GLL
Geomatics, Landmanagement and Landscape No. 3 • 2025, 191–203

ISSN 2300-1496 https://doi.org/10.15576/GLL/210754

Research paper

Received: 1.08.2025
Accepted: 15.09.2025
Published: 3.11.2025

Analysis of the consistency between a digital terrain model (DTM) generated from aerial photographs and a model obtained using airborne laser scanning (LiDAR)

Paulina Modlińska 0009-0000-5086-1608

Faculty of Geoengineering, Mining and Geology, Wrocław University of Science and Technology
Corresponding author: paulina.modlinska@pwr.edu.pl

Summary

The aim of the study was to analyze the consistency of two digital terrain models (DTMs): one generated from aerial photographs using the Delta photogrammetric workstation, and the other developed based on airborne laser scanning data (LiDAR, ALS). The comparison was conducted in the area of the village Chańcza and the Chańcza Reservoir, characterised by varied morphology (flat areas, forested and built-up zones). The analysis aimed to assess the geometric consistency of both models, identify elevation differences, and evaluate their suitability in the context of diverse terrain conditions. The source data included digital aerial images and a LiDAR point cloud with an average density of 4 points/m². Processing involved the reconstruction of TIN models on the Delta photogrammetric workstation and using Terrasolid software (including the TerraScan and TerraModeler modules), as well as spatial comparison using CloudCompare tools (cloud-to-cloud analysis). The results showed that the average height difference between the models was 4.14 cm, with a maximum deviation of 23.41 cm, mainly in forested areas. The smallest discrepancies were recorded in flat areas. It was also noted that the differences increase with terrain elevation. The analysis demonstrated that both photogrammetric data and LiDAR can be effectively used to generate digital terrain models. However, the choice of data acquisition method should always depend on the terrain morphology and the expected accuracy of the final model. This approach ensures that the task is performed cost-effectively and to a high standard.

Keywords

digital terrain model (DTM) • airborne laser scanning (ALS) • model comparison • light detection and ranging (LiDAR)

1. Introduction

Modern geoinformation technologies play an important role in spatial analysis and modelling. One of the basic tools used in this type of analysis is the digital terrain model (DTM), which is a digital representation of the earth's surface, without elements of land cover such as vegetation or buildings [Gaździcki 2001]. The precision of such a model has a direct impact on the quality of analyses conducted not only in the fields of science, but also in practical applications, e.g. spatial planning. Depending on the chosen technology, terrain models may vary in terms of geometric accuracy and terrain representation. Comparing models originating from different data sources allows for the assessment of their compatibility and suitability for use in geodetic applications, among others.

Software dedicated to this task offers an extensive set of functions and analytical tools. However, detailed documentation on the implementation of the used algorithms is usually limited or incomplete. Therefore, it is necessary to verify the efficiency of a given tool, identify its limitations, and analyse the impact of input parameters on the results generated by individual computational modules.

Data for shaping numerical terrain and surface models can be obtained using both passive and active sensors. Passive sensors (e.g. photogrammetric cameras, optical satellites) record natural electromagnetic radiation reflected from the Earth's surface, and the accuracy of the mapping depends on atmospheric conditions, lighting and sensor resolution [Rodríguez-Gonzálvez 2014, Dwivedi 2018]. Active sensors (e.g. LiDAR, SAR radar), on the other hand, emit their own electromagnetic signal and record its reflection, which makes it possible to capture data independent of sunlight and, to a large extent, weather conditions [Rodríguez-Gonzálvez 2014, Zhu et al. 2018].

In engineering practice, there are two main approaches to structuring elevation data: models based on regular grids (GRIDs) and models developed using irregular grids (TINs, Triangulated Irregular Networks). In the case of the former, the surface area is divided into evenly spaced squares, to which an elevation value is assigned at the grid nodes. The density of this grid directly affects the detail of the representation – the smaller the cell size, the higher the resolution of the model. Advanced solutions employ adaptive structures in which the density of the grid depends on the local variability of the terrain [Wood 1996].

The TIN model, on the other hand, is based on a network of triangles generated from a set of measurement points, usually involving Delaunay triangulation [Delaunay 1934]. The TIN structure allows the original elevation values of the input points to be preserved and the grid to be dynamically adjusted to the complexity of the terrain. It makes this method particularly useful in areas with highly varied morphology. Each triangle forms a local approximation of a surface fragment, and their arrangement minimises interpolation errors [Zhu et al. 2008].

