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The assessment of elevation data consistency. A case study using the ALS and georeference database in the City of Kraków

Izabela Piech[1], Agnieszka Policht-Latawiec[1], Lenka Lackóová[2], Paulina Inglot[1]

[1] University of Agriculture in Krakow, Faculty of Environmental Engineering and Land Surveying, al. Adama Mickiewicza 21, 31-120 Kraków, Poland

[2] Slovak University of Agriculture in Nitra, Faculty of Horticulture and Landscape Engineering, Department of Landscape Planning and Ground Consolidation, 949 76 Nitra, Slovak Republic

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Abstract: The integration of geodetic and photogrammetric data has become a new tool that has expanded the existing measurement capabilities, as well as it found its application outside the geodetic sector. As a result, over the past decades, the process of topographic data acquisition has caused cartographic industry to move from classical surveying methods to passive and active detection methods. The introduction of remote sensing technology has not only improved the speed of data acquisition but has also provided elevation data for areas that are difficult to access and survey. The aim of the work is to analyse consistency of elevation data from the Georeference Database of Topographic Objects (Pol. Baza danych obiektów topograficznych – BDOT500) with data from airborne laser scanning (ALS) for selected 15 research areas located in the City of Kraków. The main findings reveal discrepancies between elevation data sources, potentially affecting the accuracy of various applications, such as flood risk assessment, urban planning, and environmental management. The research gap identified in the study might stem from the lack of comprehensive investigations into the consistency and accuracy of elevation data across different databases and technologies in urban areas. This gap highlights the need for a thorough examination of the reliability of various data sources and methods of urban planning, disaster management, and environmental analysis. The integration of diverse databases and technologies, like ALS and geodetic measurements, in various applications introduces potential discrepancies that can significantly impact decision-making and outcomes.

Keywords: airborne laser scanning (ALS), Digital Surface Model (DSM), Digital Terrain Model (DTM), Georeference Database of Topographic Objects (BDOT500), IT System for the Protection of the Country (ISOK), point cloud

