Comparative Analysis of Achieved Accuracy Using Low-Cost Mobile Phone LiDAR and Remote Sensing Techniques

Petra KRNJAK[1], **Ana KOSOR**[1], **Hrvoje TOMIĆ**[1], **Ante MARENDIĆ**[1], and **Rinaldo PAAR**[1,*]

[1] *University of Zagreb - Faculty of Geodesy, Institute of Applied Geodesy, Zagreb, Croatia, (petra.krnjak@geof.unizg.hr, ana.kosor@geof.unizg.hr, hrvoje.tomic@geof.unizg.hr, ante.marendic@geof.unizg.hr, rinaldo.paar@geof.unizg.hr)*

[*] *corresponding author*

Abstract

The technological development of measurement technologies and associated sensors has transformed geodetic surveying methods. Contemporary geodetic techniques are efficient and reliable, employing a variety of passive and active sensors. This frequently results in the creation of new products, such as point clouds, meshes, textured meshes, digital surface models, and orthophotos, whose application sometimes necessitates adapting existing data formats or developing new ones and/or standards. In engineering geodesy, it is essential to evaluate whether a specific measurement technology meets the required precision and accuracy standards. Unmanned Aerial Vehicles (UAVs) equipped with imaging sensors are now frequently used for a wide range of surveying tasks, using a digital photogrammetric method. With recent advancements in sensor technology, systems with LiDAR 3D laser scanners are now available on smaller and relatively affordable UAVs. Recently, mobile phones have also been equipped with LiDAR sensors which are cost-effective solutions for various ground-based geodetic measurements and tasks. Terrestrial Laser Scanners (TLS) are a type of 3D scanning technology that provides exceptional precision and efficiency, widely utilized to capture large-scale environments in 3D. This paper explores the application possibilities of various methods for surveying, detecting geometric changes of measured objects from the point clouds in different epochs and calculating the volume of embankments, excavations, and other similar projects. The survey of the embankment dam will be performed using a low-cost mobile device equipped with a LiDAR sensor. Also, the same embankment dam will be measured by remote sensing techniques using a laser scanner and UAV. This way the analysis of achievable accuracy using all mentioned methods will be done. This paper analyses the advantages and disadvantages of the applied survey methods and evaluates their suitability based on achievable accuracy for various surveying tasks.

