkerboard through a non-planar water surface.

3. Strict geometric modelling

To consider wavy water surfaces in point coordinate determination based on stereo-photogrammetric forward intersection, we formulated a comprehensive and rigorous model that goes beyond the frequent assumption of a static planar water surface by including the elevation and inclination of the water surface as a prerequisite for the strict geometric modelling of refraction. This requires the development of suitable models for spatial or spatio-temporal modelling of local water surface patches. Thus, the photographic image data are exploited twofold in order to simultaneously determine i) the dynamic water surface and to perform ii) an overdetermined photographic ray intersection for 3D water bottom point coordinate determination.

As a first step towards the full model, we implemented and evaluated the determination of the water surface, assuming known object coordinates of the water bottom. We therefore simulated an experiment with four cameras, a non-planar water surface and a submerged checkerboard pattern (Figure 2, Top). The units in the simulation are chosen in a way that the median water level is z = 0 with a range of [-0.2, 0.2], the underwater object is located at z = -1, and the cameras at z = 5.

We were able to reconstruct the simulated water surface with cubic splines (15 x 15 knots). We therefore minimized the distance of all underwater rays to the according (known) object points in a bundle block adjustment. The adjustment starts with the assumption of a planar water surface. This leads to an RMS of 0.08 at the water surface (water height compared to ground truth) and 0.04 at the water bottom (distance of image rays to object points). After the adjustment, the RMS values have decreased to 0.006 at the water surface and 0.01 at the water bottom. Figure 2 (bottom) shows the deviations of the water surface to the ground truth water surface for the initial plane (left) and the adjusted splines-reconstruction.

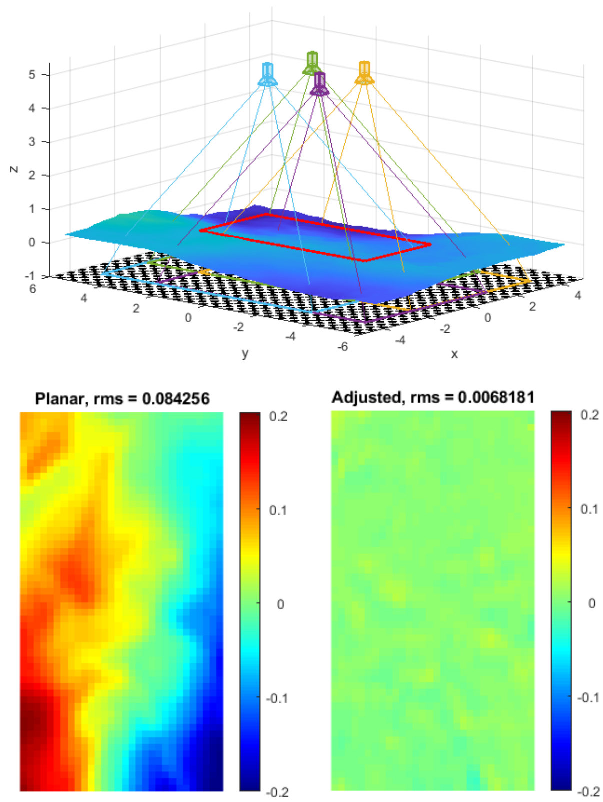

Figure 2. Determination of water surface from simulated data. Top: Camera set-up. The red rectangle depicts the reconstructed area that is seen in all four images. Bottom left: a-priori deviations at the water surface, assuming a plane. Bottom right: a-posteriori deviations at the water surface using cubic splines.

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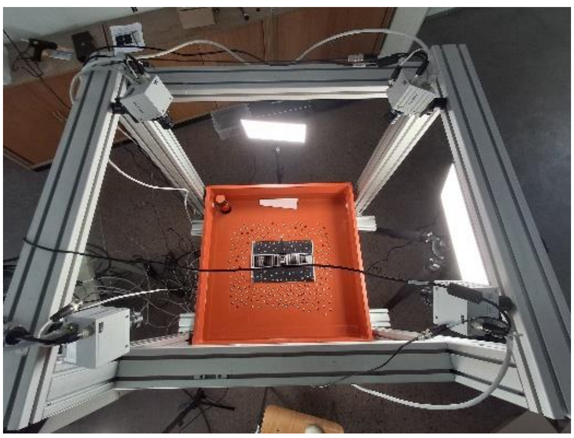
Besides implementing this in our simulation pipeline, we also tested it on laboratory experiment data. Thereby, four synchronized cameras observed a water tank with coded and uncoded circular markers (Figure 3a). The camera orientations (interior and exterior) were determined beforehand. In the first step of the experiment, the water was calm, and object coordinates could be determined applying a multimedia bundle adjustment including the parameters of the planar water surface. We thereby get object point coordinates of all markers with an RMS of 0.05 mm. Those object points coordinates serve as control points with known coordinates for the next step of the experiment, where waves were excited on the water surface. For this study, only one image quadruplet out of a time-lapse sequence was evaluated. Image coordinates of all markers were measured with ellipse fits in all four synchronized images of that frame. The point numbers were allocated to the according object points using a semi-automatic procedure. The measured image points in the four images and the known object point coordinates were then used for an adjustment of the water surface, using cubic splines with 25 x 25 knots. The resulting water surface is shown in Figure 3b.