INTRODUCTION

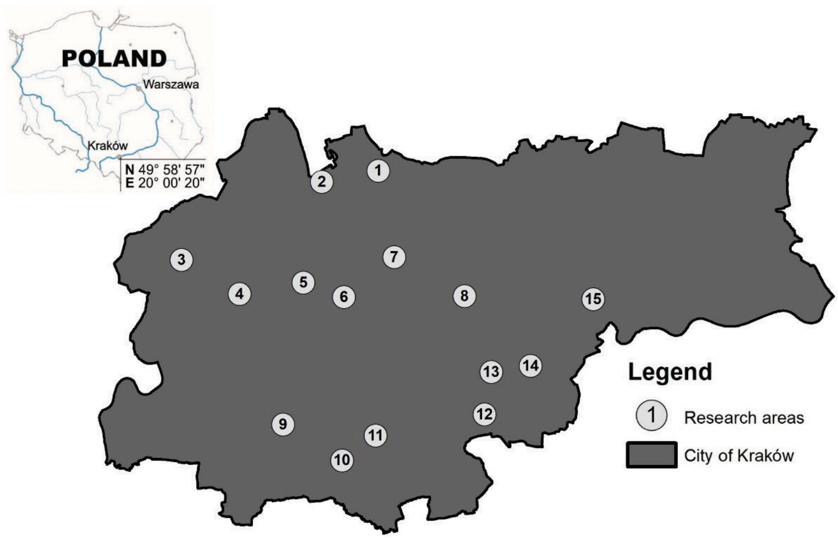
In today's world, data has become an integral part of our daily lives, together with various man-made databases responsible for storing the data. Notable among these databases are the Georeference Database of Topographic Objects (BDOT500), Geodetic Records of Land Utilities Network (GESUT), and Records of Land and Buildings (EGiB). In Poland, there has been a growing frequency of extreme phenomena over the years, leading to significant social and economic losses. To address this, the IT System for the Protection of the Country (ISOK) was developed, incorporating hydrographic divisions of Poland and flood hazard and risk maps for crisis management (Kurczyński and Bakula, 2013; Ouzahar *et al.*, 2018). Furthermore, by using Airborne Laser Scanning (ALS) technology, which leverages high-density source data regardless of lighting and weather conditions, accurate Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) depicting elevation data of specific regions can be obtained (Forkuo, 2008; Baszkiewicz *et al.*, 2014; Mikrut and Głowienka (eds.), 2015; Okolie and Smit, 2022; Polidori and Hage, 2022). These models are the integral part of the IT System for the Protection of the Country (ISOK), contributing to the creation of 3D models across various economic and scientific domains (Doskocz and Lewandowicz, 2022; Wojak, Strużyński and Wyrębek, 2023). A significant advantage of the ALS lies in its capacity to swiftly classify data into distinct categories (Song, Han and Kim, 2002; Estornell *et al.*, 2011), as well as to determine fundamental vegetation parameters, such as tree height (Morsdorf *et al.*, 2003), crown diameter, forest density, biomass estimation, and forest boundaries (Pitkänen, Maltamo and Hyyppä, 2004; Weinacker *et al.*, 2004; Hyyppä *et al.*, 2005). In a related study, Sefercik *et al.* (2016) demonstrated the effectiveness of the ALS as a remote sensing technology for providing precise three-dimensional 3D dense point clouds through analysing a large-size ALS digital surface model (DSM) covering the entire Istanbul Province using point-based and model-based statistical approaches. Their findings revealed that terrain roughness significantly impacts the vertical accuracy of ALS DSMs. In another context, Bartmiński, Siłuch and Kociuba (2023) presented a comparison of data acquired from three LiDAR sensors from different manufacturers, namely, Yellow Scan Mapper (YSM), AlphaAir 450 Airborne LiDAR System CHC Navigation (CHC), and DJI Zenmuse L1 (L1) in the north-western part of the Lublin Province in eastern Poland. Their findings highlighted significant variations in terrain models calculated from point clouds, ranging from the CHC sensor with differences exceeding 2.5 m to the L1 sensor with RMSE at 0.31 m. This underscores the importance of accurate data acquisition and processing, especially when utilising UAVs for very high-resolution data in challenging environments. Furthermore, Căţeanu and Ciubotaru (2020) discussed the challenges of using LiDAR data for modelling the ground surface in forested mountainous areas. They conducted a comparative analysis of interpolation accuracy for nine algorithms used to generate Digital Terrain Models from ALS data in a densely forested mountainous terrain. Their findings shed light on the performance of these algorithms and their varying accuracy levels, influenced by factors, such as model resolution, ground slope, and point cloud density. In the domain of deep learning, Lê *et al.* (2022) addressed the extraction of DTMs from ALS point clouds using a deep neural network approach named DeepTerRa. They collected a large-scale dataset of ALS point clouds and corresponding DTMs, training a deep neural network for direct DTM extraction through rasterisation techniques. Their agnostic data-driven approach demonstrated submetric error levels compared to methods specifically designed for DTM extraction. In the realm of aligning diverse laser scanning data, Liang *et al.* (2020) introduced a novel skyline context-based method for the automatic localisation of terrestrial laser scanning (TLS) scans to ALS point clouds. This method utilised skyline contexts and a 3D skyline-based k-d tree to achieve accurate localisation, demonstrating precision and adaptability in challenging scenarios.

The authors of the paper formulated two research questions: 1) is there consistency between the elevation data from the BDOT500 database and the data from the ALS for selected areas in the City of Kraków? and 2) what is the accuracy of ALS data and data measured directly in the field using geodetic techniques?

STUDY MATERIALS AND METHODS

STUDY AREA

The scope of the research covered 15 selected areas of various sizes (0.40–33.78 ha) located in Kraków, the Małopolskie Voivodship (Fig. 1). They were signalled in the form of polygons using QGIS (version 3.28). It was important for the study to select the surface of research areas in order to optimise the calculation time in the subsequent stages of the analysis. When selecting the study areas, attention was paid to the well-developed BDOT500 database due to the modernisation works related to the strengthening of the embankments and regulation of the Vistula River in the Kraków area. Therefore, they are monitored and updated on an ongoing basis.



Number of study area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Area (ha)	1.28	10.61	0.40	2.09	2.84	2.06	1.33	0.83	1.97	1.26	0.43	2.56	20.18	1.98	33.78

Fig. 1. Location of study areas in Kraków (and location of Kraków in Poland); source: own elaboration

STAGES OF DATA PREPARATION FOR THE ELEVATION COMPLIANCE ANALYSIS

The polygons in the Kraków area were imported to the QGIS software. Data from 2017 were downloaded from the ALS in the form of 32 point clouds in the .las and metadata format to determine the timeliness of the set, vertical accuracy, average number of points per m^2 and reference systems (Fig. 2). For selected test areas, density in individual clouds was 12 points per m^2, and the plane coordinate reference system was selected in the National Geodetic Coordinate System 1992 (PUWG 1992), (EPSG 2180). To analyse the consistency of the height data between the BDOT500 database and the ALS data, the ALS set was selected only for points classified as "ground" (Fig. 3). When compiling ALS data, it was important to identify points belonging to the appropriate surfaces (Nurunnabi *et al*., 2021). All point clouds were combined and then divided according to the boundaries of research areas, and then 15 files in .csv format were exported to CloudCompare to be imported for further analysis in QGIS.