Keywords: Low-Cost LiDAR, Mobile Phone, Quality Analysis, TLS, UAV

1 Introduction

In engineering geodesy, it is crucial to assess whether a particular measurement technology meets the necessary precision and accuracy requirements. Various surveying methods and instruments can be employed to collect spatial data, depending on the desired accuracy, achievable precision, and suitability for specific projects. Nowadays, remote sensing techniques can generate high-resolution 3D maps to monitor the atmosphere or to measure the Earth's surface to determine the characteristics of the object without physical contact (Aslan & Polat, 2022; Shafikhani, 2018). The LiDAR system generates a high-resolution terrain surface and collects measurement data more efficiently with a high degree of data coverage. The first smartphone iPhone Pro with integrated LiDAR-based sensors was launched in 2020. This technology allows the creation of point clouds, enabling data collection in challenging environments without physical contact or in areas where optical sensors have limitations. The measurement process with the smartphone can greatly reduce the measurement time, but also the necessity for additional instruments and equipment (Hakim et al., 2023). Currently, mobile devices like iPhone Pro are widely used and can easily fit into a pocket or bag. Integrating iPhone Pro with a LiDAR sensor can accelerate the data acquisition and processing stages. Moreover, the technical capabilities, affordability, and ease of use of mobile devices present an alternative to traditional range-based methods like TLS or UAVs, which are extensively used in various industries (Spreafico et al., 2021). When comparing the prices of LiDAR devices and iPhone Pro devices equipped with a LiDAR sensor, the iPhone Pro provides low-cost solutions when determining the 3D position of an object (Tondo et al., 2023). Remote sensing techniques can be used depending on the characteristics of the object, required accuracy, surveying area or the required level of detail. They can be implemented in specific spheres to generate 3D models or landscapes, inspection of infrastructure in hard-to-reach areas (bridges, pipelines, wind turbines), monitoring of constructions and analysing deformations of buildings and bridges, volume calculations, mining activities or detailed topographic surveys for infrastructure development and land management. TLS procedure is characterized by an extremely high sampling rate, capturing hundreds of thousands of 3D points per second in real-time (Kogut & Pilecka, 2020; Miller et al., 2008). For this reason, traditional geodetic methods cannot provide a high resolution of measured data and measurement speed compared to TLS (Miller et al., 2008). To achieve greater accuracy and better coverage of the scanning area or supplement the area of previously scanned objects the TLS scanning procedure is performed from multiple scanning positions (Kogut & Pilecka, 2020). It can also record a large amount of accurate topographic information in a short time which is extremely useful in detecting surface displacements (Fan et al., 2014). UAVs have wide applications in various branches such as aviation, engineering, computing, robotics, and remote sensing (Telli et al., 2023). Additionally, UAVs are increasingly used due to their mobility and flexibility, with the rapid development in the fields of artificial intelligence, machine learning, and information technology (Pasha et al., 2022). Generated 3D models obtained by UAV accurately display the actual size and shape of the measured objects and model this object with accurate georeferencing (Aslan & Polat, 2022). Furthermore, UAV has the possibility of covering a larger area with high accuracy and with fewer recording positions, while TLS due to its static nature requires more scanning positions to achieve higher measurement precision which therefore requires more measuring time. In contrast to TLS, iPhone Pro has higher time efficiency (scanning time) but provides less accurate measurements. The embankment designed for stormwater drainage was measured in combination with iPhone Pro with LiDAR scanning technology, UAV photogrammetry and TLS . This research was conducted to determine the precision, accuracy, and cost-effectiveness of a low-cost mobile device equipped with a LiDAR sensor in comparison with remote sensing techniques. The detection of geometric changes in the measured objects and the calculation of their volumes were also performed.

2 Field Measurements

The research goal was to analyse the accuracy and cost-effectiveness of the low-cost mobile phone LiDAR measurements in comparison with remote sensing techniques (photogrammetry and terrestrial laser scanning) for various applications. The research area was an embankment dam for stormwater drainage Planički jarek located in Dugo Selo, Zagreb County 20 km east of Zagreb, Croatia. The location coordinates are 45°48'46.8" in the north and 16°13'49.5" in the east, related to the World Geodetic System 1984 (WGS84). Planički jarek is an embankment dam with maximum height of 9.3 m, and the length and width of the dam crown 167 m and 4 m, respectively. The instruments and equipment used in this paper are shown in Figure 1.

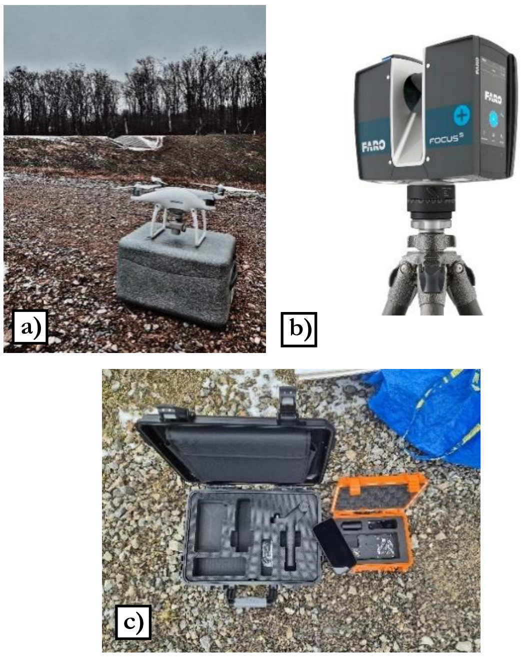

Figure 1. The measurement equipment: (a) DJI Phantom 4, (b) Faro 3D Laser Scanner S150 Premium and (c) iPhone Pro with Emlid Scanning kit (Emlid Reach RX) and viDoc RTK rover

