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Smartphone-based LiDAR for generating Digital Outcrop Models (DOMs) with field validation

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Abstract
Rock outcrops are crucial for geological studies, providing insights through direct observation and sampling. However, some outcrops are temporary, especially in tropical regions and dynamic environments like mining sites. Digital Outcrop Models (DOMs) address this challenge by offering 3D representations for remote analysis, typically generated via LiDAR and photogrammetry. However, these methods often require costly equipment and extensive processing. Recent advances in mobile technology, particularly the integration of LiDAR sensors in smartphones, present a cost-effective alternative for geoscientific data collection. Despite its potential, concerns remain about the accuracy of smartphone-derived LiDAR compared to traditional methods, particularly regarding scanning configurations and range settings. This study compared different acquisition parameters across scales and assessed iPhone-based LiDAR accuracy in a mining environment. Additionally, an optimized workflow for DOM acquisition was proposed. Among the free applications tested, *Scaniverse* yielded the best results in terms of measurement precision and user experience. The study found that accuracy depends significantly on acquisition range. The 0.3-meter range provided the highest accuracy but required longer acquisition times. The 2.5-meter range offered the best balance between accuracy and efficiency, making it ideal for fieldwork. The 5-meter range, however, did not provide substantial advantages. For detailed analyses, traditional post-processing software like CloudCompare is recommended. These findings highlight the potential of smartphone LiDAR for geoscience, emphasizing the need to optimize acquisition parameters and use efficient post-processing tools to enhance precision and field efficiency.

Keywords Mobile LiDAR, Fieldwork, Digital modeling, Virtual outcrops, Apple iPhone LiDAR

1 Introduction

Rock outcrops are defined as visible exposures of bedrock or other geologic formations at the surface of the Earth. These features are prominent in the landscape and are often studied through observation, measurements, structural analysis, and in situ sampling [1]. One of the major challenges is the ephemeral nature of certain outcrops, particularly those found in tropical biomes that are more susceptible to rapid weathering, or in projects with high local dynamics, such as active mining operations or construction sites. Therefore, the preservation, visualization, analysis, and interpretation of geological data can be optimized using relatively new techniques, such as Digital Outcrop Models (DOMs) or Virtual Outcrop Models (VOMs)—we are employing DOMs, as our research indicates a predominance of this term in the literature (Fig. 1).

A DOM is a three-dimensional, photorealistic, georeferenced model of an exposed geological surface that facilitates the remote description and interpretation of large and sometimes inaccessible outcrops [2], including those that may no longer exist. Currently, there are various widely adopted technologies that enable the generation of DOMs, particularly traditional Light Detection and Ranging (LiDAR) techniques (e.g., terrestrial and airborne laser-scanning) [3] and photogrammetry [4]. Photogrammetry usually relies on data acquired from visible light sensors, commonly mounted on remotely piloted aircrafts (RPAs) or drones (in the sense of [5]), using the Structure from Motion – Multi-View Stereo (SfM-MVS) processing technique [6, 7]. This method projects tie points recognized across a set of overlapping images taken from different viewpoints, thereby reconstructing their positions within a three-dimensional space [8]. The working principle of LiDAR equipment is to calculate the distance from the equipment to a target through the time of flight of a laser pulse having a specific wavelength. Some equipment also uses phase recognition to improve the measurement precision; however, the data volume increases considerably when using this approach [2, 3]. Both techniques often require expensive equipment and medium to high-weight devices, as well as considerable time for data acquisition and post-processing. Therefore, the portability of devices and sensors, along with faster and more sophisticated processing techniques, represents a significant scientific frontier.

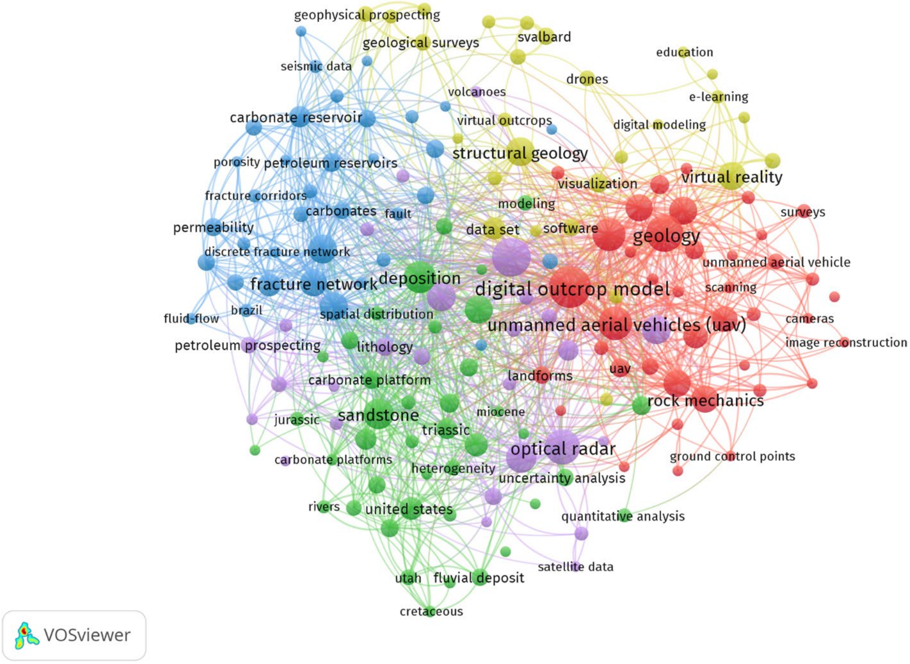

Fig. 1 Cloud of interconnected terms is derived from the titles and keywords of 282 papers that mention Digital Outcrop Models (DOMs) or Virtual Outcrop Models (VOMs) – Scopus database. This visualization was created using the VOSviewer Java application, with the size of the circles indicating the frequency of each term. Larger circles represent more frequently occurring words, highlighting the key concepts and themes present in the literature related to DOMs and VOMs

Currently, the widespread popularization of smartphones leads to significant advances each year in the portability and dissemination of mobile sensors. The year 2023 marked a significant turning point, as more than half of the global population started utilizing smartphones for their daily activities [9]. Numerous everyday tasks have become intrinsically dependent on mobile technology, driven by sophisticated and robust software and hardware on smartphones [10]. This technological advancement continually expands the possibilities not only for routine applications but also for various scientific fields. Since their inception and subsequent popularization, these technologies have been refined, tested, and applied across a wide range of studies [11–13]. In the field of geosciences, mobile technologies are relatively widely utilized, particularly in geoconservation and geotourism [14–17].