Data from the BDOT500 database were downloaded for selected areas of Kraków in the form of .giv files. Two classes of objects "natural elevation point" and "artificial elevation point" were specified, for which the following attributes were obtained: coordinates (X, Y, H); source of data acquisition; measurement date; application number (ID) or the KERG. Only in the case of the date of measurement, their absence was noted and the ID or KERG attribute was an alternative to it. Horizontal reference frames are designated as PL-ETRF2000 and PL-ETRF89, which are the mathematical and physical implementation of the European Terrestrial Reference System ETRS89 (Doskocz, 2016). The valid elevation system in Kraków is "PL-EVRF2007-NH", and for the purposes of further analysis, the heights were converted to the "PL-KRON86-NH" system. The heights difference between the systems was 0.18 m using Python. The .giv files were saved in the .csv format in order to harmonise them with the ALS data imported into the QGIS. At this stage, data were prepared for two analysis variants – point approach and surface approach. Additionally, Ali-Sisto *et al.* (2020) proposed an automated correction method to enhance the accuracy of vertical position information in digital aerial photogrammetry (DAP) based point clouds. Their method involved co-registering each

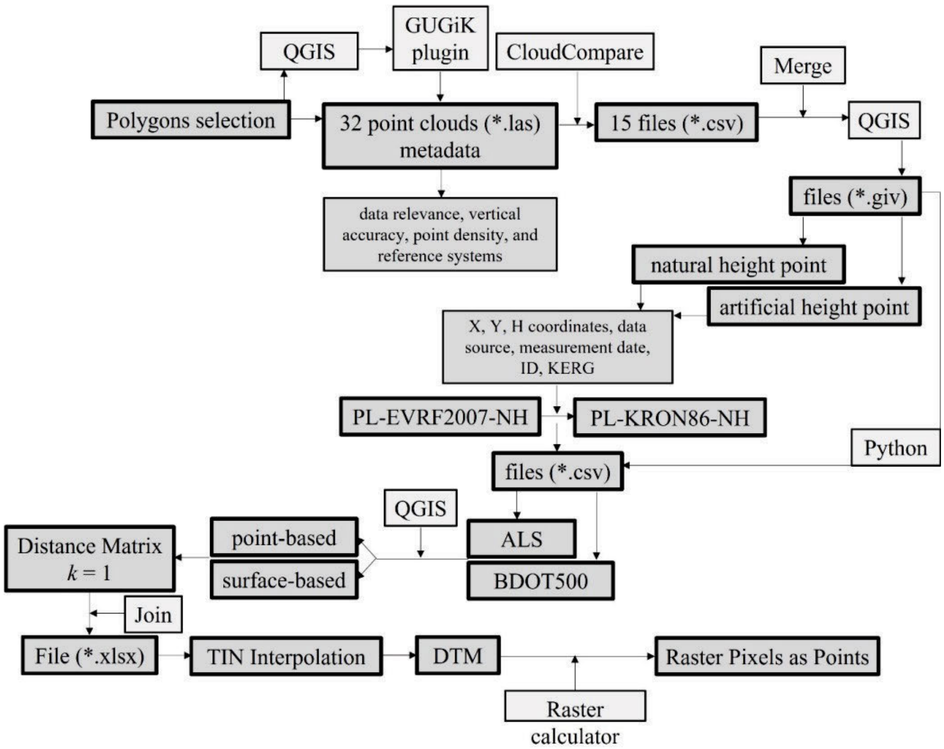


Fig. 2. Stages of data preparation for elevation compliance analyses; source: own elaboration based on: Ackermann (1999), Hyyppä *et al.* (2000) and Maciąg, Leń and Maciąg (2022)