The data were collected using iPhone 14 Pro Max equipped with a LiDAR sensor, UAV DJI Phantom

4 and Faro 3D Laser Scanner S150 Premium. iPhone Pro LiDAR data were collected in combination with the viDoc RTK rover and in combination with Emlid Scanning Kit – Emlid Reach RX. The measurement of the embankment dam was carried out in January 2025. Six orientation points (marker 1P – 6P in Figure 2) were used as Ground Control Points (GCPs) and were established for orientation and processing purposes. Two orientation points were stabilised on the dam crown and two points on each side of the embankment dam. Additionally, 16 control points (CPs) (marker 1C – 16C in Figure 2) were established to analyse the accuracy of measured points by different methods.

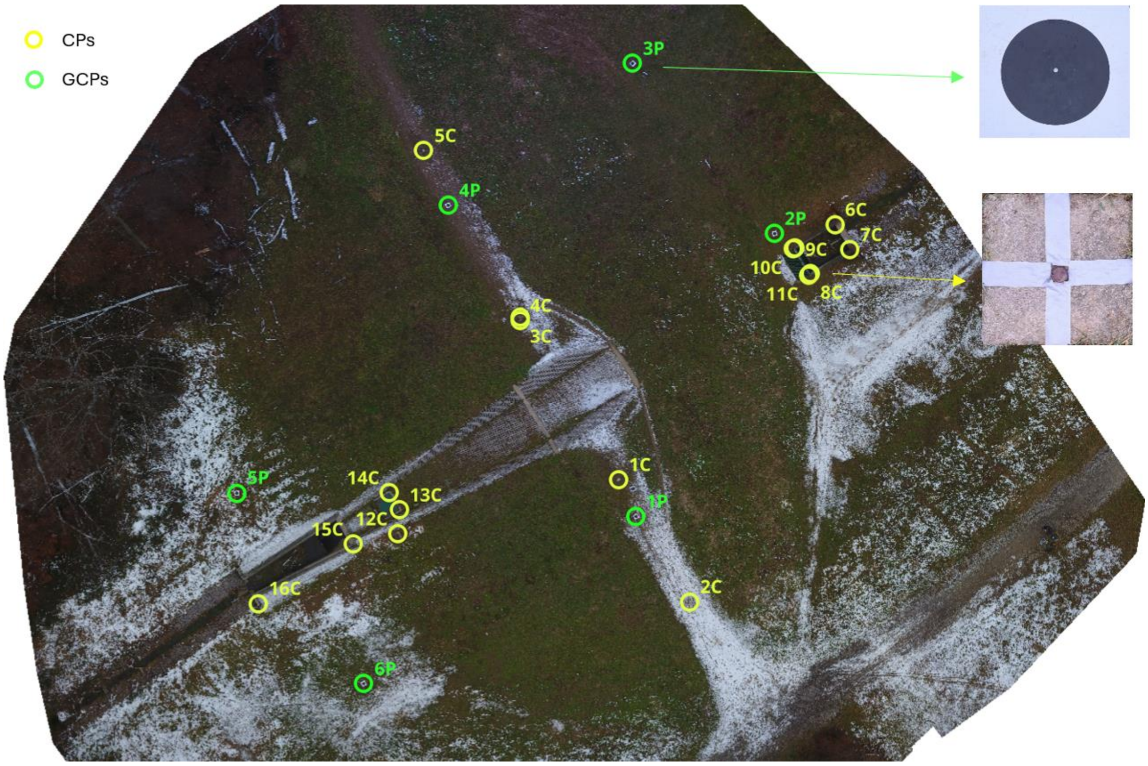

Figure 2. Orthomosaic of the embankment dam with position of GCPs and CPs and an example of point signalization for GCP 3P and CP 8C

