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Efficiency Of Lidar Technologies in Constructing Digital Terrain Models During Large-Scale Topogeodetic Surveys

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Abstract: In this study a comprehensive analysis of the efficiency of implementing LiDAR technology (Light Detection and Ranging) in the formation of high-precision digital terrain models (DTMs) in the course of large-scale topogeodetic surveys is carried out. The aim of the research is to evaluate LiDAR accuracy indicators, economic feasibility and operational performance relative to classical photogrammetry, taking into account the use of unmanned aerial vehicles (UAVs). The methodological basis of the research includes a review of publications, synthesis of data from these works and statistical data analysis. The results obtained indicate that LiDAR provides an advantage in digitizing terrain under dense vegetation cover. An algorithm for selecting the optimal method is proposed, based on multi-criteria analysis which includes vegetation density, accuracy requirements and project budget constraints. The key findings of the study emphasize the superiority of LiDAR in complex natural-landscape conditions and the economic viability of photogrammetry in areas with open terrain, which justifies the feasibility of a hybrid approach to optimize costs and improve the quality of the output DTMs. The study will be useful for surveying engineers, GIS specialists, managers of construction and infrastructure projects, as well as researchers in the field of Earth remote sensing.

Keywords: *LiDAR, digital terrain model (DTM), UAV, photogrammetry, topogeodetic surveys, accuracy, efficiency, point cloud, laser scanning, GNSS.*

1. Introduction

Current challenges in the creation and development of transportation, engineering, and urban infrastructure, as well as in the mining sector and environmental monitoring, impose unprecedentedly stringent requirements on the timeliness and accuracy of obtaining geospatial data. Digital terrain models serve as a cornerstone in the design, construction, and inspection of facilities, largely determining the success of large-scale engineering initiatives. According to the analytical report by MarketsandMarkets, the volume of the global market for geospatial data acquisition services in 2024 reached 502.6 billion dollars with a compound annual growth rate of 13.2%, which testifies to the growing demand for high-precision and up-to-date cartographic solutions [1].

In this context, Earth remote sensing technologies — in particular, airborne laser scanning (LiDAR) and photogrammetry using unmanned aerial systems — are becoming leading tools in the execution of topographic and geodetic surveys. However, the choice between them remains a complex task: to date, no comprehensive methodology for comparative evaluation has been developed that takes into account not only accuracy characteristics but also economic and operational aspects. Scientific publications generally limit themselves to narrowly focused comparisons under specific conditions, without proposing a universal approach to selecting the optimal technology.

The objective of the study is to conduct a broad comparative analysis of the efficiency of applying LiDAR and photogrammetry for the generation of digital terrain models within the framework of large-scale topographic and geodetic projects, to identify their key advantages and limitations, and to formulate criteria for the rational selection of the method, taking into account the specific conditions of the task.

The scientific novelty of the work lies in the proposal of a systematic approach to the selection of a remote sensing technology based on multi-criteria analysis, in which technical accuracy parameters are complemented by economic and operational factors.

The author's hypothesis is that neither LiDAR nor photogrammetry in isolation can serve as a universal solution: maximum efficiency and economic feasibility are achieved through hybrid strategies or adaptive method selection based on formalized criteria — vegetation cover density, required levels of detail and accuracy, as well as the project's budgetary and temporal constraints.

2. Materials and methods

A literature review shows that research on the effective application of LiDAR-technologies in generating digital terrain models can be conventionally divided into several thematic areas.

On one hand, corporate analytical reports MarketsandMarkets [1] and Grand View Research [9] forecast rapid growth of the global LiDAR-technology market in the segment of engineering-geodetic and topogeodetic works, indicating a compound annual growth rate (CAGR) and the expected market volume.

An important group comprises comparative experimental studies in which UAV-LiDAR is compared with digital aerial photography (DAP). Pinton D. et al. [2] in a study of coastal salt marshes concluded that LiDAR data provide accuracy in ground elevation determination, outperforming photogrammetry under dense shrub-grass cover. Zhou L. et al. [3] compared measurements of tree canopy height in an urban environment and showed a high correlation between UAV-LiDAR and ground-based measurements, whereas DAP approaches sharply lose accuracy when the proportion of non-ground cover exceeds a threshold. In a eucalyptus forest stand, Winsen M., Hamilton G. [12] compared dense point clouds obtained by LiDAR and NIR-photogrammetry and found that LiDAR preserves the vertical structure of crowns, yielding more reliable estimates of forest parameters under a dense canopy.

