Accuracy assessment of bathymetric LiDAR using planar reference geometries and total station measurements

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Abstract

Airborne laser bathymetry (ALB) is an efficient and accurate tool for mapping submerged environments, particularly shallow water bodies that are difficult to access with surface vessels. Modern ALB systems can achieve accuracies comparable to SONAR. However, multiple factors, including geo-referencing, water surface modelling, and range measurements, influence the resulting point cloud, making analytical error propagation challenging. Empirical evaluation against reference data is therefore essential, but difficult: ALB accuracy is typically in the low centimetre range, requiring reference data of equal or higher accuracy. Robotic total stations enable acquisition of underwater reference data for shallow water depths, e.g., up to $4.5\,\mathrm{m}$, with expected accuracies between $3\,\mathrm{mm}$ to $10\,\mathrm{mm}$, depending on water depth, which approaches the inherent accuracy of ALB and limits the evaluation significance. In this study, we assess a UAS-based ALB data set from a mountain lake in Austria using reference planes and points acquired by robotic total stations. We separate the accuracy analysis into trueness and precision to isolate the effects of geo-referencing and water surface modelling from the intrinsic uncertainty of the LiDAR sensor. The results show that geo-referencing introduces the largest systematic bias, while the precision of the ALB data remains approximately $1\,\mathrm{cm}$ to $2\,\mathrm{cm}$, even for submerged measurements. These findings demonstrate the high accuracy of state-of-the-art ALB systems and provide a framework for rigorous accuracy assessment in shallow aquatic environments.

1. Introduction

The mapping of water bodies has received widespread scientific interest due to increasing ecological awareness and the availability of efficient mapping techniques such as photogrammetry, SONAR, and bathymetric LiDAR (Mandlburger, 2022). Bathymetric LiDAR can be operated from aerial platforms, which are particularly well suited for mapping lakes that are difficult to access with surface vessels. In addition, aerial operation allows large strip widths in shallow waters and higher platform speeds compared to SONAR-equipped surface vessels, resulting in efficient surveys. As with every surveying technique, the achievable accuracy of such systems is therefore a relevant question for operators, clients, and decision makers.

Based on ISO 5725-1:2023 (International Organization for Standardization, 2023), accuracy can be defined as the combination of trueness and precision. While precision describes the homogeneity of a data set (BIPM et al., 2008) and is often, for example, estimated from discrepancies in overlapping parts of a point cloud (Pfeifer et al., 2014) or the scattering of the point cloud, trueness and, consequently, accuracy are more difficult to assess. Trueness describes the average deviation of the data set from the true value. Therefore, the assessment of trueness and accuracy requires reference values that approximate the true value. In submerged environments, i.e. the operational domains of SONAR and bathymetric LiDAR, establishing such reference data is particularly challenging. Ideally, reference data should have a higher accuracy than the system being evaluated in order to allow well-founded conclusions. Consequently, for bathymetric LiDAR and SONAR, reference data should have an expected accuracy better than $1\,\mathrm{cm}$. Although achieving this level of accuracy is difficult to obtain in practice, total stations have been shown to allow highly accurate reference data for bathymetric mapping systems (Dammert et al., 2025a).

In general, the accuracy assessment of geodetic sensors under different conditions is a common topic in geodesy (Walter et al., 2025; Li et al., 2025). This task is greatly facilitated when artificial structures are present or can be introduced into the scene (Menna et al., 2016; Walter et al., 2025), or when superior measurement techniques can be employed to collect reference data (Thalmann and Neuner, 2021; Tombrink et al., 2023). However, for underwater scenarios, acquiring reference data with superior accuracy compared to airborne laser bathymetry (ALB) or multibeam echosounders is laborious (Dammert et al., 2025a; Rhomberg-Kauert et al., 2025a) and often limited to shallow water depths, with accuracy typically decreasing as water depth increases. For water depths shallower than $1.5\,\mathrm{m}$, conventional pole measurements using, for example, total stations are feasible. For greater depths, alternative approaches are required (Menna et al., 2024), and the achievable accuracy of the reference data quickly converges with the accuracy of the investigated sensor (Dammert et al., 2025a).