For the UAV mission, GCPs were used for georeferencing of UAS-derived products and were signalised using a white square plate, with a black circle and metallic benchmark placed at the centre of it (Figure 2). Based on the flight parameters, 101 images were captured at an altitude of 25 meters above ground level across eight flight lines. Afterwards, the TLS survey was done from eight different scanning positions across the measurement area. Four scanning positions were on the dam crown and two scanning positions were on each side of the embankment dam. Georeferencing of TLS point cloud was performed using six GCPs stabilized for UAV mission. For the purpose of connecting scans, from different scanning positions, four additional orientation points were stabilized on tripods and placed in the scan area. The scanner settings used are typical outdoor measurement settings – 3x scanning quality, 1/4 resolution, colour mode. The third survey was conducted using the iPhone 14 Pro Max LiDAR in combination with a viDoc RTK rover and in combination with an Emlid Reach RX rover. Free roam walking scheme was used with two different approaches to survey the embankment dam for both iPhone rover combinations. For the first approach, where the iPhone only scanned from the dam crown, all data that was more than 5 meters away from the current position of the iPhone was determined with the photogrammetric method within the iPhone. While in the second approach a free roam walking scheme was used across the entire measurement area. The movement trajectories of the different approaches with iPhone and viDoc RTK rover are shown in Figure 3.

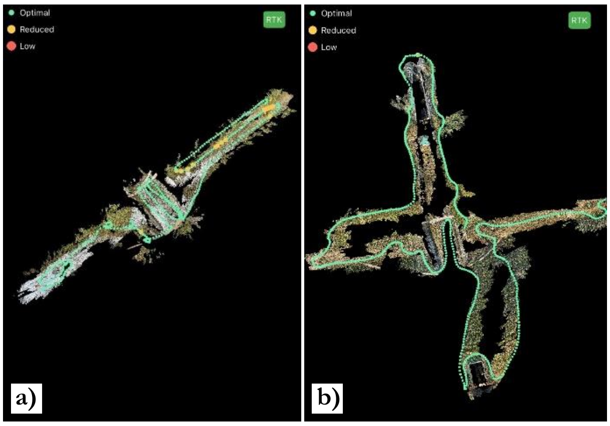

Figure 3. The display of iPhone trajectory when the survey was done: (a) from the dam crown and (b) on the entire measurement area

3 Data Processing

The raw data collected by TLS were pre-processed in the FARO Scene 2023.1.0.11127 software which generated a point cloud, while the pre-processing of the UAV and iPhone LiDAR raw data was carried out in PIX4Dmapper 4.9.0. and PIX4Dmatic 1.72 software, respectively. FARO Scene software is designed for processing, managing and analysing 3D laser scan data (URL 1), while PIX4Dmapper generates highly accurate 3D models and point clouds from aerial images captured by UAVs (URL 2). The PIX4Dcatch Professional mobile application was used to capture an accurate 3D model of embankment dam, while the data processing and point cloud generation were performed using PIX4Dmatic software (URL 2). The georeferencing of the point clouds generated by TLS and UAV, from the local to the HTRS96/TM (Croatian Terrestrial Reference System 1996) coordinate system, was carried out using six GCPs. The coordinates determined by the iPhone are absolute, meaning they are already referenced to a global coordinate system. As a result, the point cloud does not need to be georeferenced. The generated point clouds were exported in LAS and LAZ formats and further processed in CloudCompare software where they were analysed, compared and visualized. The initial coordinates of GCPs were determined using GNSS RTK rover Emlid Reach RX connected to the CROPOS (Croatian Positioning System) GNSS CORS. The final coordinates of GCPs and CPs were determined with a Robotic Total Station (RTS) Leica TPS1201 using the resection method based on the initial coordinates of GCPs. Afterwards, the GCPs were re-measured to obtain their final, more precise coordinates that were used for accuracy analysis.

4 Results and Discussion

This paper presents the results of three different analyses: a comparison of the point coordinates determined by above mentioned methods with their more precise values (obtained with RTS), a comparison between point clouds obtained by different methods and a comparison of embankment dam volume calculation from the results of the various surveying methods. In the first analysis, the accuracy of point coordinates determined with iPhone LiDAR, TLS and UAV was compared to the coordinates of 16 CPs obtained with RTS. The coordinates of CPs were obtained manually from the point cloud using PIX4Dmatic software. Figure 4 illustrates how the coordinates of the measured points were determined.