In recent years, the sensors integrated into smartphones for media acquisition (e.g., photos and videos in the visible light spectrum) have significantly improved spatial resolution to meet the growing demands of consumers [18]. In 2020, Apple Inc. (apple.com) has taken a major step forward in this advancement by incorporating LiDAR technology into its devices – iPhone 12 Pro and iPad Pro versions. These devices were the first mobiles equipped with a native LiDAR scanner, capable of capturing 3D scenes directly in the field. The Apple-LiDAR has undergone scientific testing that validates the quality of the sensor, which has indicated extensive potential applications in general areas of geosciences [19–21]. The pointed uses are particularly relevant for small to medium-scale 3D representations of the environment, especially in the context of monitoring changes over time [22, 23]. The validation of geological data acquired using smartphone-mounted LiDAR has been increasingly tested, particularly through structural data and their subsequent comparison with structural measurements obtained by compasses or by drones using Structure-from-Motion Multi-View Stereo techniques [24].

Despite the potential for qualitative data acquisition being tied to visual image response in geosciences, quantitative quality lacks more specific studies that compare different acquisition parameters and data processing with in situ measurements collected through traditional methods, such as the use of rulers and tapes, in a multi-scale. A paradigm shift is required to transform a technology originally developed for everyday applications into one that is scientifically validated and unequivocally accepted for the extraction of quantitative field data—particularly through an approach that emphasizes the practical aspects of data acquisition, such as acquisition range, acquisition time, and the size of files generated on mobile devices, as well as their relationships with spatial resolutions and data quality. Also, the constant and exponential evolution of devices, algorithms, applications, and software encourages the academic community to continually update case studies to test innovations, aiming to validate data for scientific applications and to provide solutions for industry and society.

The objective of this study is to compare different mobile applications for LiDAR data acquisition using smartphone-embedded technology, evaluating their performance in producing Digital Outcrop Models (DOMs) using the native in-app processing pipelines. The analysis focuses on variations in acquisition range, spatial resolution, and data collection time, with the aim of proposing an optimized workflow for DOM acquisition tailored to general geoscientific applications.

2 Methodology

2.1 Smartphone-based LiDAR scanner and data acquisition

The smartphone used for data acquisition is an iPhone 15 Pro Max with 1 TB of storage, featuring an A17 Pro chip and a camera system that includes (apple.com): (1) 48MP Main Camera: 24 mm focal length, *ƒ*/1.78 aperture, second-generation sensor-shift optical image stabilization, 100% Focus Pixels, and support for super high-resolution photos (24MP and 48MP); (2) 12MP Ultra-Wide Camera: 13 mm focal length, *ƒ*/2.2 aperture, 120° field of view, and 100% Focus Pixels; (3) 12MP 2x Telephoto Camera (enabled by quad-pixel sensor): 48 mm focal length, *ƒ*/1.78 aperture, second-generation sensor-shift optical image stabilization, and 100% Focus Pixels and; (4) LiDAR Scanner for improved depth perception and low-light performance – in the lower right corner of the sensors setting (Fig. 2).

The LiDAR Scanner operates based on time-of-flight (ToF) principles and consists of a photon source (emitter) and a receiver, namely VCSEL and SPAD [22]. In earlier models (iPhone Pro 12 to 14), the emitter featured 16 stacks of 4 vertical-cavity surface-emitting laser (VCSEL) cells, totaling 64, produced by WIN Semiconductors and Lumentum. These 64 laser pulses are enhanced by a 3 × 3 diffraction optical element (DOE), resulting in a total of 576 pulses [19]. The new VCSELs, manufactured by Sony, emit pulses that are reflected from object surfaces and detected by a single-photon avalanche diode (SPAD) image sensor, which measures the time of flight of the photons. The iPhone 15 Pro Max is equipped with the Sony IMX591 ToF-type SPAD sensor, offering an estimated resolution of 0.01 megapixels and a pixel pitch of 10.1 microns. An essential component in the device is the Apple sensor fusion software (SW). The 3D LiDAR depth sensing is enhanced by the fusion of the camera, LiDAR, and other sensors, including the accelerometer, gyroscope, and magnetometer, providing an improved depth map [25].