A number of studies are devoted to comparative analysis of software tools for constructing 3D models. Jarahizadeh S., Salehi B. [4] tested AgiSoft PhotoScan, PIX4DMapper and DJI Terra on forest 3D-modeling tasks, noting significant differences in processing speed and memory requirements, as well as deviations in DTM depending on the software. Sterpin A., Medici M. [7] within the framework of the low-budget project DIACHRONIC LANDSCAPES demonstrated that combining inexpensive UAV-photogrammetric platforms with GNSS receivers allows obtaining DTMs with minimal errors under optimal flight parameters.

Applied use cases of LiDAR cover a wide range of tasks. Silva-Fragoso A. et al. [5] used a LiDAR drone for morphostructural analysis of an active caldera on the island of Ischia (Italy), where the increased accuracy of the DTM made it possible to identify subsurface deformations and monitor the dynamics of slope tilts. Sestras P. et al. [6] integrated UAV-DAP and LiDAR for optimal urban planning, noting that the hybrid approach significantly reduces the volume of engineering earthworks and minimizes the cost of preliminary topographic surveys. Kanostrevac D. et al. [13] conducted an empirical comparison of two terrain models — one constructed based on photogrammetric data, the other on laser scanning. The authors note that although the elevation differences along profiles are generally small and the change in slope at the shoreline is captured by both technologies, the LiDAR model provides a clear fixation of the water boundary due to the preliminary fixation of the water level during processing in Microstation, which is absent in the photogrammetric model. The superiority of LiDAR is also emphasized in forested areas owing to the ability of the laser beam to penetrate through the canopy and obtain more ground points, making it especially promising in archaeological investigations within forest massifs.

An important direction is algorithmic processing of point clouds. Shi S. et al. [8] developed a method of multispectral classification of land cover based on LiDAR with multiscale selection of spatial-spectral features. Galanakis D. et al. [10] applied SVD decomposition for rock-by-rock segmentation of point clouds in cultural heritage tasks. Li B. et al. [11] proposed the deep neural network Terrain-Net for ground filtering in forest conditions without parameter tuning, reducing the share of false classifications compared to classical algorithms.

Thus, the literature has formed clearly defined approaches: market analytics indicate the strategic significance of LiDAR in topogeodesy; comparative experiments emphasize the superiority of LiDAR in complex natural and urbanized environments; the choice of software and processing algorithms significantly affects DTM quality; and applied studies demonstrate the effectiveness of hybrid methods in engineering tasks.

Despite the considerable volume of work, the literature shows contradictions — Pinton D. et al. [2] and Silva-Fragoso A. et al. [5] report LiDAR errors at the level of several centimeters, whereas Sterpin A., Medici M. [7] and Shi S. et al. [8] record errors of up to tens of centimeters under similar conditions. In addition, the scaling of UAV-LiDAR surveys to the regional level, the integration of LiDAR with multispectral data for DTMs over large areas, as well as systematic investigation of the influence of flight parameters (altitude, overlap) and point density on the final accuracy and efficiency of processing large point clouds are insufficiently addressed.

3. Results and Discussion

The conducted analysis allowed for the identification and structuring of key performance indicators of LiDAR and photogrammetry in large-scale topographic mapping tasks. The comparison was performed based on three criteria: the metrological accuracy of the digital terrain model, the productivity of acquisition and processing, and the economic feasibility of application.

In assessing the metrological accuracy of the digital terrain model (DTM) the decisive factor is the principle of elevation data acquisition. LiDAR as an active remote sensing method registers the time delays of laser pulse returns, which ensures direct measurement to the reflecting surface, including cases of penetration through the vegetation canopy and capture of the true ground contour. In contrast photogrammetry is based on the passive analysis of cross-similarity of optical images, and therefore in the presence of dense vegetation cover or artificial obstacles it reproduces the geometry of above-surface objects rather than the terrain itself [6, 7].

The results generalized from the materials of studies [2, 3, 4, 12] indicate that in open areas both methodologies provide an accuracy level corresponding to the requirements of topographic surveying at a scale of 1:500. However, with increasing vegetation density photogrammetric models demonstrate a significant decrease in accuracy, whereas LiDAR maintains stable metrological characteristics.