The choice between GRID and TIN structures depends on the purpose of the analysis, the nature of the data and the required precision of the model. Contemporary technical standards increasingly point to the importance of integrating field measurements with advanced interpolation methods and adapting the grid structure to terrain conditions. According to technical instruction K-2.8, two degrees of terrain difficulty are assumed for orthorectification purposes: easy terrain that is flat or undulating with gentle slopes, where DTM maps only the terrain relief, ignoring coverage; difficult terrain, with large and variable slopes (e.g. mountainous) or undulating surface, where DTM takes into account selected anthropogenic elements such as bridges, viaducts or hydrotechnical structures.

The main focus of this paper is to compare the DTM model developed at the Delta digital station with the model (LiDAR data) derived from airborne laser scanning (ALS) in order to determine the degree of consistency and potential elevation differences between selected elements of surface representation, such as land use and vegetation.

2. Study area

A section of the village of Chańcza, together with the Chańcza Reservoir located in the municipality of Raków in the Kielce county, was chosen as the study area. The absolute height range in the municipality is over 200 m [Raków Town and Municipality Office, 2013]. The reservoir is located at an altitude of 216.8 m above sea level. The reservoir area covers the buffer zone of the Cisowsko-Orłowiński Landscape Park and the Chmielnicko-Szydłowski Protected Landscape Area [Raków Municipal Council 2017].

The analysis used colour aerial photographs on a scale of 1:7,000, including the left photograph (No. 20049) and the right photograph (No. 20050) of the stereogram (Fig. 1a, b).

a. b.

Source: Author's own study

Fig. 1. Aerial photographs accepted for analysis: a. left image of the stereogram, b. right image of the stereogram

These materials were obtained from the resources of the Department of Agricultural Surveying, Cadastre and Photogrammetry at the University of Agriculture in Krakow.

The study area features a varied terrain, including flat terrain, such as farmland and arable fields, as well as areas of varying elevation covered with lush forests, road infrastructure and buildings.

3. Materials and methods

3.1. Nature and source of data

The study made use of digital colour aerial photographs and LiDAR data in the form of an unclassified point cloud captured by aerial laser scanning. Their technical parameters are summarised in Table 1.

Table 1. Specification of measurement data used for analysis

Aerial photographs	LiDAR
DMC camera: • focal lenght: 120 mm • pixel dimensions 12 × 12	Representation of the terrain in the form of a cloud of measurement points with specified XYZ coordinates and an average density of 4 points/m2.
Format: *tiff	Format: *laz
Date of execution: 2009 r.	Date of execution: 2023 r.
Spatial resolution: 0,20 m (RGB and infrared)	Average elevation error: 0.15 m
	Average location error: 0.30 m
	Horizontal coordinate system: PL-1992 Elevation coordinate system: PL-EVRF2007-NH
	Retrieved sheets: M-34-55-A-a-1-4 M-34-55-A-a-2-3 M-34-55-A-a-3-2 M-34-55-A-a-3-4 M-34-55-A-a-4-1 M-34-55-A-a-4-2 M-34-55-A-a-4-3
	Source: Geoportal

3.2. Software and tools

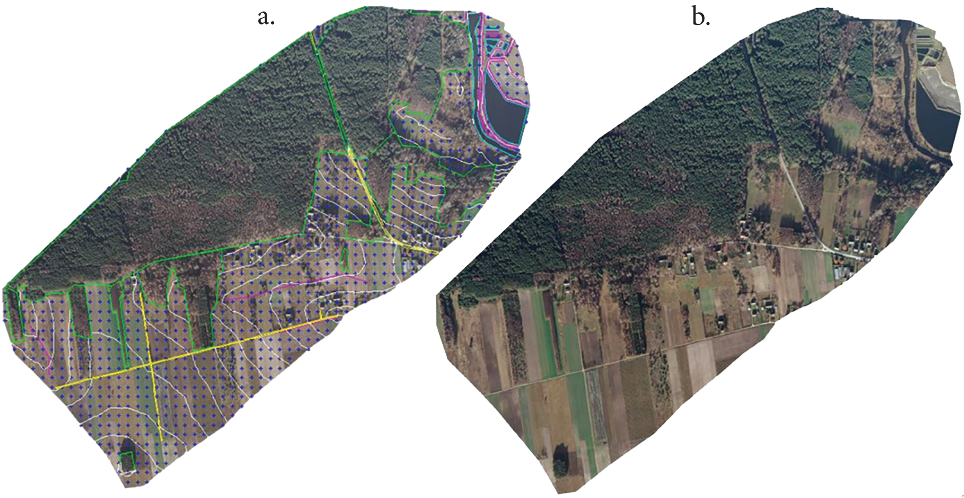
The study required the use of specialised software capable of processing spatial data obtained from two different sources – airborne laser scanning (ALS) and digital aerial photographs. In order to provide consistency in the analyses, the software was selected for full control over the processing, from the initial data processing stage, through the reconstruction of elevation models, to the assessment of their spatial consistency and accuracy. This study used both commercial software and open source tools, including:

- *Delta photogrammetric station*. It is a digital photogrammetric computer unit equipped with tools for processing photogrammetric data, enabling a full cycle of map creation: photo orientation, triangulation, generation of digital terrain models (both mono- and stereoscopic) as well as editing and printing of maps/orthomosaics. Stereoscopic observation of images is possible thanks to the use of polarising glasses or a stereoscope [Kwoczyńska et al. 2009].
- *Terrasolid* (*TerraScan*, *TerraModeler*). A software package operating in the MicroStation (Bentley) environment, designed for advanced LiDAR data processing. It enables, among other things, point cloud classification, TIN and GRID model generation, and error filtering [Terrasolid 2025].
- *CloudCompare*. An application designed, among other things, for comparing point clouds using the cloud-to-cloud (C2C) and cloud-to-mesh (C2M) methods. It enables the calculation of elevation differences, the generation of error histograms and differential maps [CloudCompare 2025].

3.3. Data processing at the Delta photogrammetric station

The work began by setting three orientations for the aerial photographs. Internal orientation involved determining the relationship between the coordinates on the image plane and the camera coordinate system, taking into account internal parameters, such as focal length, principal point location and lens distortion parameters [Bernasik 2003]. The measurement was taken in the screen coordinate system, which was then converted to ground coordinates using an affine transformation [Piech 2011]. Mutual orientation consisted in arranging a pair of photographs (stereogram) in such a way as to reproduce their mutual position at the moment the photographs were taken, which was achieved by eliminating transverse parallax throughout the model. This process relied on determining five orientation parameters relative to the left image or base [Bernasik 2003]. This task was performed at a photogrammetric station by transforming the ground coordinates to the model coordinate system. This required measuring homologous points, known as Gruber points. Absolute orientation, on the other hand, consisted in transforming the model created after mutual orientation to an external geodetic reference system. This then required the establishment of three rotation angles, a scale and three shifts, which meant that at least three photopoints had to be measured [Kurczyński 2014]. In the case of the described analysis, five points of the photogrammetric grid in the PUWG 1992 system were utilised.

The above-mentioned operations served as a basis for the next stage of development, which was the creation of a digital terrain model. For this purpose, five thematic layers were defined: road network, wooded and shrubby areas, slopes, terrain and watercourses, as illustrated in Fig. 2a. They were then plotted on a stereogram, taking into account the elevation variation of the terrain, so that the drawn polygons were neither below nor above the studied terrain. The next stage involved generating a 30 × 30 m grid and verifying the correctness of the horizontal and vertical positions of the created points. Wrong locations were corrected. The final stage of the process was to develop a digital terrain model (DTM) based on a triangulated irregular network (TIN). Contour lines with an interval of 2.5 m were generated on this basis (the value was determined by the terrain characteristics according to the K-2.8 instructions). Next, the incorrectly drawn contour lines were adjusted in areas where their appearance was incorrect, such as roads or forests (Fig. 2b).