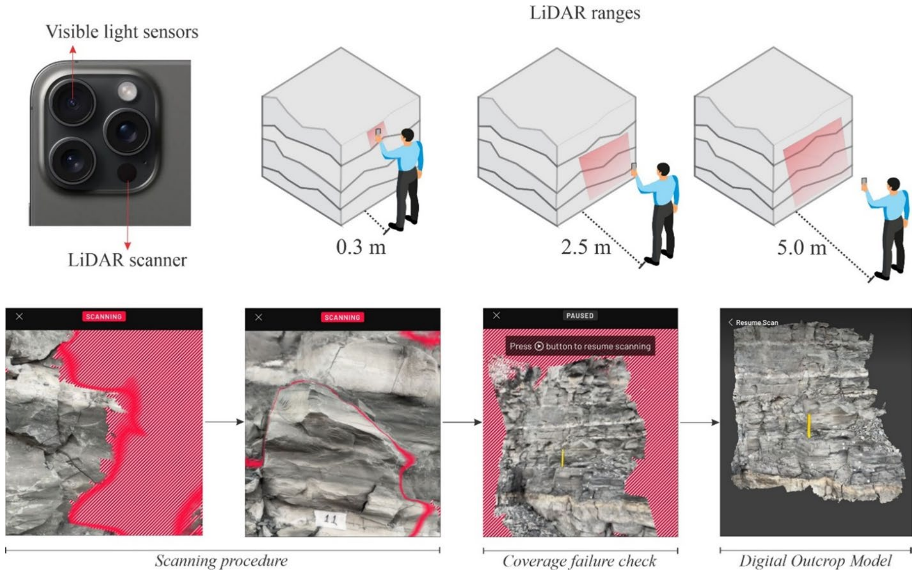

Fig. 2 LiDAR scanner sensor at iPhone 15 Pro Max; Different tested LiDAR acquisition ranges were set at 0.3 m (minimum allowed), 2.5 m, and 5.0 m (maximum allowed). This was followed by the acquisition workflow, which included a scanning procedure covering the entire outcrop (the dashed red line indicates locations where acquisition was successfully completed), the generation of the mesh, and preliminary processing within the *Scaniverse* app

The test was divided into two stages: the first involved testing on a Rubik's cube to preliminarily identify the Open Access application that would provide the best user experience and the most reliable data in a controlled environment, i.e., an indoor environment with uniformly incident led-white light on the object. The following applications were tested, in alphabetical order: DOT3D, KIRI Engine, LiDAR Scanner, Luma 3D, Modelar, *PolyCam*, *Scaniverse*, SiteScape, and 3D Scanner App. Scanning and processing were conducted in-apps, utilizing the most accurate acquisition and processing settings available on each platform.

The second stage consisted of a field survey in the mining setting, using the application that performed best in the initial tests – *Scaniverse* app. The parameters to be measured in the field were defined to allow the testing of different sensor-to-target distances and to assess the potential impacts on data quality with geoscientific significance. Since the LiDAR operates based on the time-of-flight (ToF) principle, the measurement accuracy is expected to vary with the distance between the sensor and its target) [26]. For this reason, we tested three different ranges: 0.3 m, 2.5 m, and 5 m from the outcrop. The 0.3 m distance represents the minimum allowed by the app settings, while 5 m is the maximum. Acquisition times were also measured using the native stopwatch feature of the iOS operating system, installed on a separate iPhone (iPhone 14 Pro) in the field. Data acquisition was performed following a predefined scanning pattern, moving the device in overlapping passes to ensure full coverage of the outcrop. The scans were carried out under natural light conditions, with the operator maintaining a constant distance from the surface. This acquisition scenario was chosen to minimize occlusions and to optimize both point density and accuracy of the reconstructed models. Acquisition times were recorded from the immediate start of the scanning process by the software to the immediate end. It is considered complete when the entire area of interest on the outcrop no longer shows any location with visible dashed red lines (Fig. 2).

2.2 Data processing

The data were pre-processed in the field using the processing algorithms provided by the *Scaniverse* app, evaluating their performance in producing Digital Outcrop Models (DOMs) with the native in-app pipeline. For this reason, the data collection was carried out directly through the LiDAR application, which simultaneously acquires the point cloud and the accompanying images within a single workflow. The measurements obtained were three-dimensional, with scaling and coordinate assignment handled internally by the application through the device's built-in sensors. Since the purpose was to test the reliability of the native acquisition pipeline, no additional external scaling, orientation correction, or distortion adjustment was applied beyond what is embedded in the app's default processing. The processing options can be defined as 'Speed,' a fast option for preview visualization; 'Areas,' which is recommended for rooms and general spaces; and 'Detail,' which the app suggests is best for textured objects. All field processing tests were conducted using the 'Detail' option to ensure that the data was correctly collected. The raw data (point cloud) were saved and exported – Any application often provides the export option with great versatility, in various formats, such as .fbx, .gbl, .las, .obj, .ply, .stl, and .usdz [23].

After being exported in .fbx, the data were loaded into the open-source software *CloudCompare* v2.13.1 (danielgm.net/cc/), a 3D point cloud (and triangular mesh) processing software, to extract measurements at the same locations where the real (ground truth) measurements had been taken.

2.3 Measurements validation

Real measurements (ground truth) were taken in the field using measuring tapes and rulers - simple, traditional measurement tools commonly employed in fieldwork were selected. These measurements were supplemented by detailed high-resolution photographs captured with the LiDAR device (iPhone 15 Pro) for potential comparison with measurements obtained after the digital processing of the data.

Both in the first stage (Rubik's cube modeling in a controlled environment) and in the second stage (Digital Outcrop Model in a mining environment), the digitally extracted data were statistically compared with the in-field measurements. The Mean Absolute Error (MAE) was calculated to quantify the average absolute difference between the measured values and the corresponding ground truth. It is computed by taking the absolute difference between each measured and actual value and averaging these differences across all data points (Eq. 1). A smaller MAE indicates higher accuracy, providing a clear measure of the typical error in the measurements.

$$\mathrm{MAE} = \frac{1}{n}\sum\nolimits_{i=1}^{n}\left|y_i - \widehat{y_i}\right| \tag{1}$$

Where y_i is the real value, $\widehat{y_i}$ is the digital measured value, and n is the number of data points.

The Root Mean Square Error (RMSE) was also calculated to assess the differences between the measured values and the corresponding ground truth (DOMs) (Eq. 2). RMSE provides an overall measure of the magnitude of errors, with lower values indicating better accuracy and predictive performance.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}\left(y_i - \widehat{y_i}\right)^2} \tag{2}$$

Where y_i is the real value, $\widehat{y_i}$ is the digital measured value, and n is the number of data points.

Both MAE and RMSE were calculated to provide a comprehensive evaluation of measurement accuracy. While MAE represents the average magnitude of errors and is robust to individual outliers, RMSE penalizes larger errors more strongly, highlighting extreme deviations that may occur in the data. Using both metrics together allows us to assess both the typical measurement error and the potential impact of occasional large discrepancies, offering a more complete understanding of the reliability of the LiDAR in-app processing.