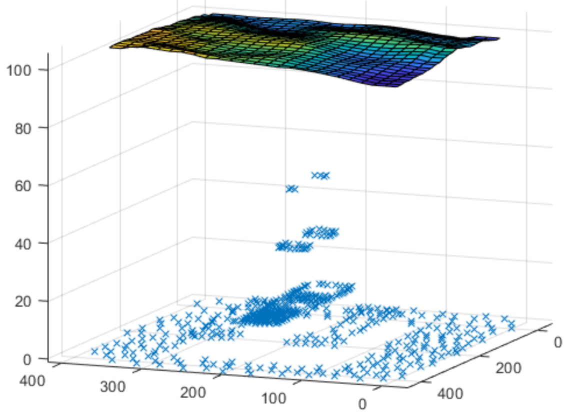
As there was no ground truth for the water surface, we could only observe the (minimized) distance between underwater image rays and object points. The RMS at the object points is reduced from a-priori 1.4 mm (wrongly assuming a plane) to an a-posteriori 0.3 mm with the adjusted splines reconstruction of the water surface. The reprojection error in image space was reduced from a-priori 1.6 pixels to a-posteriori 0.6 pixels. The peripheral area of the water surface was penetrated by a smaller number of image rays and therefore more difficult to determine, resulting in the largest errors at the markers in the corners of the images. Figures 3c and 3d show the re-projection errors in the image of camera 1, assuming a planar water surface (c) and after the splines reconstruction (d).

The next step in the upcoming evaluations will include the remaining images of the recorded sequence. By adding temporal filtering, the movement of the wave will be determined in a joint adjustment. We furthermore aim to determine water bottom point object coordinates and water surface geometry simultaneously in future experiments. Our current tests suggest, that a certain percentage of the water bottom points will have to be control points with known coordinates in order to stabilize the adjustment.

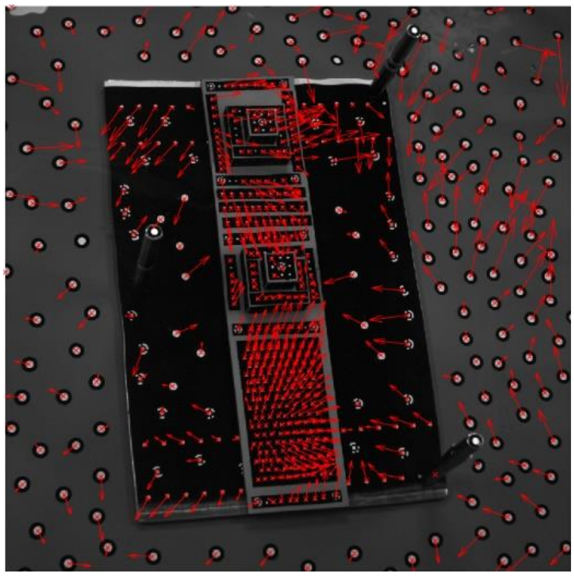


a

b



c



d

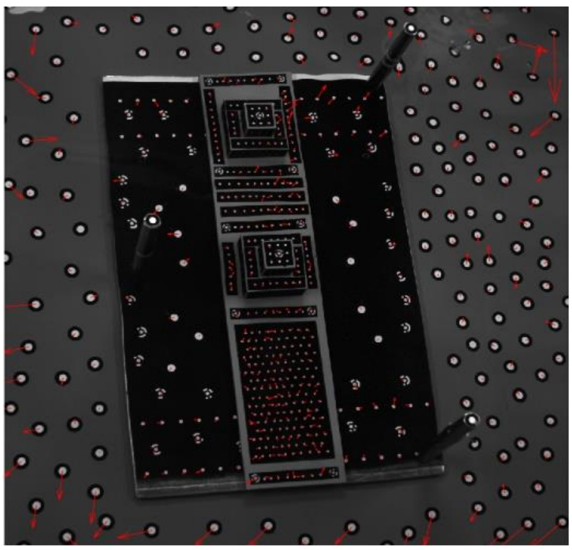


Figure 3. Laboratory Experiment. a: Four synchronized cameras observe a small water tank with a submerged marker-based test field. b: The resulting reconstruction of the water surface with control points (unit: mm). c: residuals, when a planar water surface is falsely assumed (20x exaggerated). d: residuals, using the reconstructed water surface (20x exaggerated).