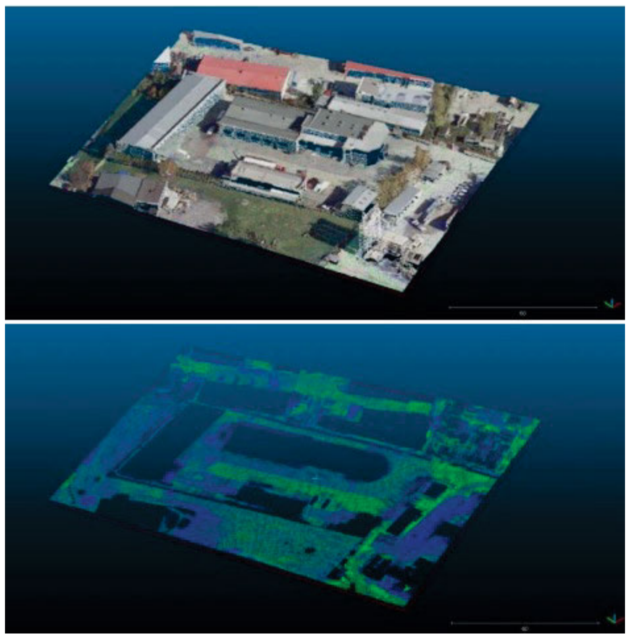


Fig. 3. Point cloud and "ground" class for the selected area number 9; source: own elaboration

DAP point cloud to a common ALS based digital terrain model, resulting in improved prediction accuracy of forest variables. This approach showed the potential of rectifying vertically misaligned DAP data to deliver near ALS data quality.

In the point approach, due to the characteristics and size of both sets, points of the BDOT500 base corresponding to the points of the ALS set were determined, and then columns were added in both sets: "ID_BDOT500" and "ID_ALS". These are identifiers for individual points. When analysing this variant, a point from the ALS set was found for each point of the BDOT500 database. For this purpose, the "Distance Matrix" algorithm was used, can find "k" nearest points in relation to the input layer, $k = 1$ was assumed. The algorithm helped to obtain a new vector point layer, which adopted the geometry after the layer of the BDOT500 set. The new set provided information about the point identifier from the BDOT500 set (InputID), the ALS set identifier (TargetID), and the distance (Distance), which connected the corresponding points. In order to obtain information about attributes of points from the BDOT500 database and the elevation of points from the ALS, the attributes were combined for selected vector layers and thus a vector set of points was obtained. This included the following attributes: coordinates (X, Y, H) of the point from the BDOT500 database, distance in which the algorithm found the closest point for the BDOT500 database in the ALS set, information about the source of obtaining the point data from the BDOT500 database (i.e. warp measurement or digitisation and vectorisation), information about the class of the BDOT500 database point (i.e. "natural elevation point" or "artificial elevation", year of data acquisition, elevation of the nearest point in the ALS set and the number of the research area. The attributes were saved in the .xlsx format and used for further analyses.

In the surface approach, it was checked whether the DEMs created on the basis of points from both sets are consistent with each other. The "TIN Interpolation" algorithm in the QGIS was used to create the DEM. The points were selected in such a way that they were also outside the research area for interpolation. This approach allowed to generate elevation in the full range of the analysed areas without the need for extrapolation. The areas were cut to the study areas. Then, differential models were made for all 15 pairs of elevation rasters using the "raster calculator" algorithm. For further analysis, raster data was converted into numerical data using the "Raster Pixels as Points" algorithm. Thus, a point was generated in the centroid of each pixel, which took the value of a pixel (Fig. 4), and it was possible to export raster data to a tabular form, which offers more possibilities for analysis (Fig. 2).

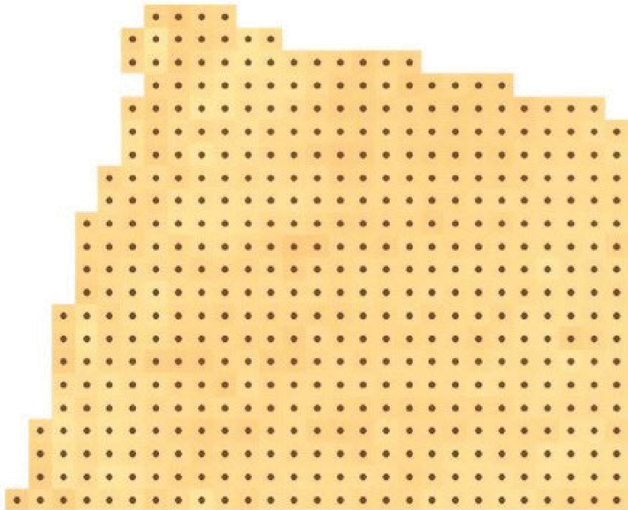


Fig. 4. Operation of the "Raster pixels as points" algorithm; source: own elaboration

Table 1. Number of points in study areas

Number	Altitude point	
	natural	artificial
1	57	25
2	380	121
3	0	44
4	18	60
5	0	340
6	1	63
7	0	119
8	0	19
9	2	157
10	3	101
11	0	41
12	0	323
13	124	70
14	34	19
15	126	535
Total amount	**745**	**2037**

Source: own study.