To facilitate an understanding of the factors influencing the uncertainty of an ALB data set, we list the most important contributors to the uncertainty of bathymetric data acquired with UAS-based ALB (Mandlburger, 2022; Pfennigbauer et al., 2025; Westfeld et al., 2017):

- Position and orientation of the ALB sensor (i.e. the trajectory)

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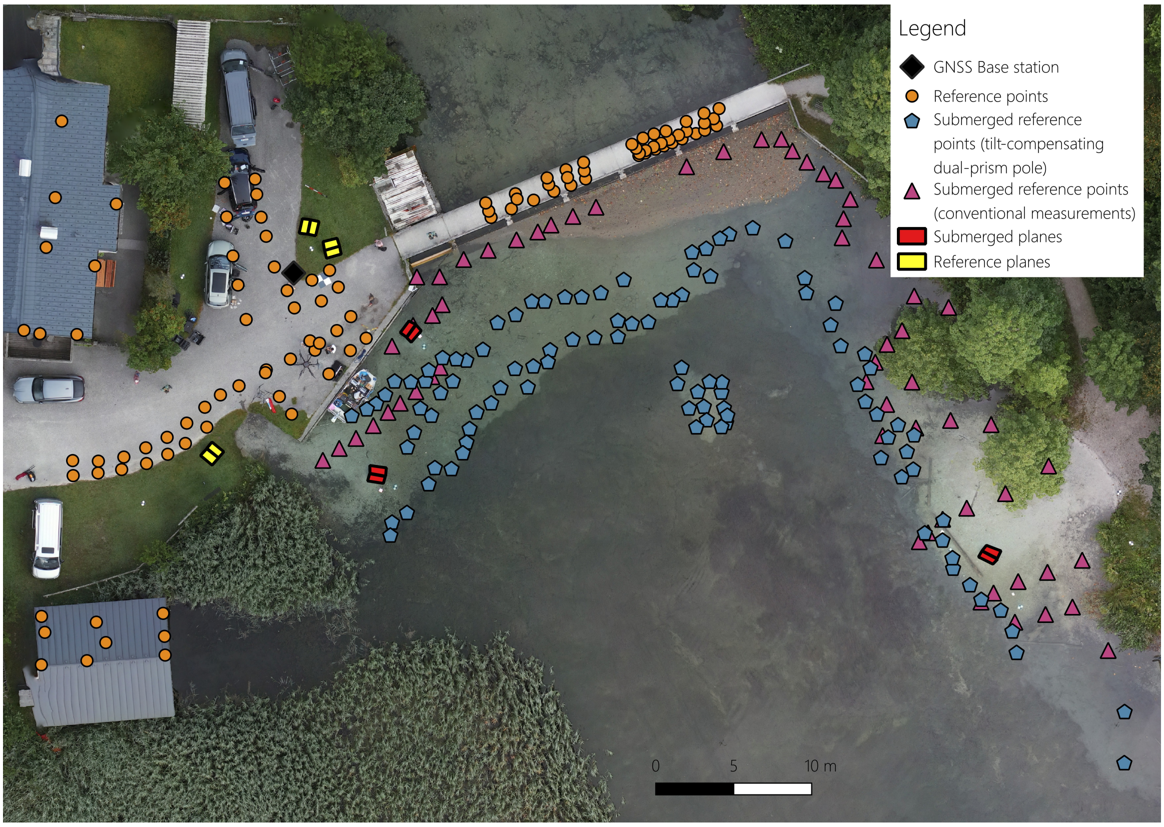

Figure 1. Study area at lake Almsee.

- Point measurements of the ALB sensor, derived from range and angle measurements
- Water height, orientation of the water surface normal, and refraction coefficient used for refraction correction.

