Studia Geotechnica et Mechanica, Vol. XXXI, No. 3, 2009

APPLICATION OF DIGITAL TERRAIN MODEL GENERATED FROM AIRBORNE LASER SCANNING DATA IN HYDRODYNAMIC MODELLING[1]

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Abstract: Airborne laser scanning (ALS) is becoming a basic method of data extraction for generation of digital terrain models (DTMs). The method has a number of advantages, especially when used for vegetated river valleys. This paper describes experiments that were carried out using ALS to generate DTM of the Widawa river valley as well as observations made from this process. DTM was built for the purpose of hydrodynamic modelling. For the estuary of the Widawa river, we generated DTM, whose height accuracy was: ±0.46 m for woodlots and forests, ±0.44 m for the areas covered with thickets and high grass, ±0.27 m for meadows and arable lands and ±0.17 m for the flat, unvegetated areas (e.g. roads). This accuracy was verified on the basis of GPS measurements. DTM was generated for different variants, viz. both regular and irregular grids.

The generated DTM was used in hydrodynamic modelling. Modelling was carried out using a SMS package. We modelled the discharge of $Q = 130\ \text{m}^3/\text{s}$ which was used to design the capacity of the Widawa river valley. The outcomes we got are comparable to the results obtained for previous models generated for the Widawa river. However, the model we generated has number of additional advantages, e.g. it facilitates the analysis of the river flow velocity in vulnerable spots such as road and rail bridges.

Streszczenie: Lotniczy skaning laserowy (LSL) staje się coraz częściej podstawową metodą pozyskiwania danych do budowy numerycznych modeli terenu (NMT). Technika ta ma wiele zalet, zwłaszcza w odniesieniu do porośniętych roślinnością dolin rzecznych. W pracy przedstawiono doświadczenia i spostrzeżenia związane z wykorzystaniem LSL do budowy NMT doliny rzeki Widawy na potrzeby modelowania hydrodynamicznego. Dla odcinka Widawy przy jej ujściu zbudowano NMT charakteryzujący się dokładnością wysokościową: w terenie zalesionym i zadrzewionym ±0,46 m, na obszarze porośniętym zaroślami i wysoką trawą ±0,44 m, na łąkach i polach ornych ±0,27 m oraz w terenie płaskim, niepokrytym roślinnością (np. drogi), ±0,17 m. Dokładność ta została zweryfikowana na podstawie bezpośrednich pomiarów terenowych techniką GPS. Zbudowano NMT dla różnych wariantów siatki zarówno regularnej, jak i nieregularnej.

Otrzymany NMT wykorzystano w modelowaniu hydrodynamicznym, które przeprowadzono, korzystając z pakietu SMS. Modelowano przepływ $Q = 130\ \text{m}^3/\text{s}$, dla którego zaprojektowano przepusto-

[1] Calculations were made in MATLAB ® (licence no.: 101979), within the processing time grant awarded by Wrocław Centre for Networking and Supercomputing.

wość doliny Widawy. Otrzymane wyniki są porównywalne z wynikami modeli, jakie były dotychczas budowane dla Widawy, jednak nasz szczegółowy model ma wiele dodatkowych zalet, np. umożliwia analizę rozkładu prędkości przepływu wody w newralgicznych miejscach, jakimi są mosty drogowe i kolejowe.

Резюме: Авиационный лазерный сканинг (АЛС) становится все чаще основным методом поиска данных для построения численных местностных моделей (ЧММ) Эта процедура имеет многие преимущества, особенно по отношению к поросшим растениями речным долинам. В настоящей работе представлены испытания и примечания, связанные с использованием АЛС для построения ЧММ долины реки Видавы для гидродинамического моделирования. Для отрезка Видавы вблизи ее устья построена ЧММ, характеризующаяся высотной точностью: в лесистой и обсаженной деревьями местности ±0,46 м, вместности, покрытой зарослями и высокими травами ±0,44 м, на лугах и пашнях ±0,27 м, а также в плоской местности, не покрытой растениями (напр. на дорогах), ±0,17 м. Эта точность была проверена на основе непосредственных местных измерений с использованием GPS. Построена ЧММ для разных вариантов как регулярной, так и нерегулярной сеток.

Полученная ЧММ была использована в гидродинамическом моделировании, корое было проведено с использованием SMS. Моделировалось течение Q = 130 м^3/с, для которого была запроектирована пропускная способность долины Видавы. Полученные результаты были сравнены с моделями, построенными до сих пор для Видавы, однако наша подробная модель обладает мнгими приметами, она дает напр. возможность анализа распределения скорости течения воды в невральгических местах, какими являются дорожные и железнодорожные мосты.