All calculations and graphs were performed and generated using Python. Bar charts were created to compare the real Rubik's Cube data with measurements taken from the *Scaniverse* and *PolyCam* applications. A scatter plot was used to analyze the differences between the real data and the measurements obtained using the *CloudCompare* software across three different LiDAR acquisition ranges. Additionally, bar charts were produced to display the MAE and RMSE values for real data and across various ranges. A final graph was created to show the relationship between MAE and acquisition time for each range in minutes.

3 Results and discussion

3.1 App-based data acquisition comparison: 3D models and reality measurements deviation

A Rubik's Cube was selected as the test object due to its geometric regularity and fine-scale surface detail, providing a consistent reference for evaluating scan fidelity and usability. The object was scanned using the eight most popular LiDAR scanning applications available on the Apple Store, selected based on download volume as an indicator of widespread use. For each application, scans were conducted using the optimal acquisition resolution settings recommended by the developers, ensuring that comparisons reflected the best possible performance within each platform's intended operational parameters. All scans were processed directly within the respective applications to assess three key aspects: data acquisition capability, processing performance, and the intuitiveness and user-friendliness of the user interface (Fig. 3). This approach allowed for a comprehensive evaluation of the practical usability of smartphone-based LiDAR tools in real-world scenarios where field efficiency and ease of use are critical.

A preliminary visual assessment allowed for the immediate exclusion of several applications due to their inadequate performance in generating digital models with realistic geometry, satisfactory resolution, and an intuitive user interface. Among the eight tested platforms, *PolyCam* and *Scaniverse* emerged as the most effective, delivering superior results in both model fidelity and user experience. To evaluate the dimensional accuracy of the scans, reference measurements were obtained using a physical ruler and subsequently compared to measurements extracted within each application. At this stage, a limitation of the applications themselves should be noted: they do not allow extremely precise positioning (extreme zoom-in) to ensure perfect measurement accuracy. Accordingly, we applied the best practical methods available within the apps, simulating an in-app analysis and reflecting realistic usage conditions. For consistency, measurements were taken in two orthogonal directions on each visible face of the Rubik's Cube: one set aligned parallel to the central black dividing line, and another set perpendicular to it. These values, along with their comparative analysis, are presented in Fig. 4.

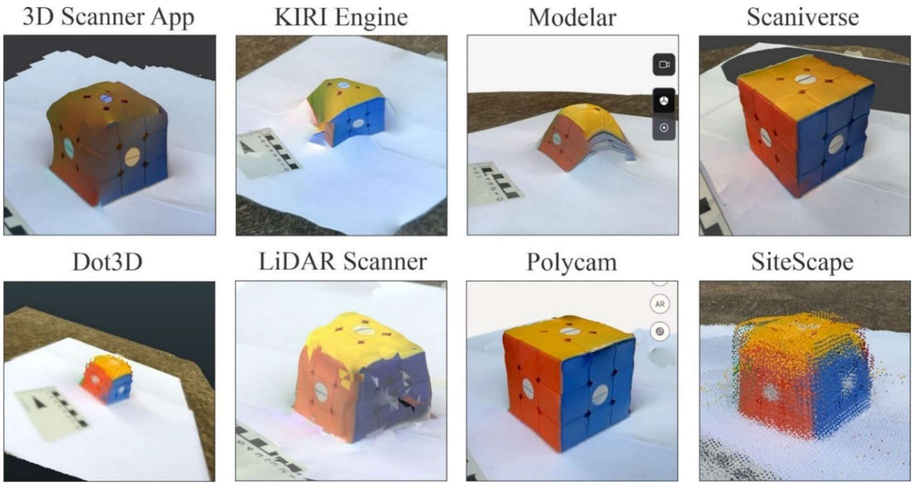

Fig. 3 Scans were performed with 8 different applications, following the same scanning configurations (standardized at the best acquisition resolution of each application) and processed in-app to compare data acquisition capabilities, processing, and the intuitive and user-friendly interface