All of these factors influence both the trueness and the precision of the resulting data set. For example, a constant bias in the position, a scale error in the LiDAR range measurement, or an incorrectly assumed refraction coefficient will introduce a systematic error in the data set. However, if such effects vary over time or their impact is not constant, e.g. due to varying angles of incidence, they also affect the precision of the data set.

Despite the growing use of ALB, robust accuracy assessments remain challenging due to the limited availability of high-quality reference data, particularly in submerged environments (Dammert et al., 2025a; Mandlburger et al., 2025). As a consequence, discrepancies within the point cloud and between the point cloud and available reference data must be carefully analysed in order to distinguish systematic effects from random variations.

Existing studies often rely on limited reference data (Rhomberg-Kauert et al., 2025b; Mandlburger et al., 2025), making it difficult to disentangle systematic effects from measurement noise in ALB data sets. This study addresses this gap by combining planar reference surfaces (Figure 3) and discrete reference points located both above and below the water surface. This approach allows us to separate and quantify the trueness and precision of UAS-based ALB data, providing a rigorous accuracy assessment under shallow alpine lake conditions.

The remainder of the paper is structured as follows. First, we introduce the study site and the material (Section 2), followed by a description of the evaluation methods (Section 3). Subsequently, we present the results (Section 4) and discuss their significance and limitations (Section 5).

2. Material

This study uses a UAS-borne bathymetric LiDAR data set of a mountain lake in Austria (Almsee, $47°45'N$, $13°57'E$). Figure 1 shows the northern part of the study area, which contains the majority of the reference data, the extent of vegetation in water body, and the positions of the reference measurements. The complete study area ranges $300\,\mathrm{m}$ from north to south. The figure also shows the positions of the six submerged and six on-land reference planes, as well as the locations of the terrestrial and bathymetric reference points.

2.1 LiDAR data

Bathymetric LiDAR data were acquired with a *RIEGL* VQ-840-GE sensor (Figure 2), operated at an altitude of $100\,\mathrm{m}$ above the water surface with a beam divergence of $1\,\mathrm{mrad}$. This results in a laser footprint of approximately $10\,\mathrm{cm}$.

The average point spacing is approximately $14\,\mathrm{cm}$, although large variations occur due to the Palmer scanning pattern of the scanner. However, the overlap of the three strips considered in this study significantly increases the point density. Consequently, the average measured point density below the water surface is approximately $50\,\mathrm{points/m^2}$.

The bathymetric LiDAR data are georeferenced using a local GNSS base station (Figure 1) and post-processed kinematic

Figure 2. *RIEGL* VQ-840-GE airborne bathymetric laser scanner mounted on a UAS.

positioning. Refraction correction is performed using the scientific point cloud processing software OPALS (Pfeifer et al., 2014) and its *Snellius* module. The water surface in the study area is assumed to be planar, and its height was measured with a total station. The refraction correction is applied using a refractive index of $k = 1.3356$, based on the measured water temperature of $13\,^{\circ}\mathrm{C}$ (Parrish, 2020).

2.2 Reference data

All reference data were acquired with a total station. To connect the total station measurements with the local GNSS base station, the position of the GNSS base station was measured with the total station. Using GNSS-RTK measurements, the orientation of the total station coordinate frame can be transformed into a higher-order coordinate system. For our evaluation, we use the coordinate reference system ETRS89 / UTM zone 33N (EPSG: 25833).

2.2.1 Reference planes Twelve temporary reference planes (approximately $80\,\mathrm{cm} \times 60\,\mathrm{cm}$) were installed pairwise in the study area (Figure 3). These planes, six above and six below the water surface (Figure 1), are oriented in different directions to enable the estimation of a three-dimensional translation vector between the LiDAR data and the reference data.

The parameters of the reference planes are estimated using a least-squares plane fitting based on at least eight measured points per plane. To facilitate processing with standard point cloud analysis tools, e.g. CloudCompare (Girardeau-Montaut and CloudCompare contributors, 2024), each plane was subsequently sampled with 5 000 points. This representation allows the planes to be stored and processed as point clouds.