Source: Author's own study

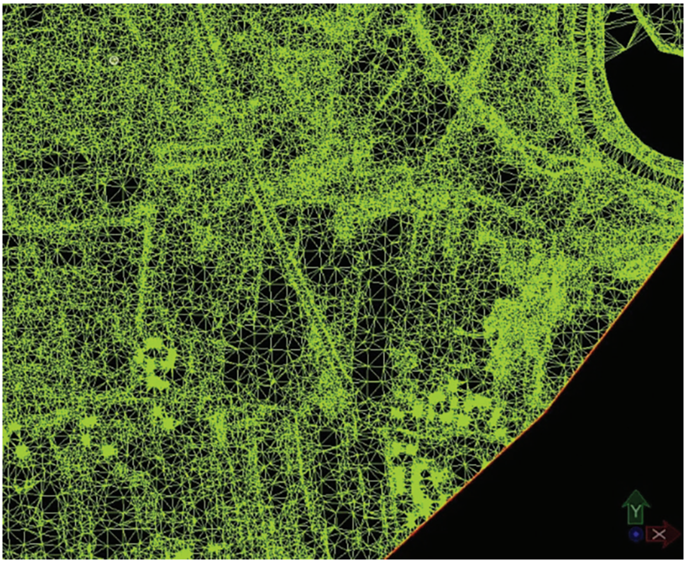
Fig. 2. View of selected thematic layers (a) together with the generated orthophoto map (b)

3.4. Processing of LiDAR data

The second part of the analysis involved processing data from aerial laser scanning, which consisted of automated differentiation of cloud points based on their height above the terrain. As a result of this process, they were assigned appropriate thematic classes, which are presented in Table 2 [ASPRS 2019]. After the classification, a digital terrain model was created, also using a triangulated irregular network (TIN) – Fig. 3. Due to the limited range of LiDAR data, the area was reduced in further parts of the analysis.

Table 2. Point cloud classification

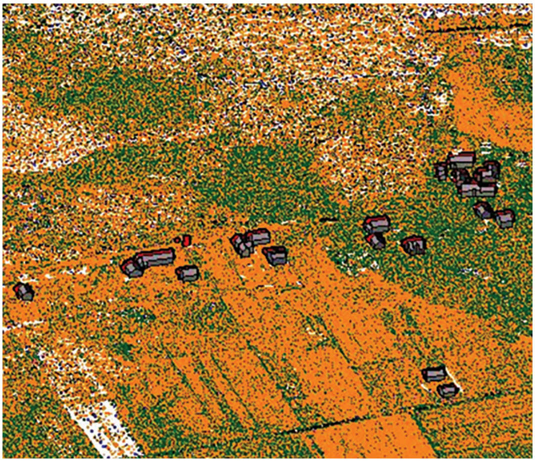
Class no.	Class	No. of points	Minimum elevation	Maximum elevation
1	Area	1 597 627	204.79	250.53
2	Low vegetation	1 065 066	204.89	250.73
3	Medium vegetation	115 832	205.33	252.18
4	High vegetation	1 882 865	206.99	288.33
5	Buildings	24 416	211.23	272.43
6	Low points	64	205.02	248.87
7	Key points in the model	65 710	204.80	250.60



Source: Author's own study

Fig. 3. Visualization of a fragment of DTM in a triangle mesh view

Additionally, a digital terrain cover model (DTCM) was generated that takes into account not only the morphology of the terrain, but also the elements above its surface, such as buildings and high vegetation (Fig. 4).



Source: Author's own study

Fig. 4. Visualization of a section of the DTCM – buildings

3.5. Criteria for assessing model consistency

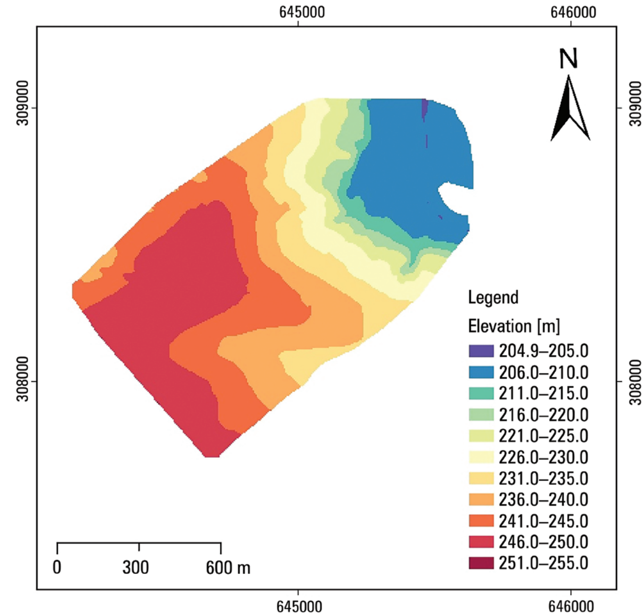
In order to compare numerical terrain models, it was necessary to adopt objective criteria for assessing their consistency. This chapter sets out an analytical approach for identifying differences between models based on their spatial structure and elevation values. The parameters taken into account for the assessment are presented below:

- Deviations in elevation.
- Analysis of elevation differences between corresponding points in two models (mean, standard deviation, minimum, maximum).
- Model coverage and completeness.
- Influence of local terrain conditions.
- Visual assessment of models.