1. INTRODUCTION

In recent years, airborne laser scanning (ALS) has become the main source of data for generation of Digital Terrain Models (DTMs). This technique ensures very accurate and detailed digital terrain descriptions, especially in the woodlot areas where other surveying techniques cannot be used. The accuracy of the final product (DTM), interpreted as a difference between the elevation that is measured using classical surveying techniques and the elevation that is interpolated from DTM, depends on three factors: the accuracy of primary laser scanning data, the efficiency of the filtration method and the DTM interpolation method. The prominent factor affecting the accuracy of DTM is certainly the accuracy of primary laser scanning data, which is influenced by a number of features such as the photogrammetric flight stability, the navigational data quality, the calibration accuracy, precision of the laser distance measurement, the lay of the land and land cover. It is hard to evaluate the involvement of each of the features separately and therefore we will consider their influence on the accuracy of the final product jointly.

Laser scanning data was extracted in the framework of the research project that used ScaLARS system and was concerned with generation of DTM for the Widawa river valley for the purpose of hydrodynamic modelling (BORKOWSKI et al. [1], BORKOWSKI et al. [2]). The most part of the Widawa river valley is used for farming and only its estuary is the woodlot area. The lay of the land in the valley is characterised by numerous depressions and elevations. Filtration of the data was performer automatically using our own algorithms, which are based on robust approximation with polynomial surface model. In the paper (GOŁUCH et. al. [7]) we present the evaluation of ALS data obtained with ScaLARS, and in the paper (GOŁUCH et. al. [8]) we discuss the accuracy of the final product, namely DTM. This paper describes application of DTM generated by our research team for the purpose of hydrodynamic modelling.

2. WIDAWA RESEARCH OBJECT

We selected the Widawa river as the research object to investigate the possibility of using ALS in hydrodynamic modelling (BORKOWSKI at al. [1]). The research object is situated north of Wrocław and covers the area of approx. 40 km^2 of the Widawa river valley (Fig. 1).

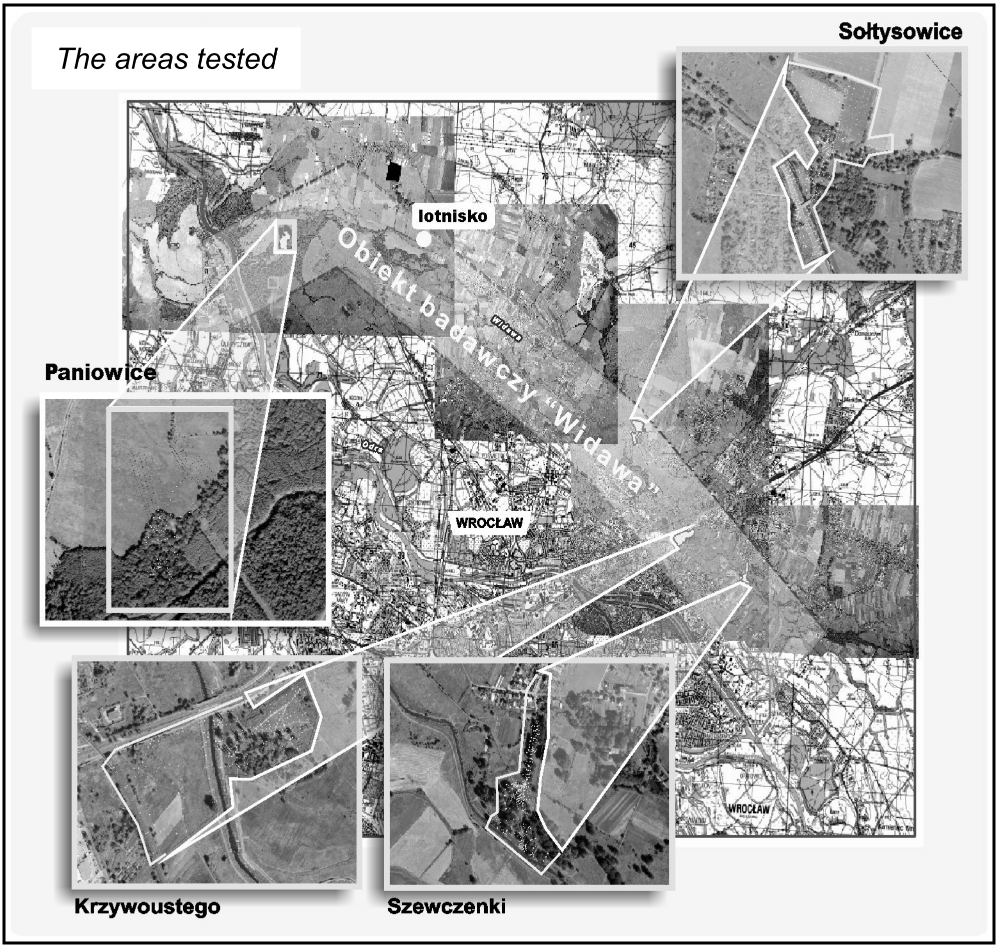

Fig. 1. The "Widawa" research object with marked testing areas (GOŁUCH et al. [7])

Laser scanning was carried out in November 2005 using ScaLARS system placed on the board of AN-2 plane flying at the height of 550m (BORKOWSKI at al. [2]). Due to the width of the research object (river valley) reaching 2 km, 11 scanning strips were planned. The width of a single strip on the ground was 280 m, and the overlap of points in two adjacent strips was designed on the level of 30%.