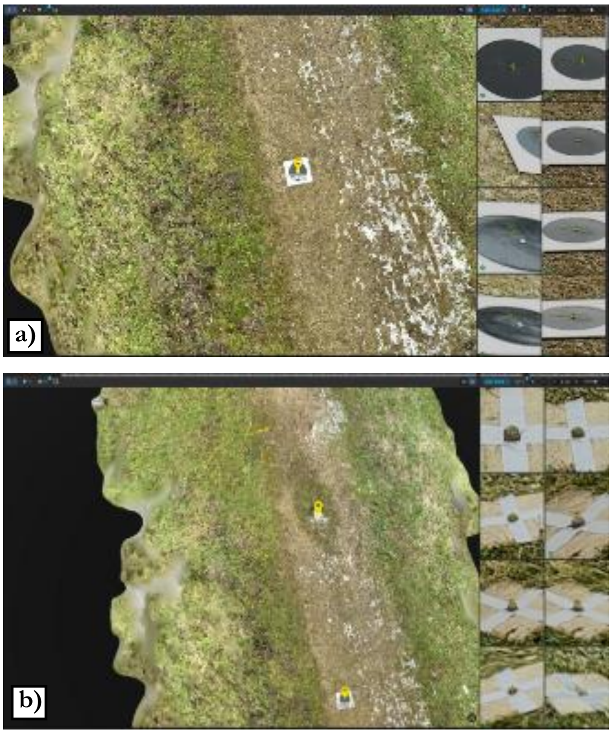

Figure 4. Determination of the (a) GCP coordinates and (b) CP coordinates, collected by iPhone LiDAR in PIX4Dmatic software

Table 1 shows statistical data of the differences between the coordinates of each method in relation to the reference coordinates and the corresponding RMSE values in horizontal plane and in 3D space. In further analysis, the following measurement names were used for iPhone LiDAR measurements: viDoc RTK – 1 – measurement of the embankment from the crown in combination with the viDoc RTK rover, viDoc RTK – 2 – measurement of the embankment by measuring the entire area in combination with the viDoc RTK rover, Emlid Reach RX – 1 – measurement of the embankment from the crown in combination with the Emlid Scanning Kit and Emlid Reach RX – 2 – measurement of the embankment by measuring the entire area in combination with the Emlid Scanning Kit.

Table 1. Comparison of the coordinate differences between the GCPs, CPs and the reference coordinates (RTS)

	viDoc RTK – 1			**viDoc RTK – 2**			**Emlid Reach RX – 1**			**Emlid Reach RX – 2**			**UAV**			**Faro**		
	Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz	Δx	Δy	Δz
Mean coord. diff [cm]	-1.5	-1.1	4.2	-0.3	-0.8	5.4	-3.2	1.1	-3.2	-2.2	-2.0	4.3	-0.2	0.0	0.2	-0.7	-0.2	0.5
Range	5.7	7.0	6.1	7.5	8.3	8.3	10.5	9.3	5.6	8.3	8.3	12.5	6.7	6.9	2.7	5.7	9.2	2.6
St. dev. [cm]	2.4	2.7	2.5	2.9	3.1	2.7	4.0	3.4	2.1	2.7	2.0	5.8	2.2	2.3	0.8	1.8	3.0	1.0
2D RMSE [cm]	4.1			4.3			5.9			4.4			3.0			3.4		
3D RMSE [cm]	5.9			7.7			6.6			7.1			3.1			3.6		