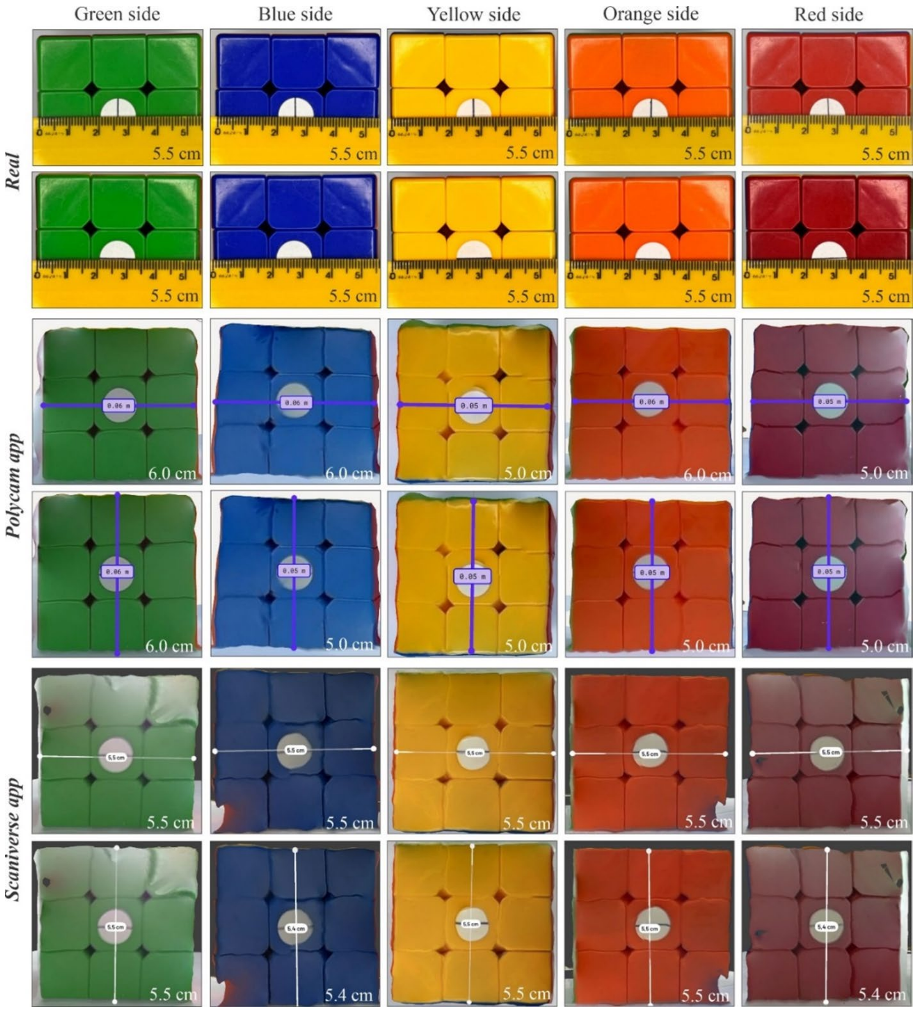

Fig. 4 Measurements with a ruler of the Rubik's cube. The upper measurements represent the direction perpendicular to the black line drawn in the center of the cube, while the lower measurements represent the dimension parallel to the black line. The white side was chosen as the base of support on the surface and is not shown in the image and calculations

The real measurements, consistently recorded at 5.5 cm, provide a stable reference value for comparison. In contrast, the measurements obtained with *PolyCam* exhibit a broader range, fluctuating between 5 cm and 6 cm, which suggests higher variability and potential inaccuracy in the generated model. On the other hand, *Scaniverse* demonstrated greater consistency, with measurements predominantly aligning closely to the real value of 5.5 cm, showing occasional minor deviations, such as 5.4 cm. These results indicate a higher degree of accuracy and usability in *Scaniverse* compared to *PolyCam*, as illustrated in Fig. 5. This could reflect either a more realistic modeling of the surface or in-app usability that provides a less satisfactory user experience, potentially causing errors in the actual measurements, as illustrated in Fig. 5.

The *PolyCam* application demonstrates a larger interquartile range and the presence of potential outliers, which suggests a relatively higher level of imprecision in its measurements. In contrast, *Scaniverse* provides a more consistent performance, with smaller fluctuations and fewer deviations from the real measurements. Although both applications exhibit some level of discrepancy from the real values, *Scaniverse* emerges as a

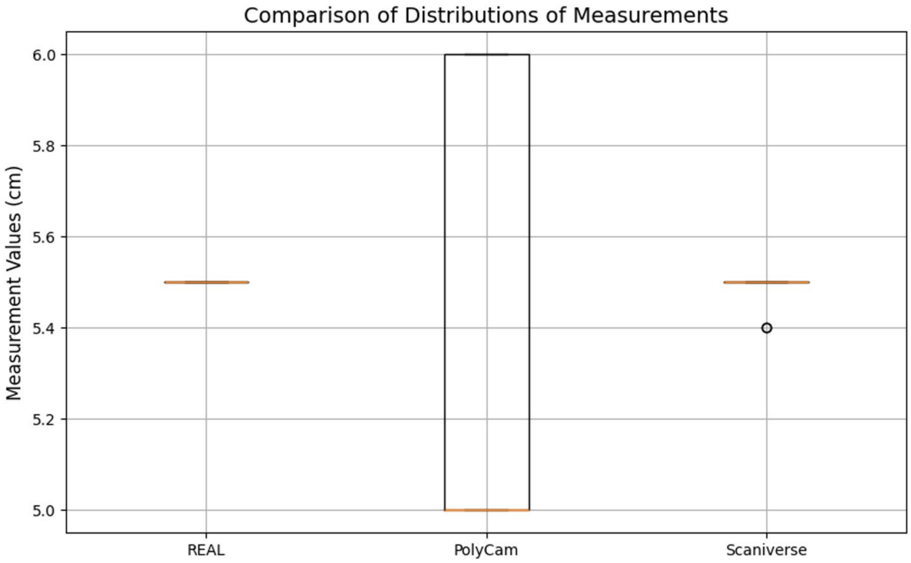

Fig. 5 Boxplot to compare the distributions of each set of measurements

more reliable alternative, with fewer discrepancies and greater overall consistency. This analysis is essential for assessing the accuracy and reliability of different measurement techniques for applications requiring high precision.

3.2 Validation of multi-scale measurements in Digital Outcrop Models (DOMs)

Although the iPhone LiDAR provides the possibility of a maximum operational range of 5 m, it is informally perceived that this value introduces many limitations and associated errors. Therefore, testing of different acquisition ranges has the central idea to assess the overall performance of the application and suggest possible uses and applications based on the tests and samples collected and compared. While some studies indicate the use of the iPhone LiDAR for educational and geological outreach purposes only, the most relevant study was conducted with the first generation of the device with the embedded LiDAR (iPhone 12 Pro) and primarily relied on the lack of satisfactory geolocation for their conclusions [19]. In this study, we opted for a test focused on the analysis of an outcrop, which was primarily based on the multi-scale analysis capability in relation to different target distances – a factor that directly influences the acquisition time and the size of the collected, analyzed, and stored data.

The tests were conducted at three range configurations, with 0.3 m and 5 m as the minimum and maximum ranges, respectively. As an intermediate criterion, a range of 2.5 m was defined. The total acquisition times for the data, that is, for the complete scanning of the area of interest in the outcrop, were 4:28 min (0.3 m range), 1:54 min (2.5 m range), and 1:32 min (5 m range). Additionally, the storage sizes of the scans (raw data immediately after acquisition) were 462 MB, 280 MB, and 241.4 MB, respectively.

In the field, 9 measurement points were defined to cover different features that are generally important in an outcrop, such as the thickness of depositional layers, fracture spacing, fracture size, and the size of inclusions (in this case, flint portions within the layer), composing geological features at decimeter, centimeter, and millimeter scales. Subsequently, all measurements were also extracted from the digital models of the outcrop (see supplementary material).