4. Short image sequence processing based approach

A completely different approach to solve the problem of wavy water surfaces is the compensation of the effect by analysing the variation of grey values in short image sequences taken by a stationary camera. The basic idea is to use statistical parameters of these image sequences to (largely) compensate for wave effects. For this, image sequences need to be taken with stable exterior orientation. This is simple for a lab environment, but more sophisticated for moving platforms such as UAV's. However, by activating the hovering mode and using a gimbal, the motion effect can be reduced to a decent amount. Small movements inside an image sequence can be further compensated by co-registration of all images to a reference image (e.g. a frame in the middle of the sequence) based on stable tie points on dry land (Mandlburger et al., 2022). The RMSE of this co-registration was in the order of 0.1 pixel.

The stack of co-registered images can then be forwarded to the pixel-wise analysis of grey values within the sequence. Due to the random movement of the water around the idle state, moments with horizontal orientated water surface elements should occur more frequently than others. The basic task is to identify of the 'right' grey value for each pixel within a sequence. So far, empirical evidence has shown that median filtering on the time axis for each pixel is an effective method to achieve good results (Mulsow et al. 2024). Then, a corrected image with a geometry as if it would have been captured through a horizontal water surface can be forwarded to the standard multi-media photogrammetry pipelines for forward intersection of homologous image points. Figure 4 shows results of an image sequence processing. Figure 5 shows a comparison of SfM results using original and image-sequence-processed image data.

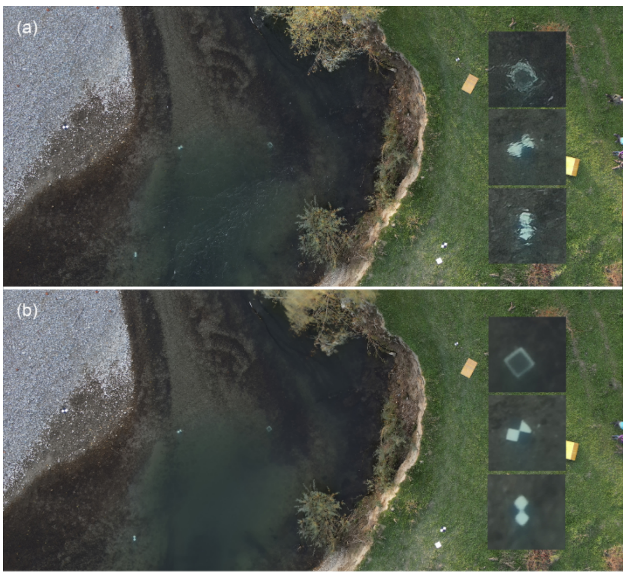


Figure 4. Exemplary results of image sequence processing: (a) original image captured from a UAV. (b) Corrected image with the geometry of an image as if it would have been taken through a calm flat water surface, obtained from a sequence of approximately 100 images. The small image inlets illustrate the de-blurring effect at submerged checkerboard targets.

In a lab experiment similar to the setup shown in Figure 3, several image sequences were taken while the water was moving. The tracking of underwater features showed position variances up to 60 Pixel within a sequence. After the processing of the sequence, the positions of features were compared against the reference (image taken through calm water). Here an RMS of under 1pixel could be achieved, which shows the potential of this method (Mulsow et al. 2024).