2.2.2 Reference points In addition to the reference planes, approximately 100 ground points were measured above the water surface using a standard measurement pole setup, resulting in an expected point accuracy better than $3\,\mathrm{mm}$. Points on house roofs were measured reflectorless. Approximately 220 bathymetric reference points were acquired below the water surface in non-vegetated areas of the lake bed (Figure 1). These measurements were conducted in water depths ranging from $0.1\,\mathrm{m}$ to $3\,\mathrm{m}$, with an expected accuracy of $3\,\mathrm{mm}$ to $10\,\mathrm{mm}$.

For all points in water depths greater than $1.5\,\mathrm{m}$, a tilt-compensating dual-prism pole (Dammert et al., 2025a) was

Figure 3. Planar reference geometry above (left) and below (right) the water surface.

used. This pole compensates for tilt and movement of the measurement pole during acquisition by continuously measuring the positions of two prisms mounted on the pole. By constructing the three-dimensional vector between the two prisms and considering the known length of the pole, the position of the pole tip can be determined even under unstable measurement conditions, e.g. when measurements are performed from a boat (Dammert et al., 2025a). Previous investigations show that the height accuracy of the tilt-compensating dual-prism pole is better than $10\,\mathrm{mm}$.

However, for bathymetric reference points the dominant source of uncertainty is typically not the total station measurement itself, but the penetration of the measurement pole into the sediment at the lake bottom. To mitigate this effect, a $15\,\mathrm{cm}$ disk-shaped foot was attached to the measurement pole.

3. Method

Our study focuses on the estimation of accuracy, which consists of (i) trueness and (ii) precision (International Organization for Standardization, 2023). We first describe the workflow used to estimate the trueness, i.e. the average bias of the data set with respect to the reference data. After correcting for trueness, the remaining residuals of the ALB data with respect to the reference data describe the precision of the data set.

In addition, the precision can also be assessed by analysing the scatter of the ALB data relative to a known geometric shape. Therefore, we derive a second measure of precision using the residuals of a plane fit of the ALB data on the reference planes.

3.1 Estimation of trueness

To assess the trueness of the data, we use the reference planes (Figure 3) located above and below the water surface. The LiDAR data capture each plane with at least eight points per flight strip. Due to the irregular scan pattern, some reference planes contain a significantly larger number of points. Nevertheless, the density of the ALB data allows a reliable alignment of all planes extracted from the LiDAR data with the reference planes (Figure 4).

From both the reference measurements and the ALB data, we derive point clouds that contain only the reference planes. Using an iterative closest point (ICP) algorithm, e.g. as implemented in CloudCompare (Girardeau-Montaut and CloudCompare contributors, 2024) or OPALS (Pfeifer et al., 2014), we estimate the translation vector required to align the ALB data with the reference data. Due to the small size of the planes, we estimate only a translation and no rotation. The resulting translation vector represents the trueness of the ALB data set.

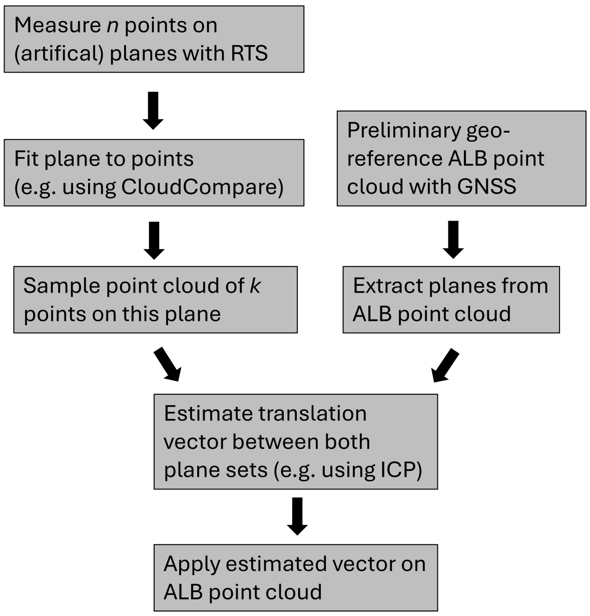

Figure 4. Flowchart of indirect geo-referencing with planar references.