After scanning, the point cloud was exported and loaded into *CloudCompare*, where all measurements were performed at the three different DOMs-ranges (Fig. 6). The three generated DOMs provided a very satisfactory coverage of the region of interest (central part, where the measurements were taken), indicating that, for general educational and outreach purposes, they are sufficient. For decimeter and centimeter measurements, it is also possible to perform in-app measurements and identify geological features at all three ranges when using the *Scaniverse* app. However, as shown in the example in Fig. 6, only at the 0.3 m range is it possible to perform measurements and identify millimeter-scale features in *Scaniverse*. At the other two ranges, the app's interface does not allow enough zoom-in. When loaded into *CloudCompare*, the processed DOMs allowed for a

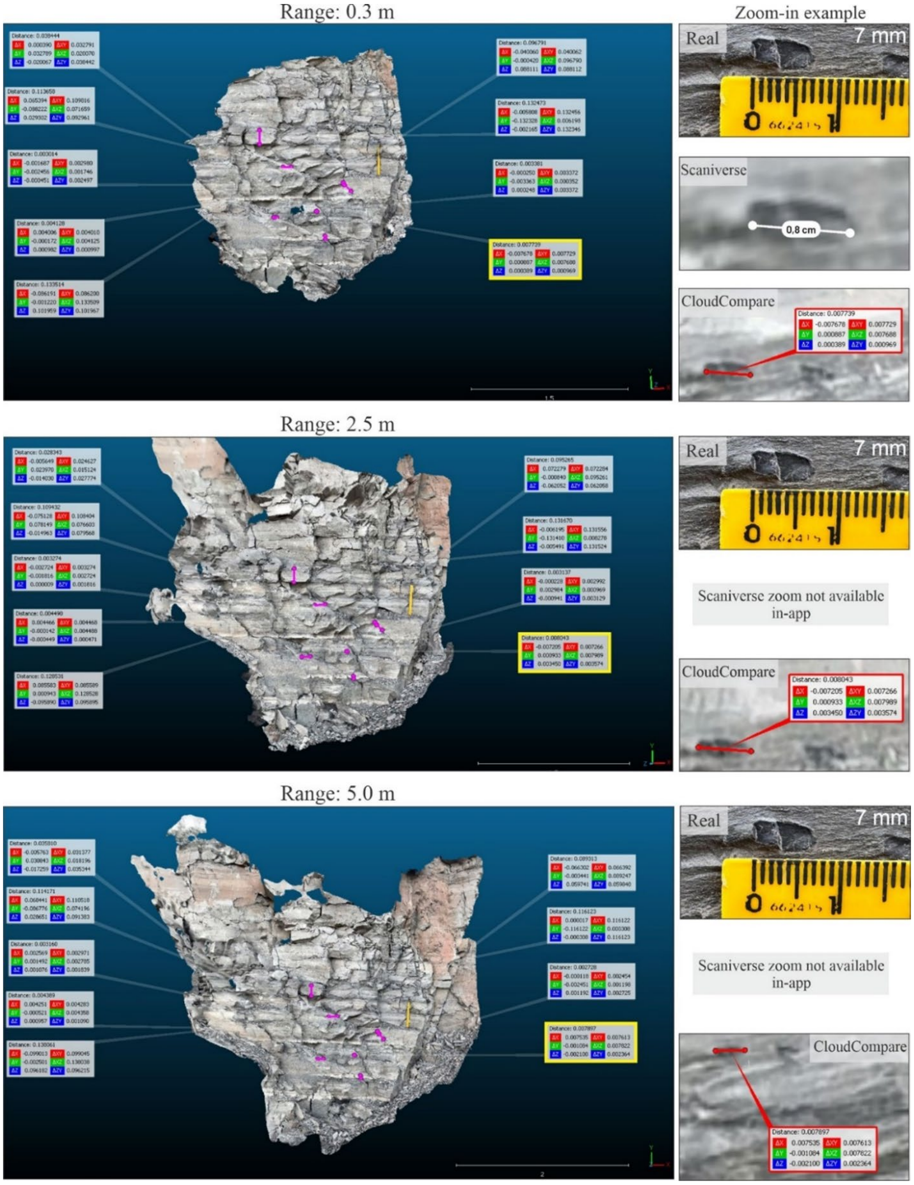

Fig. 6 Digital Outcrop Models (DOMs) generated for each acquisition at different LiDAR ranges: 0.3, 2.5, and 5 m. Measurements are shown, taken using *CloudCompare* software for each geological feature. A zoom-in is provided as an example of a feature at the millimeter scale, including the real photo with the measurement on the ruler, the measurement in the Scaniver app when possible, to be performed in-app, and the measurement and zoom-in performed in the software

complete analysis of all features, enabling sufficient zoom-in and zoom-out to analyze all target features.

The measurements from each DOM were compared with the ground truth measurements, alongside the calculation of MAE and RMSE. The scatter plots (Fig. 7) show that the 0.3 m range DOM exhibits the highest accuracy and consistency with the real data. The measurements are tightly clustered around the real values, with no significant discrepancies or outliers. The 2.5 m range DOM also shows satisfactory results, with the points tightly grouped around the real data, although some points exhibit slight deviations, indicating minor inaccuracies. On the other hand, the 5 m range DOM generally shows a good correlation with real data, but there is one measurement with a significant discrepancy, which substantially impacts the overall data quality. As the range increases, a noticeable measurement discrepancy is observed, with larger discrepancies associated with decimal and centimeter-level measurements, and smaller observed with millimeter-level measurements.

Thus, it is evident that as the range increases, the associated MAE and RMSE errors also increase, likely due to a noticeable degradation in resolution (pixel-based) observed in the DOMs (Fig. 7). Minor discrepancies between MAE and RMSE can also reflect the presence of residual noise in the measurements. Therefore, for studies requiring multiscale detail, smaller smartphone-LiDAR ranges generally provide better accuracy of the data, probably because of the in-app processing algorithms.