RESULTS

NUMBER OF POINTS IN STUDY AREAS

The survey created 15 study areas, in which 2,782 points were analysed, with over 73% of the points being artificial elevation points, and the rest natural points (Tab. 1).

DENSITY OF POINTS IN STUDY AREAS

When analysing the density in the study areas, it was noticed that the largest number of points was in area 15, where 661 points were located on an area of over 33.78 ha, and the least in area 8 with 19 points. In area 12, it was found that there were 126 points per 1 ha, and area 13 was characterised by the lowest density of points, amounting to 10 points per ha (Tab. 2).

DIFFERENTIAL MESH MODEL

While using the data, difference between the elevation values of the points from the BDOT500 database and the corresponding points from the ALS set were estimated in order to check the consistency of these data. Then, the absolute values of the obtained elevation differences were analysed. Table 3 shows the highest consistency for area 11. The average difference between

Table 2. Density of points in study areas

Number	Area (ha)	Number of points	Point density (pcs·ha^{-1})
1	1.28	82	64
2	10.61	501	47
3	0.4	44	110
4	2.09	78	37
5	2.84	340	120
6	2.06	64	31
7	1.33	119	89
8	0.83	19	23
9	1.97	159	81
10	1.26	104	83
11	0.43	41	95
12	2.56	323	126
13	20.18	194	10
14	1.98	53	27
15	33.78	661	20

Source: own study.

Table 3. Mean, maximum, minimum of Georeference Database of Topographic Objects (BDOT500) and airborne laser scanning (ALS) differences for study areas

Number	Elevation difference (m)		
	mean	maximum	minimum
1	0.13	0.83	0.00
2	0.16	2.19	0.00
3	0.28	1.48	0.01
4	0.20	2.12	0.00
5	0.04	0.58	0.00
6	0.08	1.37	0.00
7	0.18	2.22	0.00
8	0.10	0.21	0.00
9	0.15	2.34	0.00
10	0.13	1.23	0.00
11	0.04	0.13	0.00
12	0.12	2.26	0.00
13	1.35	5.77	0.00
14	0.11	0.38	0.00
15	0.66	15.90	0.00
Final average	**0.24**	**2.60**	**0.00**

Source: own study.

the elevation of the point from the BDOT500 database and the corresponding point from the ALS set was 0.04 m, while the maximum one was 0.13 m. In the case of average values, two outliers were observed for areas 13 and 15 – 1.35 m and 0.66 m, respectively. The maximum values of differences were also recorded for them; for area 13 – 5.77 m, and for 15 – 15.9 m. This might indicate a significant change in the terrain between the given measurement methods (Tab. 3). Due to divergent differences in study areas 13 and 15, they were verified with the 2004 orthophotomap. It was established that in area 15 there were industrial heaps of various heights, which resulted in excluding this area from further analyses (Fig. 5).

Fig. 5. View of industrial heaps in area 15; source: own elaboration based on geoportal.pl

In the case of area 13, while analysing orthophotomaps from 2004 to 2022, no grounds were found to exclude the area from further analyses. Area 15 was excluded, since the mean value of absolute differences in all study areas was equal to 0.24 m. Then, the consistency of the points was checked taking into account their classes. Table 4 shows that the artificial elevation points are characterised by higher consistency with the data from the ALS set. The mean of all research areas for this class was 0.12 m, and for natural points 0.53 m. On the one hand, the lowest value of differences between the analysed sets was recorded for areas 5 and 4 (0.04 m). On the other hand, for natural elevation points, the average values ranged from 0.05 m to 1.98 m. It is important that for areas 3, 5, 7, 8, 11 and 12, no natural elevation points were observed (Tab. 4).