3.2 Estimation of precision

To assess the precision, two complementary analyses are performed. The first analysis is based on point-wise reference measurements, whereas the second relies solely on the LiDAR data. After correcting for trueness, both measures can be interpreted as describing the precision of the data set.

3.2.1 Residuals from reference data To obtain a precision estimate based on the reference data, we compute the M3C2 distance (Lague et al., 2013) of each reference point w.r.t. LiDAR data, using a cylinder estimated within the $25\,\mathrm{cm}$ neighbourhood of the evaluated points. After applying the translation vector, i.e. correcting for trueness, the resulting normal distances should average around zero. The Root-Mean-Square (RMS) of these residuals therefore represents the precision of the data set.

3.2.2 Residuals of the plane fit Another approach to estimate the precision is to analyse the spread of the data around a known geometric shape. Planes are frequently used to calibrate or investigate laser scanning sensors (Heffner et al., 2025; Heinz et al., 2020; Khami et al., 2026). An ideal LiDAR sensor would measure points that lie perfectly on such a plane. Consequently, when fitting a plane to the measured points, the residuals of the plane fit should be zero. Any deviation from zero can therefore be attributed to measurement uncertainty, i.e. the precision of the sensor. However, this interpretation is only valid along the normal direction of the plane; deviations within the plane itself cannot be detected.

Because the planes used in our study are tilted and oriented in different directions, their varying orientation allows us to derive a sufficiently representative estimate of the precision across the polar measurement domain of the LiDAR sensor.

This approach is limited by potential deviations of the reference targets from a perfectly planar surface. For the reference planes shown in Figure 3, the above-water planes can be assumed to be sufficiently planar. In contrast, the underwater planes may deviate slightly from an ideal plane due to the softer surface material. Considering the manufacturer-specified uncertainty of the ALB sensor of approximately $2\,\mathrm{cm}$ (RIEGL Laser Measurement Systems GmbH, 2025), we expect this effect to be negligible.

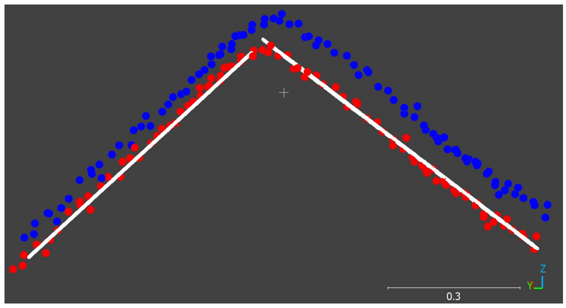

Figure 5. Saddle roof representation in point cloud - Strip 1, with high point density. White points are reference plane, blue points are measurement from ALB before application of the 3D shift and red points after application of the 3D shift.

4. Results

The results of this study are the estimates of trueness and precision derived according to the methodology described in Section 3.

4.1 Trueness

The estimated translation vector of the LiDAR data, derived from the reference planes, is approximately $[-4, 7, -7]\ cm$. This vector represents the trueness of the data set. We expect this bias to be primarily caused by GNSS conditions in the mountainous environment rather than by the LiDAR sensor itself. However, the estimated bias also includes any systematic uncertainties present in the reference data.

Figure 5 shows the ALB point cloud before and after application of the translation vector together with the reference plane constructed from the total station measurements. A rounding effect of the LiDAR data can be seen on the intersection point of both planes due to the laser footprint size of the LiDAR. However, the good fit of the LiDAR data on the reference planes is evident.

4.2 Precision

The precision is evaluated using two approaches (Section 3). Both approaches are justified and complementary. The evaluation with respect to reference data requires considerably more effort than the evaluation based on plane-fitting residuals.