3.3 Workflow proposal for doms data acquisition and processing

Protocols for using smartphone-based LiDAR have already been established for measuring and detecting changes in the Earth's surface, for example, in topographic applications [23]. These protocols aim to offer a low-cost, easy-to-use consumer-grade device and software, addressing the main steps that non-expert users can perform while still achieving high-quality results. However, the rapid and exponential advancements in the mobile market, apps, and software require constant attention and testing by the academic community to validate new releases and update workflows.

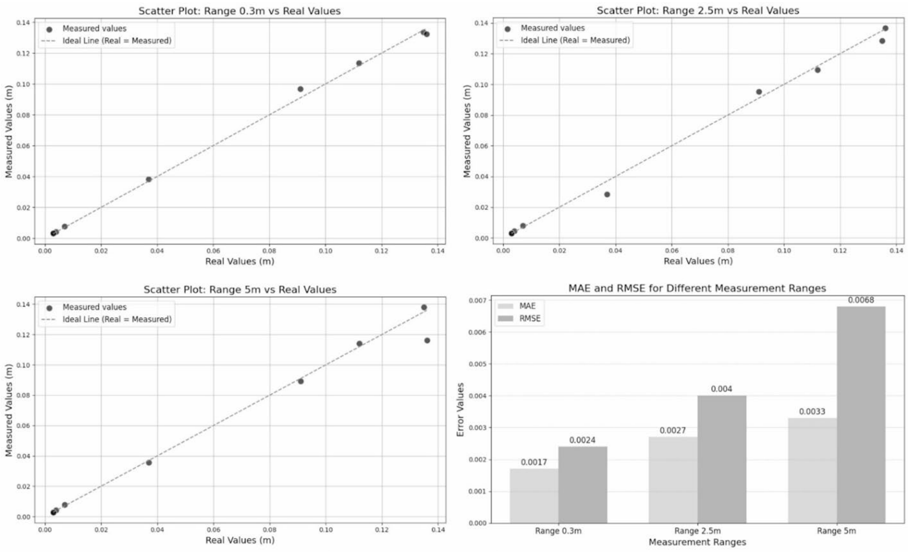

Fig. 7 Scatter plots comparing each measurement extracted from the DOMs at each range with the real measurements, along with bar graphs of the MAE and RMSE for each range

In geosciences, fieldwork often requires various types of investments, and therefore, should always be planned to ensure efficiency. To contribute to the efficiency of DOM surveys for various uses in geosciences, comparison graphs between MAE error and (a) file size and (b) acquisition time were created (Fig. 8). When assessing the efficiency of data acquisition from the perspective of storage demand, the 0.3 m DOM range generates files that are 65% larger than those produced at 2.5 m, and 91% larger than those at 5 m. While it does provide slightly lower mean absolute error (MAE) and root mean square error (RMSE) values, the improvement in model accuracy does not scale proportionally with the increased data size. This trade-off becomes especially relevant in field scenarios where storage, processing, and data transfer capabilities are limited. From a temporal standpoint, the 0.3 m configuration also exhibits reduced operational efficiency: it requires 135.09% more time than the 2.5 m range to complete a scan of the same outcrop area. While it delivers more accurate results, both the MAE and RMSE remain very low across all ranges, making the marginal accuracy gains less significant in practical terms.

Furthermore, when comparing MAE normalized by file size (MAE per MB), the 0.3 m range is approximately 2.4 times more efficient than the 2.5 m range and over 4.5 times more efficient than the 5 m configuration. However, despite this superior accuracy-to-size ratio, the absolute volume of data remains a limiting factor, particularly when multiple models need to be acquired in sequence. In this context, while the 0.3 m range offers the highest data fidelity, its practical efficiency is reduced due to longer acquisition times and greater storage consumption. The 2.5 m configuration, on the other hand, presents a more balanced trade-off between spatial resolution, file size, and acquisition duration—emerging as a more operationally viable option for repeated DOM generation in typical geoscientific field conditions.

Therefore, the proposed smartphone-based LiDAR DOM (Digital Outcrop Model) data acquisition workflow is structured around two main usage scenarios that reflect the practical and scientific demands commonly encountered in geoscientific applications. The first is geared toward rapid field deployment, in which the focus is on quickly capturing 3D representations of outcrops and surrounding environments for purposes of visual documentation, preliminary analysis, and preservation of field conditions. In this case, broader range settings (such as 2.5 m) are recommended to reduce acquisition time and file size, ensuring greater efficiency and mobility in the field. This approach is particularly suitable for reconnaissance activities, educational use, or situations requiring multiple or fast scans under time or equipment constraints.

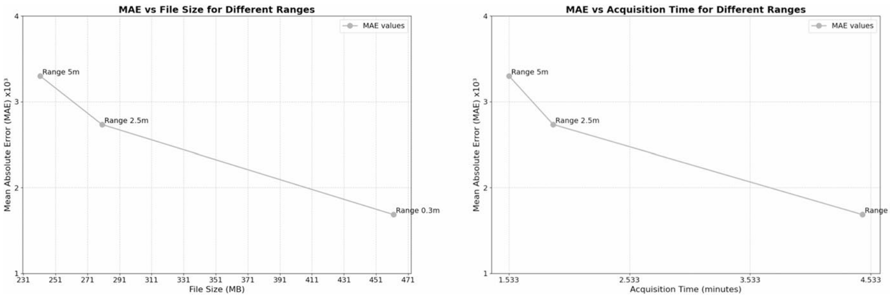

Fig. 8 Graph representing the MAE versus the File Size (MB) and data acquisition time (scanning) for the three different ranges