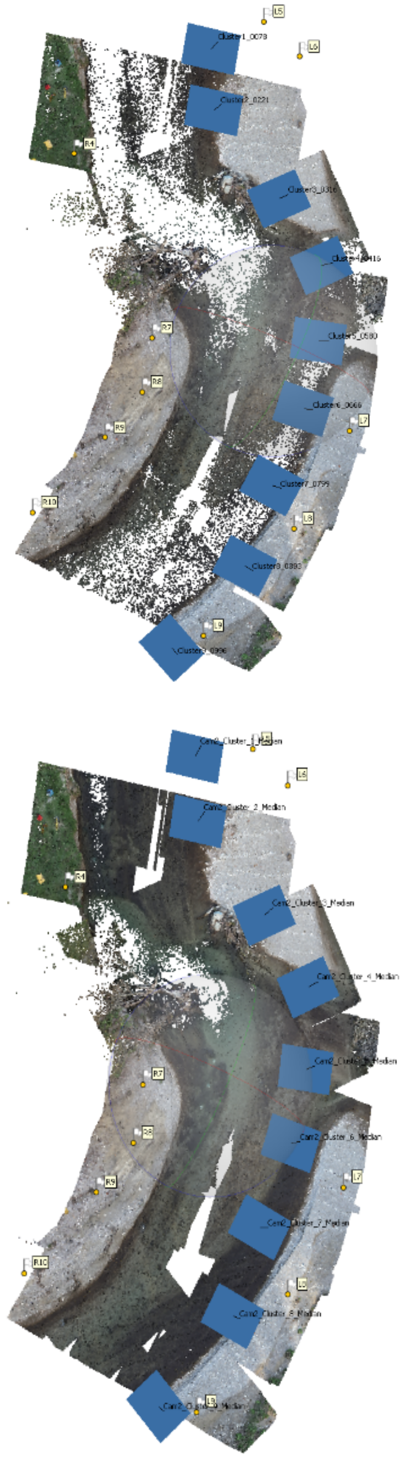


Figure 5. Point clouds extracted from original image data affected by dynamic water surface (top) and corrected image data (bottom). The improvement of quality and coverage is quite obvious.

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5. Short image sequence processing – object space based

As outlined in the previous section, the initial approach involves the analysis of the change in pixel grey values over an image sequence. The image sequence-based approach can also be formulated in 3D object space. Herein, the fundamental premise entails the identification of combinations of images from multi-view image sequences, wherein the water level is horizontal in each view. With known interior and exterior orientation for each camera, corresponding image ray vectors can be projected into object space for a chosen ground feature. These vectors can then be traced through a pre-defined plane (horizontal surface of calm water at a well-defined level) towards the water bottom. Then the distances (deviations from ideal intersection) between corresponding vectors are analysed (see Figure 6). Vector-sets exhibiting minimal distances (corresponding to small standard deviations for their intersection point) are regarded as candidates for subsequent analysis. This fundamental concept is implemented through the execution of a large number of tentative intersections between combinations of images from short image sequences from at least two cameras. From these combinations, the vector set that best fits the centre of each ground feature is selected for a final spatial intersection, which determines the 3D coordinates of that ground feature. The underlying principle of this methodology hinges on the assumption that the probability of a combination of best-fitting image rays is maximised for local, horizontally oriented surface patches.

For virtual tests, a moving water surface was simulated on a grid of 20 x 20 m with a mean level of 0 m and a min/max variation in height of -0.5/0.5 m. Virtual cameras were placed 10 m above the mean water level in a square pattern (2.5 m x 2.5 m distance). The sensors were introduced as standard machine vision cameras with a focal length of 30 mm, a resolution of 4288x2848 pixel and a pixel size of 5.5 µm. Figure 6 shows the simulated water surface together with the four virtual cameras. Four image sequences of 100 consecutive water stages were calculated and then processed for one submerged feature (see Figure 6), with the image coordinates distorted with a normal distributed error of 0.5 pixel. In the end, the best fitting quadruple of image rays were intersected in order to get the most likely point coordinates for the underwater point. A comparison against the reference showed that a RMS of 8/8/41 mm in X/YZ could be achieved for this case. This is by a factor 15-20 better than the RMS obtained for points calculated via multi-ray forward intersection based on uncorrected image measurements, where a RMS of 114/144/835 mm against the reference was reached.

As a limitation, the method relies on proper feature identification and matching in image space, which is not a challenge with simulated data. In real-world scenarios, however, the reliability and accuracy of image measurement of homologous features is expected to drop due to rather irregular image patch distortions caused by water movement.

Another variation of the discussed method would be the search for moments of collinearity between the water surface normal and the incoming image camera ray. In that case, there is no effect of refraction, and the image ray can be seen as straight from the image point to the corresponding object point as for an 'in air' scenario (see Figure 7). However, as the occurrence of such moments in multiple views is less likely than those of horizontally orientated surface patches, the computational effort of this approach would be even larger. So far, we have not worked on the implementation.