SELECTION AND ANALYSIS OF ATTRIBUTES

One of the attributes that were added to the analysed set was the date of measurement of a point in the BDOT500 database. For this purpose, the average absolute values of elevation differences compared to the 2017 analysis were compiled (Fig. 6). The highest discrepancies between the data were observed for the points obtained in 2010 and 2011, whereas the largest consistency was observed in 2020 and 2021. In addition, a trend was observed where consistency of data increased in subsequent years (Fig. 6).

Data pertaining to distances at which the algorithm found the corresponding point from the ALS set for the BDOT500 base

Table 4. Summary of average elevation differences, broken down by point class

Number	Elevation point	
	natural	artificial
1	0.14	0.12
2	0.18	0.10
3	–	0.28
4	0.19	0.20
5	–	0.04
6	0.11	0.08
7	–	0.18
8	–	0.10
9	0.05	0.15
10	0.17	0.13
11	–	0.04
12	–	0.12
13	1.98	0.25
14	0.11	0.13
Final average	**0.53**	**0.12**

Source: own study.

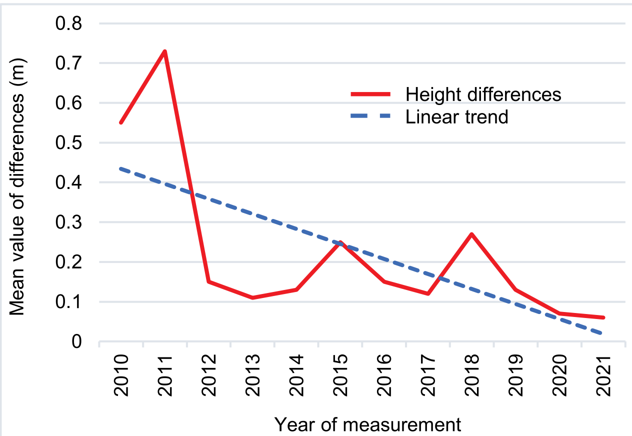


Fig. 6. Average absolute values of differences compared to 2017; source: own study

point (distance matrix $k = 1$) were compiled. Then, they were divided into five ranges, to which appropriate data were assigned. For artificial and natural elevation points, there was a relationship between the average absolute values of height differences for BDOT500 and ALS, except for the range from 0.00 to 0.05 ($k = 1.22$ m). For artificial points, it was observed that with the increase in distance at which the algorithm found the point, the height difference between the points from BDOT500 and ALS increased, and thus the data consistency decreased. The opposite situation was observed for natural elevation points (Fig. 7).

When analysing 14 research objects by the type of measurement: digitisation, vectorisation, and warp measurement, significant differences in data consistency were observed in favour of the points obtained from the warp measurement. The average absolute

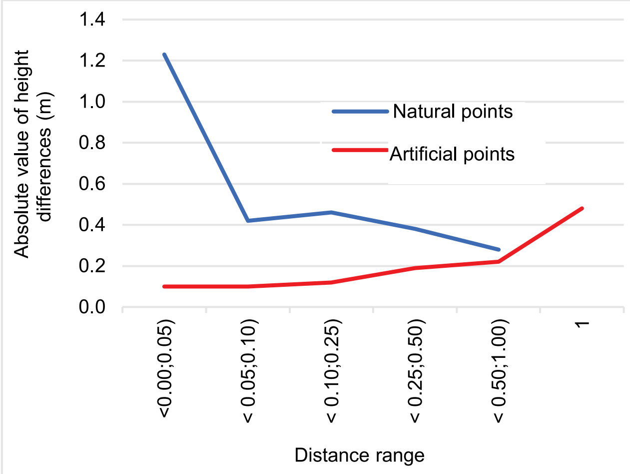


Fig. 7. Relationship between absolute values of height differences and distance ranges for natural and artificial points; source: own study

value of height differences was 0.11 m. In the case of digitisation and vectorisation, it was 0.48 m (Tab. 5). For research areas 6, 8, and 11, digitisation and vectorisation and for area 4 warp measurement were not taken into account during the analysis due to numerous errors that occurred during the measurement.

During the analysis of differential rasters created through the interpolation of data from the BDOT500 and ALS databases for the studied areas, it was found that areas 5 and 11 were characterised by the largest consistency of data in the range from 0 to 0.05 m, where 76% and 48% of pixels were observed, respectively (Fig. 8). The lowest value of 7% for this range was recorded for area 13. In addition, the largest groups were recorded in the range of 0.25 to 0.50 m for all areas. The fewest pixels were observed for the ranges from 0.50 to 1.0 m and above 1.0 m (Tab. 6).