The results in Table 1 show that the largest differences and corresponding standard deviations were observed for the iPhone measurement compared to the UAV and Faro survey. This outcome was anticipated due to the processing method, as the UAV and Faro survey used six GCPs. In contrast, iPhone measurements differed as the absolute coordinates were obtained through RTK positioning combined with the LiDAR measurements. In projects where measurements in different epochs are compared, a fundamental task is the georeferencing of point clouds where coordinates in the local coordinate system are transformed to coordinates in an absolute coordinate system. The accuracy of point coordinates determined with iPhone integrated with RTK rovers in the horizontal direction (2D RMSE) was up to 5.9 cm and in 3D up to 7.7 cm. Although the obtained accuracy of point coordinates from iPhone LIDAR measurement was lower compared to the UAV and Faro survey, it is necessary to emphasize that for this approach it was not necessary to stabilize and signalize the points at the measurement site for georeferencing purposes which simplifies the measurement process. However, it was impossible to precisely determine all coordinates of CPs in the case of iPhone measurements carried out only from the dam crown where blurry areas in the point cloud were observed (e.g. left edge in Figure 4). In the second analysis, the main goal was to analyse the usability of iPhone LiDAR measurements in combination with the RTK rover to detect geometric changes of measured objects from the point clouds in different epochs. Since all the measurements were carried out on the same day, any deviations (differences) between the point clouds represent an error in the measurement and data processing, considering no movement occurred in the period between measurements. The point clouds were compared using the open-source software CloudCompare based on the distance between them using the Cloud-to-Cloud Distance (C2C) method. In the first approach, the comparison was made between two point clouds obtained by iPhone LIDAR measurement with both rovers from the dam crown, while the second approach included measurement from the entire area. The iPhone point cloud comparisons are shown in Figure 5.

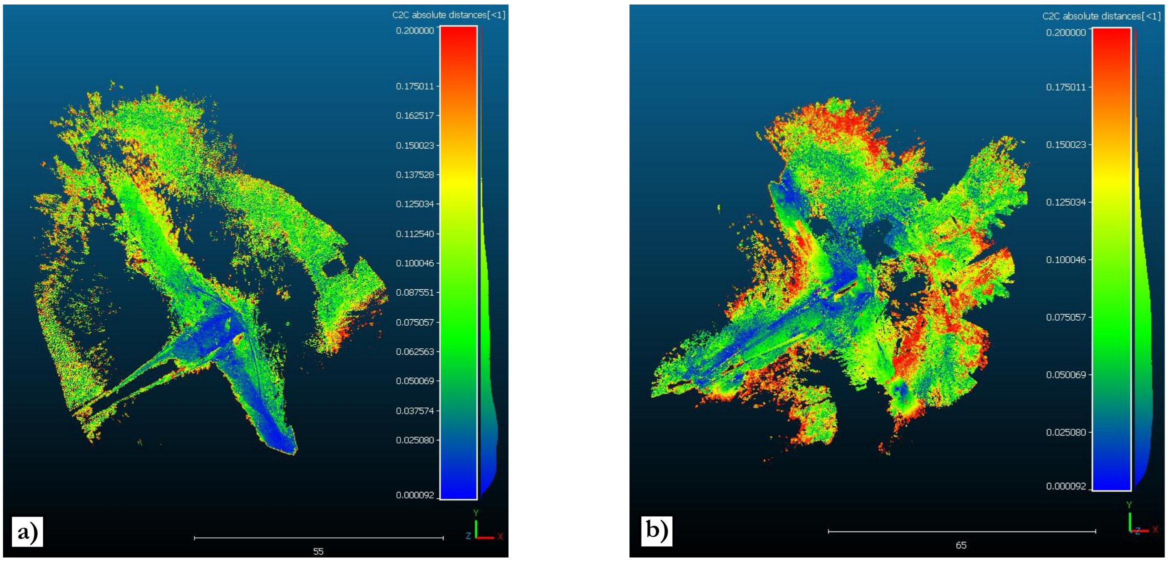

Figure 5. The display of compared point clouds obtained by iPhone LiDAR measurements on (a) the dam crown and (b) on the entire measurement area