Both precision measures are influenced not only by the ALB sensor but also by the reference data, e.g., the uncertainty of the reference data and possible deviations of the reference planes from perfect planarity. For the reference planes used in our study (Figure 3), these effects are assumed to be negligible. Consequently, the two precision measures complement each other: the plane-fitting residuals primarily reflect the precision of the LiDAR point measurements on a well-reflecting target, whereas the comparison with reference points additionally incorporates the influence of the measured target, i.e. the lake bed. Differences between the two estimates may also originate from the remaining uncertainty in the reference measurements.

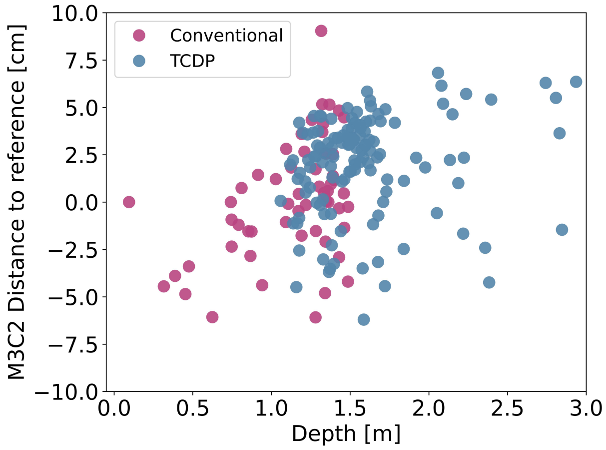

Figure 6. M3C2 Distances to reference plotted over different depths.

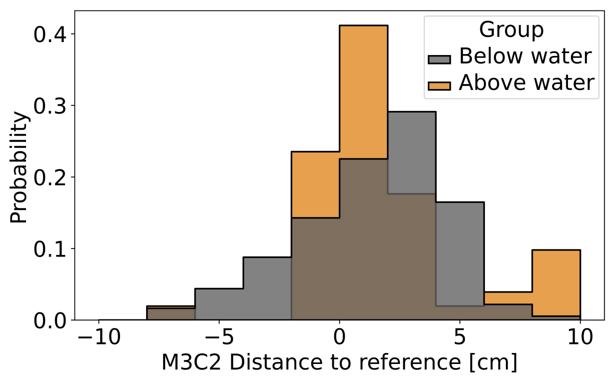

Figure 7. Distributions of M3C2 Distances to reference, grouped in above and below water.

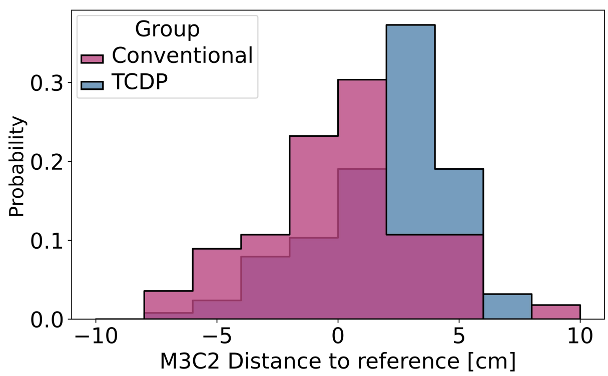

Figure 8. Distributions of M3C2 Distances of underwater points to reference, grouped in conventional and tilt-compensating dual-prism pole (TCDP) measurements.

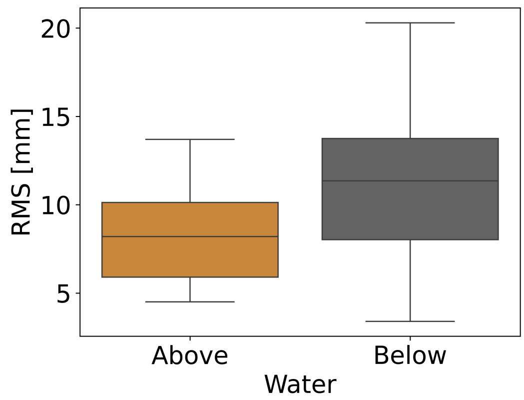

Figure 9. Residual of plane fitting above and below the water surface.