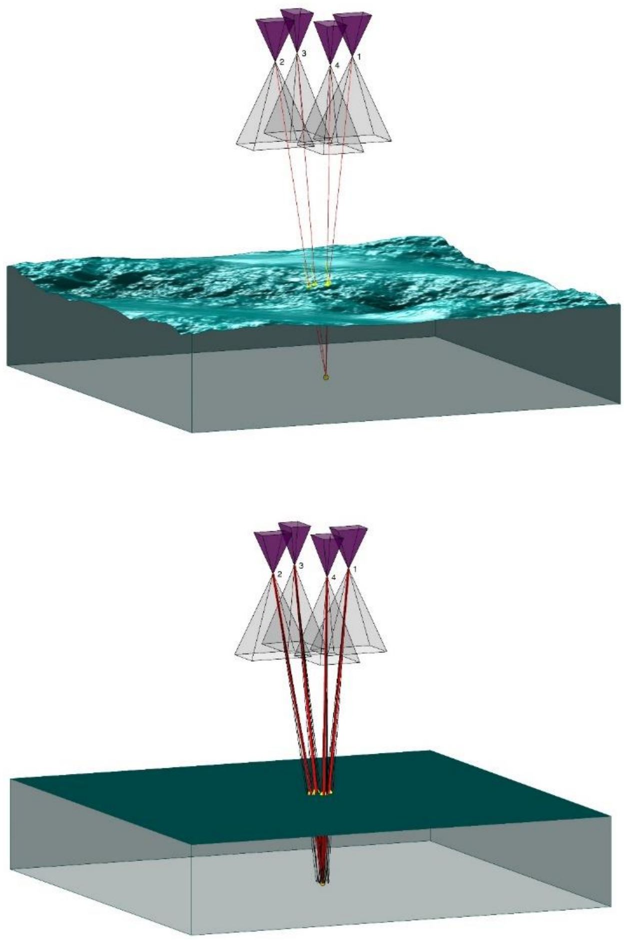

Figure 6. Top: Ray tracing for one point and four cameras in two different simulated water states. Bottom: Bundles of image rays from 10 different water states of a sequence taken for evaluating the best fitting intersection point. The quadruple of rays with the smallest distance from each other are marked in red.

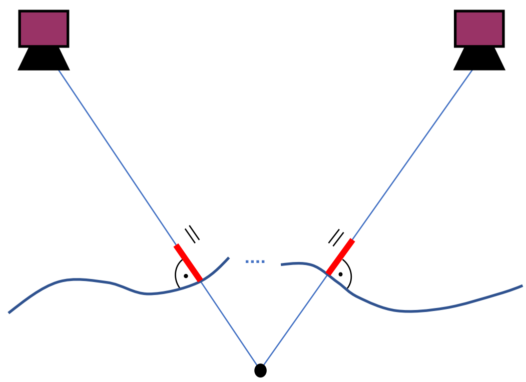

Figure 7. Principle of the refraction-free approach – the search for moments of collinearity between the water surface normal and the incoming image ray. In that case the refraction has no effect (Mulsow et al., 2024).

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6. Conclusion

Stereo-Photogrammetric measurements through open water surfaces affected by waves pose rather complex challenges in geometric modelling. To strictly model refraction, the non-planar, non-stationary water surface must be known at good accuracy. We showed several approaches to either simultaneously determine the spatio-temporally variable water surface or to significantly reduce the complexity of geometric modelling.

In a rigorous approach, we tried to determine parameters describing the water surface simultaneously with the determination of water bottom point coordinates in an extended bundle adjustment. While we could achieve first results with this approach and improve the standard deviation of water bottom points by a factor of five, the experiments also revealed severe challenges in the geometric stability of the extended bundle adjustment and the determinability of parameters.

As an alternative, we presented approaches to circumvent the necessity of strict geometric modelling by processing short image sequences from each camera viewpoint rather than single images, one formulated in image space and two in object space. A rather simple, yet efficient approach is in median filtering short image sequences on the time axis for each pixel of an image and processing the time-domain median-filtered image, rather than the original. As another brute force alternative, formulated in object space, we search for time instances in short image sequences, where the water surface is horizontal (i.e. peaks or valleys of waves) by analyzing the residuals of forward intersections in a combinatorial manner, assuming that the lowest residuals are obtained if the water surface is horizontal in both images. Similarly, one can also find time instances, where the images rays hit the water surface parallel to its normal, thus avoiding the necessity of refraction modelling. Both object-space methods have only been tested in simulations so far.

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