Point cloud comparison and their corresponding histograms on the colour scale (Figure 5) show a substantial overlap of point clouds. Regarding their histograms, the highest peaks represent the majority of differences between the two compared point clouds. According to the colour scale, blue and green indicate the minimal mutual deviation of the two point clouds. The highest concentration of differences in blue and green areas are around 3 to 4 cm. The maximum overlap occurs at the dam crown, as a thorough measurement was conducted on the embankment dam (first approach) in comparison to the entire measured area (second approach). Therefore, the resulting data validates the accuracy of the iPhone measurement. Red-coloured areas highlight the highest concentration of deviations and indicate the disparity between the reference and compared point clouds, such as non-uniform data within the same recorded area or potential gaps ("holes") in the point cloud. To obtain the accuracy and efficiency of the iPhone LiDAR measurement, point clouds regarding the remote sensing techniques were compared. Figure 6 shows the compared point clouds for iPhone LiDAR measurement, UAV (third approach), and TLS (fourth approach) on the entire measurement area.

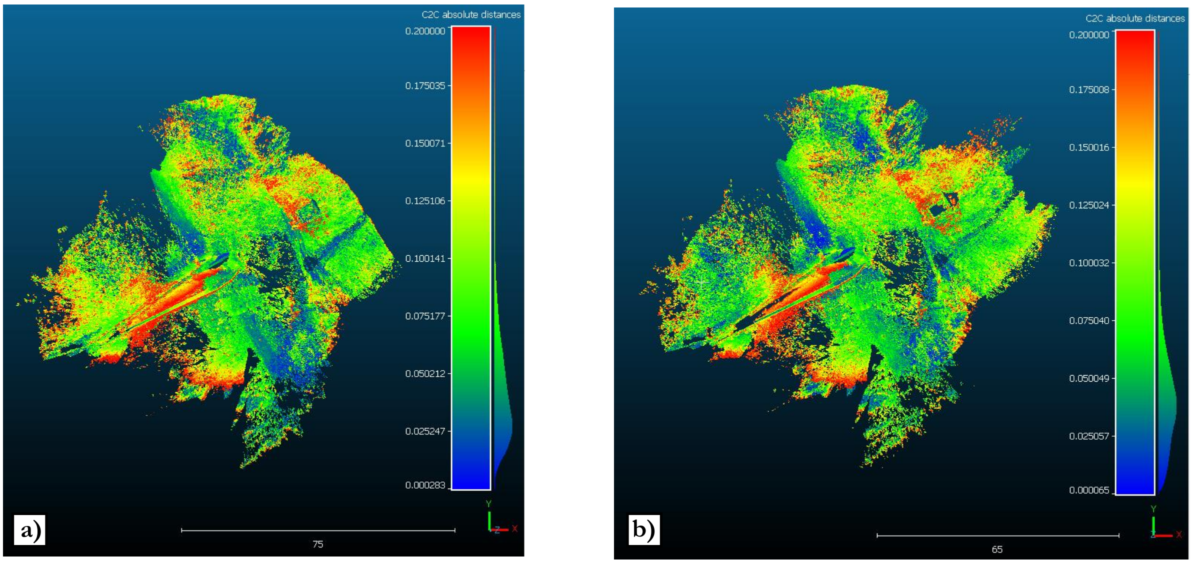

Figure 6. The display of compared point clouds obtained by iPhone LiDAR measurements with (a) UAV and (b) TLS on the entire measurement area