The obtained results related to the above criteria are described in the Results section.

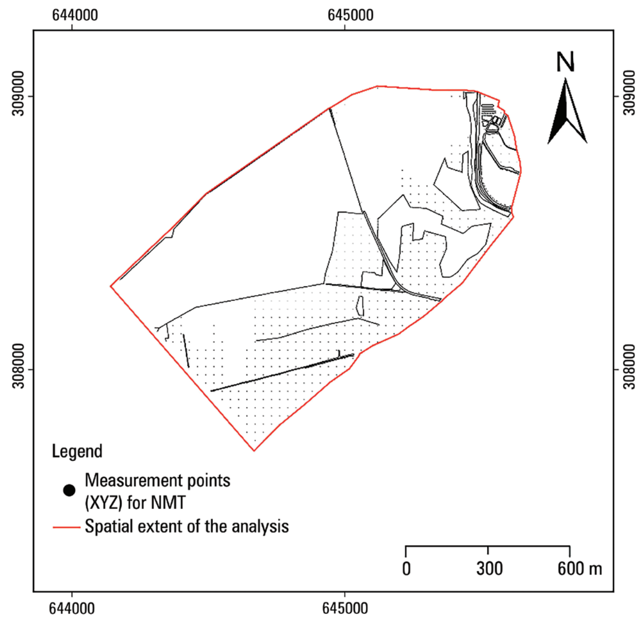
4. Results

Two models generated from data obtained from aerial photographs and aerial scanning were subjected to elevation analysis: the first model was created at the Delta photogrammetric station, and the second was generated in the TerraScan environment (Figs. 5 and 6). The aim of the comparison was to assess the consistency of both models in terms of terrain mapping. The analysis used cloud-to-cloud analysis and a difference map, supplemented with terrain cross-sections (Fig. 8). This allowed for the identification of areas with the greatest deviations and the evaluation of the spatial accuracy of both approaches.



Source: Author's own study

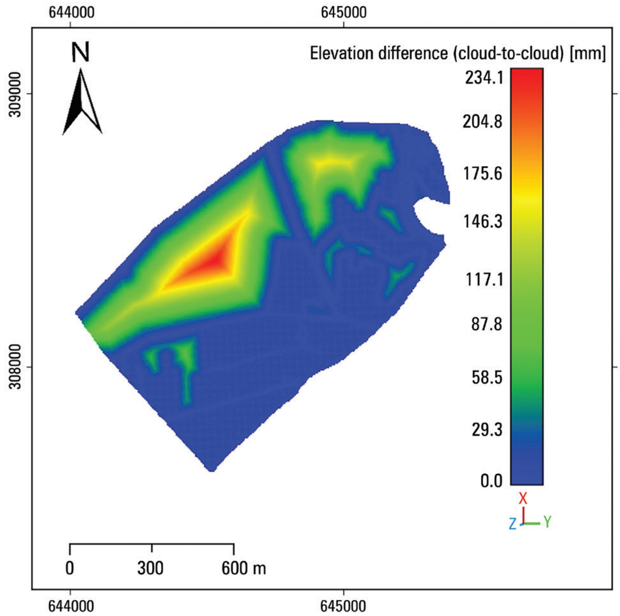
Fig. 5. Visualization of the DTM model generated in Terrasolid



Source: Author's own study

Fig. 6. Visualization of the GRID mesh generated at the Delta photogrammetric station