Table 5. Average absolute value of height differences by type of measurement

Number	Digitisation and vectorisation	Warp measurement
1	0.02	0.13
2	0.28	0.13
3	0.26	0.28
4	0.20	–
5	0.07	0.03
6	–	0.08
7	0.19	0.04
8	–	0.10
9	0.19	0.11
10	0.44	0.13
11	–	0.04
12	0.09	0.14
13	1.43	0.13
14	0.11	0.13
Final average	**0.48**	**0.11**

Source: own study.

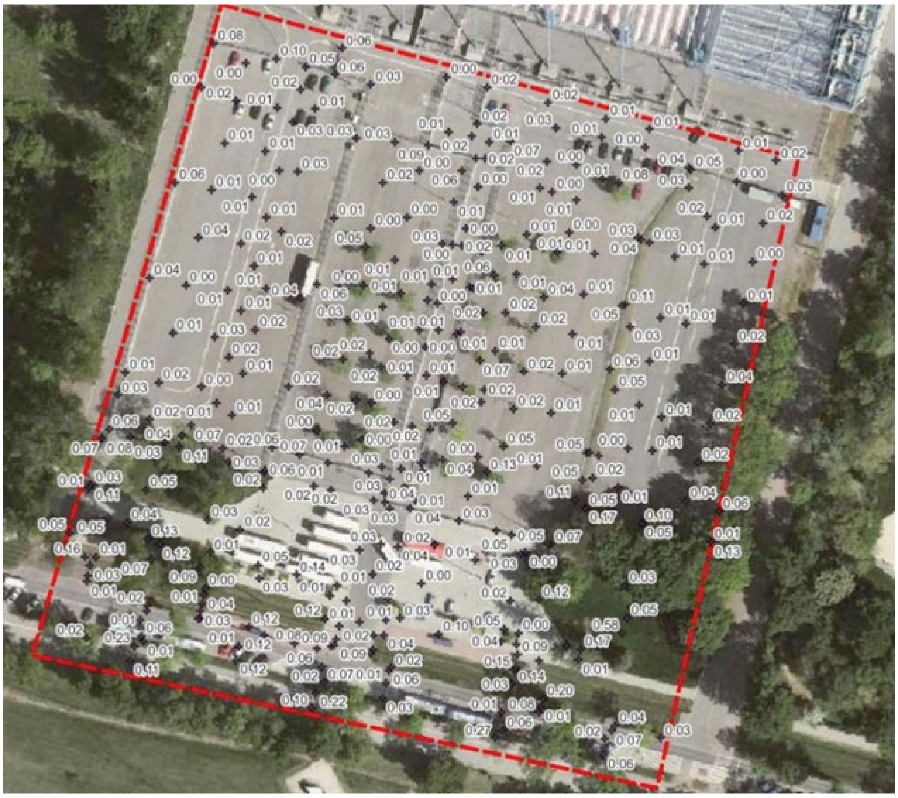


Fig. 8. Area 5 with elevation differences; source: own elaboration based on geoportal.pl

Table 6. Distance between corresponding points and height difference in %

Number	Number of pixels	Percentage of points in a given range					
		<0.00; 0.05)	<0.05; 0.10)	<0.10; 0.25)	<0.25; 0.50)	<0.5; 1.00)	1.00
1	50,884	13	14	18	27	13	15
2	424,270	19	19	17	40	5	1
3	16,019	26	23	9	35	3	4
4	83,092	11	10	31	26	19	3
5	113,308	76	13	2	9	0	0
6	82,462	16	16	23	36	7	2
7	52,974	22	20	15	37	5	2
8	33,244	19	18	13	49	0	0
9	90,767	25	19	17	26	9	5
10	50,231	24	22	15	35	2	0
11	17,120	48	31	1	19	1	0
12	102,148	28	25	7	36	3	1
13	806,567	7	6	9	12	10	56
14	78,989	29	26	7	37	0	0

Source: own study.