Operational productivity and workflows. Survey productivity is determined not only by the flight speed of the UAV but by the entire work cycle from planning to obtaining the finished DTM. The workflows for LiDAR and photogrammetry exhibit substantial differences (Figure 1).

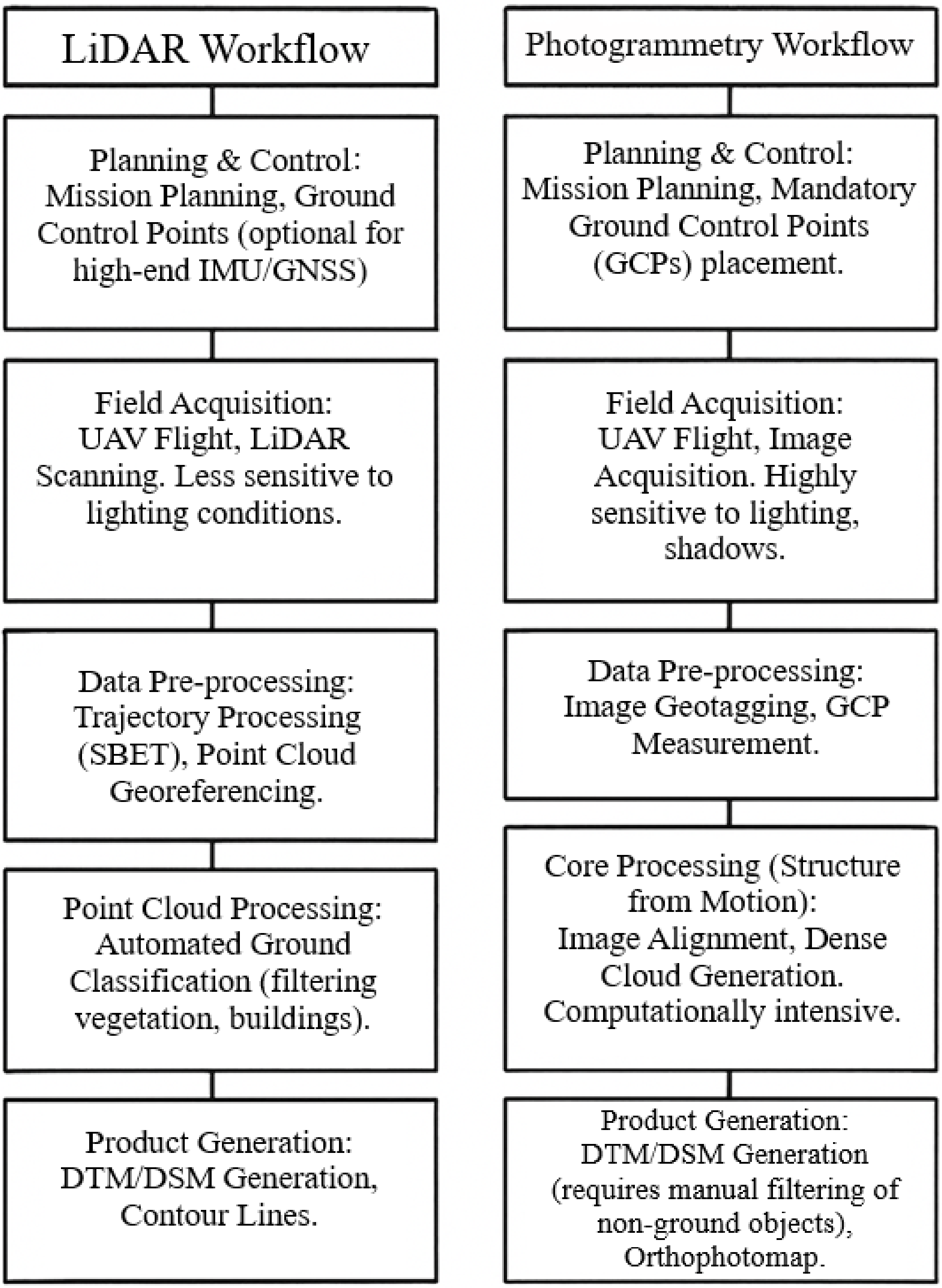

Figure 1. Generalized workflow diagram for LiDAR and photogrammetric surveying [2, 3, 4, 12]