The compared point clouds and their corresponding histograms on the colour scale (Figure 6) show a solid overlap. Regarding their histograms, UAV showed a closer fit with the iPhone measurement where the differences are within 2.5 cm intervals, unlike the Faro where the difference was about 4 cm. The green colour which represents values from approximately 4 to 12 cm, is dominant on both compared point clouds, while the red colour highlights areas where it was difficult to scan details due to vegetation, layers of snow, textured concrete sections and the channel depression. Additionally, when comparing the point clouds of the viDoc RTK and UAV, the maximum overlap occurs on the entire area of the dam crown, which was not the case with the viDoc RTK and Faro point clouds. The reason for the less accurate matching of iPhone LiDAR and Faro point clouds may be the angle of incidence of the laser beam during scanning due to poor visibility of details. As well, the LiDAR sensor used with the iPhone Pro in comparison to the TLS sensor is adapted for consumer use and provides less accurate data. The third analysis compares volume calculated from different point clouds in QGIS 3.34.15 software. The volume calculation area for each point cloud was a polygon that was defined as an area which only encompassed the embankment dam and not the surrounding parts of the point cloud that were not part of the embankment dam. Before volume calculation, TIN interpolation was used on the point cloud to create a surface model (DEM). It is important to emphasize that by TIN interpolation, individual “holes” in the point cloud are filled with a straight surface directly to the closest heights. Volume calculation was performed using the *Volume Calculation Plugin*, where the Area (Polygon Layer) and DEM Height Layer were selected. The base height of the DEM Height Layer was manually defined based on the lowest height in the chosen polygon area. The calculated volume from each point cloud was compared to the reference volume calculated from the Faro point cloud (expressed in percentages) (Table 2).

Table 2. Calculated volumes and differences in comparison to the reference volume

Method	**Volume [m^3]**	**Volume difference [%]**
viDoc RTK – 1	17,944.80	1.40
viDoc RTK – 2	17,903.80	1.17
Emlid Reach RX – 1	17,853.10	0.88
Emlid Reach RX – 2	17,839.80	0.81
UAV	17,681.40	0.09
Faro	17,696.70	–

Based on the volume calculation, the volume calculated from the UAV point cloud is closest to the reference volume (0.09%). In comparison, the volume calculated from the iPhone point cloud with viDoc RTK rover differentiates the most from the reference volume (1.40%). The calculated volumes with iPhone point clouds are within the interval 0.81–1.40% in relation to the reference volume. The volume deviations may be influenced by the interpolation method, i.e. the interpolation of “holes” in a point cloud and the way the software calculates the volume of this interpolated area.

5 Conclusion

In this paper, we compared and analysed the achieved accuracy of 16 CPs coordinates on the embankment dam using iPhone 14 Pro Max in combination with two different GNSS RTK rovers (viDoc RTK and Emlid Reach RX), UAV DJI Phantom 4 and Faro 3D Laser Scanner S150 Premium. Additionally, six point clouds from iPhone Pro (4), UAV (1) and TLS (1) measurements were compared and analysed to confirm their mutual overlap. Lastly, the volume calculation from different point clouds and the comparisons between each volume and the referent volume were made. The iPhone measurements, in combination with both rovers, achieve less accuracy than UAV and TLS measurements. The first reason is the difference in sensor quality, where the iPhone’s main purpose is commercial use, unlike the UAV and TLS. The second reason for the less accuracy achieved could be that the iPhone obtained coordinates from RTK while walking (less accurate coordinates), unlike UAV and TLS, which were georeferenced to GCPs (accurately determined coordinates). Another reason for the less accurate coordinates is that RTK relies on satellite signal quality, including the number of satellites, atmospheric conditions such as the ionosphere coefficient, and terrain conditions like obstacles, trees. When comparing the iPhone point clouds with each other, they demonstrate strong mutual consistency. Additionally, the iPhone point clouds when compared with UAV and TLS point clouds also show solid overlap, except in certain areas where there are gaps (“holes”) in the point cloud or where variations in vegetation, snow coverage, or concrete slabs occur. Upon comparing the reference volume derived from the Faro point cloud with other volume calculations, it is evident that the best match is with the UAV point cloud. In contrast, the volume obtained from the iPhone point cloud performs worse than the reference volume. This discrepancy may be attributed to the non-uniformity of the data in the point cloud, lower measurement precision, or insufficient coverage of points in the area where the volume was calculated. To conclude, the results indicate that when paired with the viDoc RTK and Emlid Reach RX rovers, the iPhone Pro can collect data with centimetre-level accuracy. The iPhone Pro can be utilized for various surveying projects, serving as a cost-effective alternative to more expensive sensors available on the market, thanks to its relatively acceptable measurement accuracy. Future research should focus on emerging low-cost solutions that offer better sensors and enhanced measurement options.

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