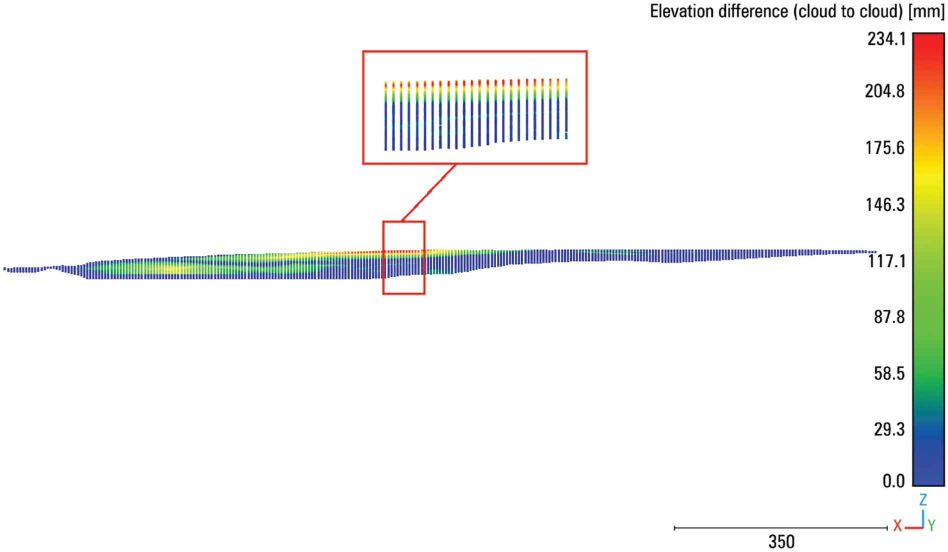
A comparative analysis using the cloud-to-cloud (C2C) method identified locations with the greatest differences between the two analysed spatial data models. The highest deviation value was recorded in the central-western part of the studied area, where the local gap reached 23.41 cm (Fig. 7). This area is characterised by a significant density of forest cover, which negatively affects the accuracy of terrain surface detection. In addition, the average difference between the points of both models was 4.14 cm, while the standard deviation fluctuated around 4.84 cm.



Source: Author's own study

Fig. 7. Differential map of digital terrain models (DTMs)

Over approximately 60% of the analysed area (i.e. 26,000 out of 43,480 points), the elevation differences between the compared models did not exceed 2.8 cm.



Source: Author's own study

Fig. 8. Horizontal cross-section of the differential model

5. Discussion

The comparison of LiDAR and photogrammetric data for terrain modelling has been the subject of several studies. Digital terrain models obtained from LiDAR are usually more accurate than photogrammetric models, especially in areas with dense vegetation and complex topography [Gil et al. 2013, Martínez-Agirre et al. 2020]. Jan [2005] found that tree crown elevations generated by LiDAR were slightly higher than those obtained from aerial photographs. LiDAR data usually better represent the terrain surface in places where photogrammetric methods encounter difficulties, most notably in forested areas with dense undergrowth [Gil et al. 2013]. The results of the analysis remain consistent with examples presented in the scientific literature. However, it should be noted that one of the main limitations of the study may be the fact that the measurement data was obtained at different times, as well as terrain conditions such as the presence of vegetation, shadows or slopes, which may limit the accuracy of the reconstruction.

6. Conclusions

In this study, the grid points determined using a Delta digital station were adopted as reference data. This choice was dictated by the use of classical geodetic measurements to establish the photogrammetric network used in the aerotriangulation of aerial photographs. Furthermore, in situ data are widely regarded as a reliable reference source in elevation analyses. Based on a comparison of LiDAR data and aerial photographs, the following conclusions were drawn:

- A comparative analysis of the average values of grid points obtained using the aforementioned methods revealed discrepancies ranging from 0 to 24.1 cm. The smallest differences were recorded in cultivated areas characterised by flat terrain. In contrast, larger deviations appeared in wooded and built-up areas, where it was difficult to reconstruct the terrain surface.
- A clear upward trend in the differences between the analysed models was observed as the elevation increased. This means that in areas located at higher elevations, the discrepancies between the elevation values generated by the individual methods became more apparent.
- When processing data using the Delta photogrammetric station in heavily forested areas, where high vegetation density limits tree canopy penetration, identifying ground structures in the stereoscopic model is significantly more challenging. This leads to increased workload and poses a risk of obtaining results with low accuracy.

Although aerial photogrammetric triangulation based on a geodetic control network ensured high accuracy of reference point locations, the results of the analysis showed that LiDAR data proved to be more effective in generating both a digital terrain model (DTM) and a digital surface model (DSM). Thanks to the high density of the point cloud and the capacity to map terrain details and coverage more accurately, the model based on LiDAR data provided a better representation of topography and anthropogenic elements, compared to the model created on the basis of aerial photographs.

Advances in photogrammetric technology not only improve the quality of source data, but also significantly streamline the processing of that data. This makes it possible to obtain end products with high spatial accuracy while reducing the amount of work and time required to complete the study.