As demonstrated by the presented scheme, photogrammetric surveying is inevitably associated with the establishment and precise measurement of a large number of ground control points (GCP) to ensure the required accuracy, which significantly prolongs the duration of field works. In contrast, LiDAR equipment, integrated with high-precision inertial (IMU) and GNSS modules, is capable of performing direct georeferencing, thereby minimizing or completely eliminating the need for GCP [10, 12]. Moreover, the stage of structure from motion (Structure from Motion) in photogrammetry imposes much higher demands on computational resources compared to processing the navigation track and direct georeferencing of the LiDAR point cloud. At the same time, a key operational advantage of LiDAR remains the automatic classification of surface points: modern algorithms, based on the analysis of three-dimensional geometry and multiple reflections, provide the automation of the separation of ground, vegetation, and architectural points, whereas in photogrammetry such work often requires substantial manual corrections [2, 9].

The economic component and criteria for technology selection represent another crucial aspect. Initial capital investments in professional LiDAR systems exceed the cost of photogrammetric complexes based on unmanned aerial vehicles by approximately three to five times. However, over extensive areas with complex vegetation cover, the savings in time and resources on field and office works, achieved thanks to LiDAR, can offset and even surpass the difference in equipment cost. At the same time, for small-scale and open objects, where there is no task of detailed undergrowth penetration, photogrammetry remains a more economical solution [5, 8].

Based on the conducted comparative analysis, an authorial decision-making scheme (Figure 2) is presented, which can serve as a practical tool for selecting the most appropriate technology for solving specific tasks.