DISCUSSION

The findings of this study highlight the synergy created by the utilisation of photogrammetric and geodetic methods for assessing the consistency of elevation data. The integration of ALS data serves as a valuable resource that bolsters the accuracy and control of elevation data acquisition. At the same time, geodetic measurements play a pivotal role in cross validating outcomes of these methods, acting as a verification mechanism to rectify potential measurement errors. This mutual validation can be perceived as a robust approach that ensures the integrity of results derived. The examination encompassed 14 distinct areas in

Kraków, where one area exhibited notable height disparities between datasets due to industrial mounds. In alignment with the assertions of Ślusarski (2015), the BDOT500 database garners recognition as a dependable repository of geospatial information, presenting high adherence rates exceeding 90% across criteria, such as data quality, completeness, relevance, and logical coherence. Echoing the study by Maciąg, Leń and Maciąg (2022), this research harnessed a streamlined methodology to assess the congruence of LiDAR data and geodetic elevation information from the BDOT500 database, yielding minor disparities. Notably, this investigation shares the outcome of Maciąg, Leń and Maciąg (2022), which has stimulated the development of a conceptual framework for modifying the BDOT500 database structure. This adaptive scheme aims to supplement numerical maps in specific regions without necessitating extensive fieldwork. Two analytical approaches related to Maciąg, Leń and Maciąg (2022) framed this study: a point-wise analysis and a surface coherence analysis.

The point-wise analysis focused on scrutinising elevation consistency between the BDOT500 database and ALS data at individual points. This process entailed the assessment of height differences and comparison of attributes across datasets. The surface consistency analysis involved generating elevation rasters through TIN interpolation based on BDOT500 base points. Fourteen pairs of elevation rasters were juxtaposed, giving rise to a differential model. Applied across various areas, this analysis highlighted the highest and lowest coherence in distinct regions. Notably, a differentiation between natural and artificial elevation points, where the latter stems from measurements on the control network, was evident. Artificial elevation points exhibited enhanced cohesion relative to their natural counterparts. A discernible trend indicated improved data coherence over successive years. Building upon this study's insights, Bac-Bronowicz *et al.* (2015) explored the interplay between conceptual models of spatial databases, focusing on BDOT500 and BDOT10k. These databases diverge significantly in their purpose and generalisation level, engendering intricate challenges in data exchange due to substantial conceptual disparities. Addressing these discrepancies requires harmonisation of databases that operate on disparate levels of generalisation, presenting not only construction but also updating complexities. Moreover, the research by Ślusarski (2017) underscores data quality's pivotal role in official spatial databases, echoing its significance in strategic decision-making and planning processes. Inglot and Kozioł (2016) contribute further by unveiling algorithms that identify topological inconsistencies within spatial databases. Thus, they further enhance our comprehension of spatial data management and analysis.

CONCLUSIONS

The integration of geodetic and photogrammetric data has ushered in a new era of expanded measurement capabilities and versatile applications across multiple sectors. This transformation has led to a shift from traditional surveying methods to modern passive and active detection techniques, driven by advancements such as remote sensing technology. The significance of accurate topographic data acquisition cannot be overstated, as it underpins crucial decision-making processes in fields ranging from urban planning and infrastructure development to disaster management and environmental research. The research presented in this paper focused on analysing the consistency of elevation data obtained from the Georeference Database of Topographic Objects (BDOT500) and ALS technology across specific areas in Kraków. By meticulously investigating both point-wise and surface coherence analyses, the study examined the extent of agreement between these datasets.

The findings highlighted several critical aspects. The study identified variations in elevation data consistency between the BDOT500 database and ALS for different areas. The meticulous analysis of elevation differences revealed that, on average, there was reasonable consistency between the datasets. Notably, some outliers were observed in certain research areas, which might be attributed to terrain characteristics, data collection methods, or other external factors. The research also highlighted the impact of point classification and the source of data acquisition on data consistency. The results also demonstrated the importance of temporal considerations, showing that data from more recent years exhibited higher consistency. This underscores the dynamic nature of elevation data and the necessity for regular updates to maintain accuracy. The study also recognised the significance of data integration in broader applications, such as urban planning, flood risk assessment, and environmental analysis.

The inconsistencies identified in this research emphasize the need for robust and consistent elevation data sources to inform decision-making processes accurately. This research provides valuable insights into the complexities of integrating geodetic and photogrammetric data for elevation analysis. The study underscores the necessity of careful data validation, methodological considerations, and the role of technological advancements in shaping the accuracy of elevation data. The collaborative insights from this study and prior research underscore the significance of data integrity in urban spatial databases and its impact on applications ranging from crisis management to urban planning and environmental analysis. As urban landscapes continue to evolve, the implications of elevation data discrepancies must be addressed, spurring the need for further research and refining methodologies to ensure the accuracy of critical decision-making processes. This research contributes to the broader understanding of data integration, ultimately enhancing the quality and reliability of geospatial applications in urban environments.

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