References

American Society for Photogrammetry and Remote Sensing (ASPRS). 2019. LAS specification version 1.4-R15. Bethesda, MD https://www.asprs.org/wp-content/uploads/2019/07/LAS_1_4_r15.pdf [acessed: 06.09.2025].

Bernasik J. 2003. Elementy fotogrametrii i teledetekcji. Kraków. Wydawnictwo AGH.

CloudCompare. 2025. Cloud-to-Cloud Distance. https://www.cloudcompare.org/doc/wiki/index.php/Cloud-to-Cloud_Distance [acessed: 27.07.2025].

Delaunay B. 1934. Sur la sphère vide. Bull. Acad. Science USSR, VII: Class. Sci. Mat. Nat., 793–800.

Dwivedi R.S. 2018. Passive Remote Sensing. In: Geospatial Technologies for Land Degradation Assessment and Management, 31‑65. CRC Press.

Gaździcki J. 2001. Leksykon geomatyczny. Polskie Towarzystwo Informacji Przestrzennej, Wydawnictwo „Wieś Jutra" Sp. z o.o.

Gil A.L., Núñez-Casillas L., Isenburg M., Benito A.A., Bello J.J.R., Arbelo M. 2013. A comparison between LiDAR and photogrammetry digital terrain models in a forest area on Tenerife Island. Canadian Journal of Remote Sensing, 39(5), 396–409. https://doi.org/10.5589/m13-047

Jan J.F. 2005. Comparison of forest canopy height derived using LiDAR data and aerial photos. Taiwan Journal of Forest Science, 20(1), 13–27.

Kurczyński Z. 2014. Fotogrametria. Warszawa, Wydawnictwo Naukowe PWN.

Kwoczyńska B., Bielski B. 2009. Wykorzystanie stacji cyfrowej Delta firmy Geosystem do opracowania elewacji Pałacu Lubomirskich w Niezdowie. https://science.lpnu.ua/sites/default/files/journal-paper/2017/may/1716/gka71200932.pdf / [acessed: 20.07.2025].

Martínez-Agirre A., García-Morales V., Álvarez-Mozos J. 2020. Comparison of digital terrain models obtained with LiDAR and photogrammetry. In: F. Cavas-Martínez, F. Sanz-Adan, P. Morer Camo, R. Lostado Lorza, J. Santamaría Peña (eds.). Advances in design engineering. INGEGRAF 2019. Springer. https://doi.org/10.1007/978-3-030-41200-5_63

Piech I. 2011. Wizualizacja numerycznego modelu terenu dla fragmentu obszaru Kamionki Wielkiej. Infrastruktura i Ekologia Terenów Wiejskich, 8(3).

Rada Gminy Raków. 2017. Uchwała Nr XXXII/189/2017 z dnia 29 marca 2017 r. w sprawie przyjęcia „Programu Rewitalizacji Gminy Raków na lata 2016–2025". Dziennik Urzędowy Województwa Świętokrzyskiego 2017. https://bip.rakow.pl [acessed: 27.07.2025].

Rodríguez-Gonzálvez P., Garcia-Gago J., Gomez-Lahoz J., González-Aguilera D. 2014. Confronting Passive and Active Sensors with Non-Gaussian Statistics. Sensors, 14(8), 13759-13777. https://doi.org/10.3390/s140813759

Terrasolid. User Guides, 2025. https://terrasolid.com/guides/user-guides/ (acessed 26.07.2025)

Urząd Miasta i Gminy w Rakowie. 2013. Charakterystyka elementów środowiska przyrodniczego. https://rakow.pl/gmina-informacje/charakterystyka-element%C3%B3w-%C5%9Brodowiska-przyrodniczego.html? [acessed: 23.07.2025].

Wood J.D. 1996. The geomorphological characterization of digital elevation models. Ph.D. thesis, University of Leicester.

Wytyczne techniczne K-2.8. 2001.

Zhu L., Suomalainen J., Liu J., Hyyppä J., Kaartinen H., Haggren H. 2018. A review: Remote sensing sensors. Multi-purposeful application of geospatial data, 19, 19–42.

Zhu Q., Zhang Y., Li F. 2008. Three-dimensional TIN algorithm for digital terrain modeling. Geo-spatial Information Science, 11(1), 79–85. https://doi.org/10.1007/s11806-008-0043-6