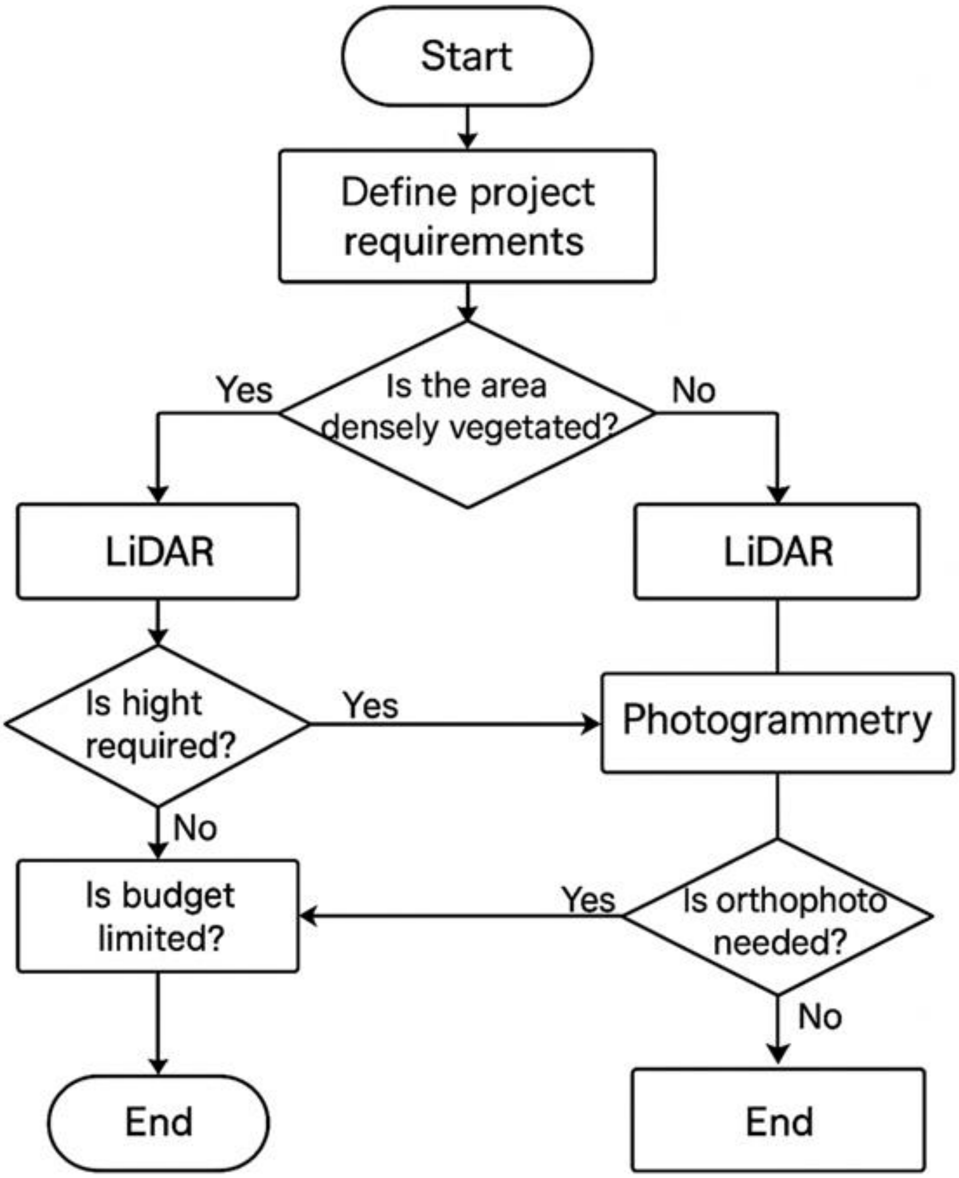

Figure 2. Algorithm for selecting technology for creating a DEM [2, 5, 8, 9]

The proposed methodology systematizes the selection process, moving it from the realm of subjective preferences into the domain of substantiated engineering decisions. At each stage it sequentially evaluates the key project parameters — the extent of vegetation cover, accuracy requirements, and budget constraints. In cases where the survey area includes both open sections and zones of dense vegetation, the methodology justifies the application of a combined approach: LiDAR technology for generating the basic three-dimensional terrain model and photogrammetric surveys for obtaining a highly detailed orthophotomap and texturing of open areas. Such synergy enables balancing the maximum quality of output data with effective cost optimization.

The following Table 1 describes the advantages, limitations and future trends of using Lidar technologies in the construction of digital terrain models during large-scale topographic and geodetic surveys.

Table 1: Advantages, limitations and future trends of using Lidar technologies in building digital terrain models during large-scale topographic and geodetic surveys.

Dimension	Advantages	Limitations / Challenges	Future Trends
1. Data Acquisition (multi-platform)	Rapid, high-density coverage over large and difficult terrain; flexible deployment (airborne, UAV, terrestrial) enables efficient surveying.	Platform constraints (UAV endurance, cost of manned systems), and shadowing in complex topography/vegetation.	Hybrid multi-platform strategies, coordinated UAV swarms, and continued sensor miniaturization to extend reach and efficiency.
2. Accuracy & Resolution	Centimeter to sub-decimeter detail captures micro-topography critical for geodetic models; high spatial fidelity.	Systematic biases (GPS/IMU drift, strip misalignment, incidence-angle effects) and terrain-induced distortions.	Tight integration of RTK/PPP corrections, AI-driven error correction, and adaptive filtering to preserve features while reducing noise.
3. Vegetation Penetration & Ground Separation	Multiple returns allow partial canopy penetration and extraction of underlying ground where other optical methods fail.	Dense or heterogeneous vegetation can obscure ground returns; misclassification in filtering leads to DTM artifacts.	Deep learning/semantic segmentation for more robust ground/non-ground separation in complex cover; context-aware classification.
4. Data Fusion & Processing Scalability	Combining LiDAR with imagery or spectral data enriches DTMs with semantic context; automated pipelines speed initial model generation.	Large data volumes strain storage and compute; heterogeneous sources complicate co-registration and consistency.	Cloud-native distributed processing, self-supervised multi-modal fusion, and embedded real-time quality assessment to scale large-area workflows.
5. Real-time Feedback & Operational Adaptivity	Early DTM previews enable adaptive survey adjustments, improving efficiency and data quality mid-campaign.	Onboard compute and bandwidth limits constrain true real-time refinement over extensive areas.	Edge AI for incremental terrain modeling, autonomous mission replanning based on live quality metrics, and integration with digital twins for decision support.

The following are recommendations for the application of LiDAR technologies in the construction of digital terrain models in large-scale topogeodetic surveys.

The selection of a LiDAR system should be based on the survey scale, required accuracy, and terrain characteristics. For large-scale topogeodetic works, dense scanners with high pulse repetition frequency and multi-beam scanning capability are preferable, which ensure sufficient point overlap and penetration through vegetation. The laser range, rangefinder accuracy, and geometric resolving power should be taken into account: under conditions of complex terrain and dense vegetation, a point density of at least several tens of points per square meter is required to obtain a reliable digital terrain model (DTM).