4.2.1 Relative to reference measurements To evaluate the precision of the bathymetric LiDAR data with respect to the reference measurements, we compute the M3C2 distance between each reference point and the LiDAR point cloud (Section 3.2.1). The resulting deviations are analysed separately for points located above and below the water surface (Figure 7). Figure 8 further distinguishes between underwater points measured conventionally and those measured using the tilt-compensating dual-prism pole.

After applying the estimated translation vector, 95% of the above-water points show deviations between $-2\,\mathrm{cm}$ to $5\,\mathrm{cm}$, whereas 95% of the below-water points lie between $-6\,\mathrm{cm}$ to $4\,\mathrm{cm}$ (Figure 7). The corresponding RMS values are $2.0\,\mathrm{cm}$ and $2.7\,\mathrm{cm}$, respectively. When further separating the underwater reference points into those measured by conventional wader and pole measurements and those measured using the tilt-compensating dual-prism pole (Figure 8), RMS values of $2.9\,\mathrm{cm}$ and $2.6\,\mathrm{cm}$ are obtained, respectively. A small bias towards positive M3C2-distances can be seen from the tilt-compensating dual-prism pole data.

These results indicate that the ALB system achieves centimetre-level consistency, and that the refraction correction of the ALB data and the different underwater measurement techniques used for reference data acquisition do not introduce visible systematic effects for depths smaller than $1.5\,\mathrm{m}$. The slightly larger deviations below the water surface likely reflect natural variability in the water column and local surface irregularities rather than limitations of the LiDAR sensor itself.

Figure 6 shows the variation of the below-water discrepancies with respect to water depth. The figure illustrates the distribution of reference points over depth and indicates that no clear trend of the M3C2 distances with increasing depth can be observed. Furthermore, no discontinuity is visible at the transition between conventional pole measurements and tilt-compensating dual-prism pole measurements at approximately $1.5\,\mathrm{m}$ water depth.

4.2.2 Plane-fitting residuals Figure 5 also illustrate the spread of the LiDAR data around the reference planes. The box plot shown in Figure 9 presents the RMS values of the plane-fitting residuals. In total, 30 individual planes were fitted. The figure distinguishes between planes located above the water surface (air) and those located below the water surface (submerged).

The mean RMS of the planes above the water surface is $8.4\,\mathrm{mm}$, which is slightly lower than the mean RMS of $11.0\,\mathrm{mm}$ obtained for the submerged planes. Considering the influence of a slightly uneven and dynamic water surface, the difference of approximately $3\,\mathrm{mm}$ is relatively small. This suggests that, after correcting for trueness, the internal point measurement precision of the ALB sensor is consistently high, and the effect of water surface conditions on the plane fit is minor.

5. Discussion

The results demonstrate that ALB is a reliable technique for acquiring bathymetric data. However, evaluation is challenging because highly accurate reference data are difficult to obtain, especially for submerged environments (Lo et al., 2024). Even when available, reference measurements become increasingly difficult, less accurate, and more costly with increasing water depth. In this study, reference data were limited to a maximum depth of $3\,\mathrm{m}$ under favourable water conditions. Consequently, these results cannot be directly extrapolated to deeper water environments.

In our study, the trueness describes the constant shift of the LiDAR data with respect to the reference data. For data sets that are georeferenced using GNSS, this shift can largely be attributed to GNSS-related uncertainties. However, the trueness may also include other systematic effects. For instance, an incorrectly modelled lever arm between the laser scanner and the GNSS antenna would also result in a constant shift of the data set. Estimating and correcting such systematic offsets is therefore a crucial step in data processing, particularly when aligning data sets from different sensors or acquisition epochs in order to enable consistent analysis and interpretation.