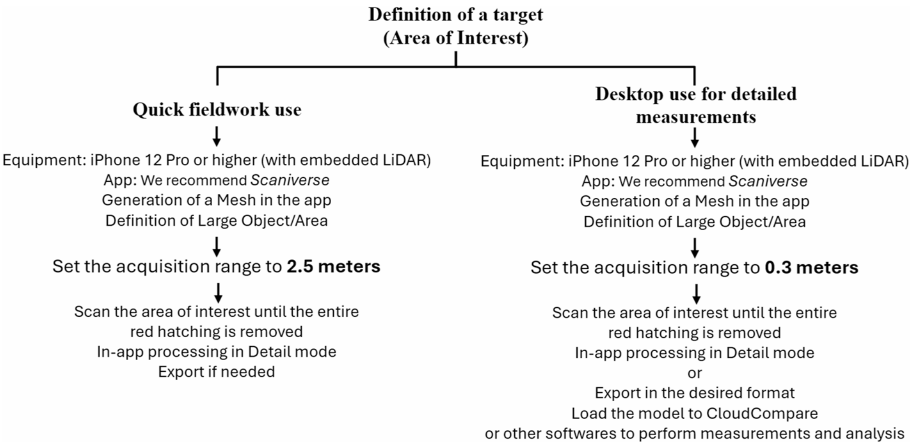

Fig. 9 Proposed workflow for the two possible DOMs proposed applications, including equipment, applications, and software, as well as instructions for acquisition settings and in-app processing

The second scenario is intended for desktop-based processing, where the objective is to perform high-resolution quantitative analyses. For this purpose, more restrictive acquisition settings (e.g., 0.3 m range) are suggested, as they yield lower error margins and higher spatial fidelity, albeit at the cost of increased acquisition time and storage demands. This configuration is better suited for detailed post-processing tasks such as structural measurements, volumetric modeling, or the generation of digital stratigraphic sections. In both scenarios, the use of free-access mobile applications and desktop software is recommended to ensure accessibility and reproducibility, particularly in academic and resource-limited contexts. The choice of acquisition parameters should be informed by the error metrics and efficiency analyses, allowing users to balance data quality with operational constraints according to their specific research needs (Fig. 9).

For rapid field-based applications, in-app processing is recommended, as it offers users an exceptionally intuitive interface with the capability to perform basic measurements directly within the application environment. This functionality greatly enhances the practicality of smartphone-based LiDAR acquisition by enabling immediate visualization and evaluation of the scanned data. One limitation, however, is that for studies requiring millimeter-scale precision, the in-app tools may be insufficient—particularly when using the 2.5 m range setting, which does not support high-detail zoom capabilities. This restricts the effective resolution to features on the order of centimeters, which, in most geoscientific applications, remains acceptable and functionally adequate. Furthermore, in-app processing enables real-time quality control and preliminary interpretation, allowing users to verify data integrity and coverage on-site, thereby reducing the risk of incomplete or unusable datasets and minimizing the need for repeated surveys.

For more detailed applications, although in-app measurements can technically be performed at the millimeter scale, the tools available within mobile applications lack the versatility and precision required for advanced analysis, particularly in terms of measurement flexibility and interaction with the digital ruler. As such, for high-resolution quantitative assessments, it is recommended that measures be conducted using *CloudCompare* or equivalent open-source desktop software. These platforms offer a wider range of functionalities, including precise distance and volume calculations, cross-sectional analysis, and the ability to work with point cloud data at various scales. This allows for a more rigorous and reproducible analysis of the digital models, making them particularly suitable for scientific studies that demand accuracy and control over the analytical process.

4 Conclusions and perspectives

Embedded LiDAR in smartphones presents a proven potential for use in geosciences, but testing different parameters, in-app processing methods, and data interpretations still offers numerous possibilities for study. Prioritizing the use of open-access applications and software ensures that non-expert users have access to new technologies and can use the tools, which is highly beneficial as it disseminates methodological applications and generates extremely valuable data for various applications in geosciences.

Among the free applications currently available, *Scaniverse* has shown the best results in detail measurements and user interface, with extremely accurate measurements in relation to real-world measurements in controlled environments. In uncontrolled environments, such as a mining setting, the application proved to be quite efficient in in-app acquisitions and processing, resulting in measurements with good accuracy. However, for more detailed studies, measurements should be taken using software (we recommend *CloudCompare* due to its open access and high efficiency).

The LiDAR sensor's acquisition ranges directly influence the quality of the measurements, with smaller ranges providing more accurate (and closer to real measurements) digital readings. The 0.3-meter range is the most accurate, despite the longer data acquisition time. However, the efficiency of the models was also tested by comparing acquisition time with the accuracy of the measured data. In this regard, the 2.5-meter range is also quite suitable for performing measurements and analyses in software. The 5-meter range, however, did not present any significant advantages, either in acquisition time or associated errors.

This study has some limitations. First, the acquisition and processing pipelines rely on in-app algorithms that are not modifiable, limiting control over noise filtering and data adjustments. Second, the test objects and controlled environments used, while suitable for evaluating the in-app workflow, do not fully represent complex natural surfaces. Third, the study focused on efficiency and usability in addition to accuracy, but results may vary with user experience, device type, and environmental conditions. Finally, the selected measurement ranges (0.3 m, 2.5 m, and 5 m) may not capture all scenarios, and further testing is needed for different scales and irregular surfaces.

This study opens perspectives for testing in different environments, especially with applications that can bring direct benefits to industry and society. Systematic and continuous testing of new devices or updates to existing ones is essential to ensure that measurements maintain scientific validity. Following this study, it is increasingly important to understand the algorithms used by applications available in app stores. It should be noted that the applications addressed are likely in constant development, with frequent updates to their acquisition and processing algorithms. Furthermore, the development of protocols and workflow guidelines should be continuously updated and adapted to different case studies.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions
Furlan, L. M.: Writing – Review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Piazentim, E. G.: Writing – Review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Data availability
Data available on request from the authors. All codes were written by Lucas Moreira Furlan in Python. All codes have been openly sourced and are available on GitHub: https://github.com/LucasMFurlan/LiDAR-Iphone-CAGEO. All the apps and software used are open-source.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
This study is original and does not involve the use of personal information, images, or unpublished materials from individuals.

Competing interests
The authors declare no competing interests.

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