Flight planning or mobile data acquisition requires careful development of the survey scheme. It is necessary to ensure longitudinal and transverse overlap of scan strips to avoid gaps and striping in the data. In areas with sharp relief changes, a reduction in acquisition altitude is required to preserve vertical resolution. When using airborne platforms, attitude correction and correct time synchronization between GNSS, the inertial navigation system (IMU), and the LiDAR sensor must be considered [3, 10].

The organization of a ground control network and calibration points is of critical importance for georeferencing. The placement of control points with high-precision GNSS/RTK ties should ensure uniform coverage of the survey area, especially at boundaries and in zones with systematic distortions. Performing precise measurements of base points with consideration of local surface deformations and verifying the accuracy of LiDAR data tying to the ground coordinate system allows reduction of systematic errors. Regular execution of boresight calibration checks between LiDAR and IMU makes it possible to account for offsets and angular shifts in data acquisition.

Processing of raw data should be carried out in stages: initial noise filtering, strip adjustment, point classification, and creation of the initial point cloud model. The application of outlier removal algorithms and adaptive filters makes it possible to eliminate artifacts from reflections off atmospheric particles, birds, or operational noise. Classification should distinguish ground, vegetation, artificial structures, and water bodies; under complex conditions it is recommended to combine methods based on local surface fitting, shadow-illumination, and elevation analysis for robust delineation of the ground surface.

Solving the problem of reconstructing the surface beneath vegetation requires the use of multi-return LiDAR systems and algorithms capable of extracting lower returns. Processing signals with multiple returns allows distinguishing gaps through the tree canopy, isolating the underlying surface, and estimating vegetation height. It is recommended to apply techniques of incremental smoothing of surface models while preserving sharp terrain contours: first a preliminary coarse ground model is constructed, then iterative refinement is performed with geometric constraints minimizing the influence of vegetation and small objects [13].

Accurate generation of the digital terrain model requires adherence to approaches for interpolation and aggregation. The choice of interpolation method (TIN, IDW, kriging, or adaptive grids) must correspond to point density and distribution, as well as the topographic complexity of the area. In sections with uneven data distribution, it is preferable to combine local methods (for example, adaptive TIN) with global regularizations to eliminate excessive oscillations. During generation, terrain gradients should be taken into account and critical elements (rills, gullies, slopes) preserved without smoothing, processing areas with sharp changes separately.

Quality control and validation of the digital terrain model should include independent ground samples, comparison with control profiles, and statistical error assessment. Calculation of difference fields between the LiDAR model and reference measurements at key points allows establishing systematic biases and random deviations. It is necessary to construct error histograms, analyze error dependence on slope, vegetation height, and point density. Decisions on model adjustment are based on permissible error thresholds defined by the technical specification for the specific application (engineering calculations, hydrology, urban planning, etc.).

Integration of the digital terrain model with other geospatial data requires unification of coordinate systems, projections, and levels of detail. Bringing the DTM to a unified system enables hydraulic modeling, flood analysis, tracing of infrastructure objects, and creation of slope maps. It is recommended to store models in multi-level representations (resolutions by zones) to ensure a balance between accuracy and performance during visualization and further use. Regular documentation of acquisition, processing, and quality control parameters ensures reproducibility and transparency of the result.

Conclusion

In the course of the conducted study a comparative analysis of the productivity of LiDAR technologies and photogrammetric methods with respect to large-scale topogeodetic mapping was carried out. The results of the study confirm the initially proposed hypothesis and serve as the basis for the formulation of the key propositions.

It was found that LiDAR scanning demonstrates a distinct advantage when generating digital terrain models in areas with complex landscapes, particularly under conditions of dense vegetation cover. The penetrating capability of laser pulses through the canopy enables registration of true surface elevations, ensuring a minimal root-mean-square height error, whereas photogrammetry under analogous conditions frequently captures the contours of foliage with deviations measured in tens of centimetres. On unshaded sites both methodologies achieve similarly high accuracy.

The operational efficiency of LiDAR projects is confirmed by a reduction in field labour effort due to the minimization of the necessity for ground control points and the high degree of automation in chamber data processing, especially at the stages of point-cloud filtering and digital terrain model extraction, despite more significant initial investments. From an economic standpoint the choice between LiDAR and photogrammetry is determined by the total costs of project implementation.

The scientific novelty of the study lies in the proposal of an ordered approach to substantiating the choice of technology, formalized in the form of a decision-making algorithm. Unlike existing models, the proposed algorithm integrates technical, operational and economic criteria, providing engineers and project managers with a practical tool for selecting the most appropriate solution.

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