The use of reference planes provides a practical means of estimating and compensating for such systematic shifts. Nevertheless, when using GNSS for the georeferencing of multi-sensor systems, offsets of several centimetres are not uncommon. To improve the georeferencing and consequently the trueness of the resulting data sets, alternative georeferencing strategies may be applied. For example, total stations can estimate the position of kinematic targets with millimetre accuracy, although they are limited to measurement ranges of approximately $800\,\mathrm{m}$ (Dammert et al., 2025b). The use of total stations to measure the trajectory of multi-sensor systems, i.e. direct georeferencing, allows the acquisition of homogeneous data sets even when multiple sensors and platforms are used.

It is also apparent that the two derived precision measures, (i) relative to reference data and (ii) based on plane-fitting residuals, differ. While the plane-fitting approach yields RMS values of approximately $1\,\mathrm{cm}$, the comparison with the reference data results in RMS values that are two to three times larger. Nevertheless, both measures consistently indicate that the difference between submerged and terrestrial measurements is relatively small.

The discrepancy between plane-based precision estimates and point-based comparisons is therefore likely dominated by uncertainties in the reference measurements rather than by uncertainties of the LiDAR data itself. In particular, defining the exact position of the lake bed is challenging. During the acquisition of the bathymetric reference data, the measurement pole penetrated the soft sediment. Even with a $15\,\mathrm{cm}$ wide pole foot, the sediment allowed the pole to sink into the ground. In our study, we recorded video footage of the pole-ground interaction using an underwater GoPro, but the exact magnitude of the penetration could not be reliably determined. For firmer sediments, such penetration occurs slowly and can be measured using the continuous measurements of the total station. However, at the study site, the sediment was extremely soft, for some parts of the study area, and the penetration occurred almost immediately upon contact with the ground, making it difficult to measure.

Such an effect would primarily introduce a bias in the reference data rather than increased measurement noise (Figure 7). Thus, it may be a reason for the positive bias of the data acquired with the tilt-compensated dual-prism pole. The reason, while the sediment penetration affects the tilt-compensated dual-prism pole measurements more than conventional pole measurements, can be the worse handling of the heavier and longer pole. Meaning, the person holding the pole can place it more gently and controlled on the ground when standing firm on the ground in shallow waters and handling a $2\,\mathrm{m}$ long measurement pole compared to handling a $4.65\,\mathrm{m}$ long measurement pole from a boat. Another possible explanation could be an increased measurement uncertainty associated with the tilt-compensating dual-prism pole. However, when separating these measurements from the conventionally acquired reference points, a slightly better RMS of $2.6\,\mathrm{cm}$ compared to $2.9\,\mathrm{cm}$ was observed, suggesting that this measurement method does not introduce additional uncertainty.

6. Conclusion

In this study, a state-of-the-art bathymetric LiDAR sensor was assessed with respect to its accuracy, defined as the combination of trueness and precision, for measurements acquired above and below the water surface. The LiDAR data were evaluated against reference measurements consisting of 12 reference planes and more than 200 submerged reference points distributed over water depths of up to $3\,\mathrm{m}$.

The reference planes enabled the estimation of a constant translation between the LiDAR data and the reference data, as well as a measure of precision derived from plane-fitting residuals of the LiDAR data. The reference points were used to obtain an additional precision estimate based on the normal distances between the points and the LiDAR point cloud.

The estimated translation vector of approximately $[-4, 7, -7]$ cm represents the trueness of the data set. This offset is mainly attributed to georeferencing uncertainties rather than to limitations of the LiDAR sensor itself. The derived precision measures range from approximately $8\,\mathrm{mm}$ (RMS of the plane-fitting residuals) to $2.0\,\mathrm{cm}$ (RMS of the normal distances to the reference points). For submerged measurements, slightly larger values of approximately $11\,\mathrm{mm}$ and $2.6\,\mathrm{cm}$ were obtained for the plane-fitting and reference-point comparisons, respectively.

These results demonstrate that modern UAS-based ALB systems can achieve centimetre-level precision in shallow submerged environments. However, the limited availability of accurate underwater reference data remains the main bottleneck for rigorous validation. Future studies should focus on evaluation strategies for deeper water and more complex environmental conditions, as well as exploring alternative reference acquisition strategies to further reduce validation uncertainty.

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