One of the scanning correctness evaluation criteria is lack of gaps between scanning strips. It means that scanning was performed in accordance with flight specifications, which were also correctly established and that the flight was stable and precise.

The factor which determines the quality of ALS data is the correct calibration of the system. Therefore, before the actual scanning the control flight aimed at the system calibration was performed. Calibration was done using control fields situated close to the airport. These control fields were marked and measured with GPS. Calibration was done semi-automatically with LASCAL software (SCHIELE et al. [10]), whose calibration parameters are estimated on the basis of Gauss-Markow model. The scanner internal calibration parameters as well as the parameters of calibration of the measurement outcomes in the local system with reference to control fields are given in the paper (BORKOWSKI et. al. [2]). Table 1 gives the final values of calibration accuracy, viz. calculated deviations, mean values of absolute errors along and across the flight direction and the height component.

Table 1

Juxtaposition of calibration accuracy parameters against control fields

	along flight direction	across flight direction	height component
Calculated deviations	± 0.6 m	± 0.4 m	± 0.15 m
Absolute error (mean value)	0.3 m	0.3 m	0.10 m

The ultimate outcome of the research is the set of points' coordinates {B, L, H} in the WGS84 coordinate system. In this research project approx. 150 million points were registered with the average density of 3 points per square metre.

3. EVALUATION OF ALS DATA ACCURACY AND THE GENERATED DTM

Four sub-areas distinguished by various land covers were selected in the research object. These sub-areas were used primarily for the evaluation of ALS data and secondarily to investigate the accuracy of DTM interpolated on the strength of these data. The selected test areas (Paniowice, Sołtysowice, Krzywoustego and Szewczenki) are located on the edges of the research object and in its middle part (Fig. 1). We selected such test areas that are situated in a distance from the airport apron for which the system calibration was done. In total, 1728 points were measures in the test areas. The measurement was done using GPS-RTK and tachymetric methods. Due to varied lay of the land and land cover of the river valley, the analysis was done for four land categories:

– forest and woodlot – the area features varied lay of the land with numerous local depressions and small ponds;

– thicket and high grass – the area along the riverbed, outside forests, is covered with thicket and very high grass, numerous slopes occur;

– meadows and arable lands – the area used for farming, mainly flat; also includes pastures and wastelands with medium-high grass (around 40–60 cm);

– roads – include dirt roads, telford roads and asphalt roads; trees, ticket, big ditches and small slopes often occur along these roads.

The errors of points' elevation measurement using GPS-RTK and tachymetric methods are one order lower than for ALS (Table 1). Therefore, it was assumed that points measured with these methods will be treated as reference points and will be used to analyse the accuracy of ALS data as well as DTM. In measurements we used GPS Ashtech Z-Xtreme receivers and Leica TCR 407 electronic tachymeter. The aim of the survey was to establish the location of points evenly distributed over the test areas taking landmarks into account. Majority of points were measured with the tachymetric method using permanently marked points of the geodetic control network. Coordinates of the geodetic control network points were established with GPS. To ensure high accuracy of GPS measurements, we considered referential corrections from the WROC station of permanent GPS/GLONASS observations on each point of the geodetic control network. Corrections were obtained directly from measurements through mobility Internet and by connecting the GPS receiver to the notebook. Owing to a small distance from test field to the GPS reference station (a few kilometres), coordinates of the geodetic network points (particularly elevations) were determined with the accuracy of 1 cm.

To provide the uniform coordinate system for GPS, tachymetric and ALS measurements, coordinates of all points were transformed to the same coordinate system. We used Transpol software and our own algorithms developed in MATLAB to convert coordinates of points to PUWG 1992 coordinate system (x, y coordinates) and to Kronsztadt 1986 system (h elevations).

ALS data form a point cloud located in the 3D space. Because the laser spot is reflected both from the objects of the land cover and the land surface itself, it is not possible to use all ALS data to generate DTM. The raw data have to be analysed to select the set of points that illustrate the reflection of the laser beam from the surface. This problem is solved automatically using the software for ALS data filtration. In this paper we used our own algorithms developed in MATLAB. The algorithms rely on robust approximation of the surface with the polynomial of second degree in every survey point (BORKOWSKI and JÓŹKÓW [3]):

$$z(x,y) = a_{00} + a_{10}x + a_{01}y + a_{11}xy + a_{20}x^2 + a_{02}y^2, \tag{1}$$

where:

x, y are plane coordinates of the interpolated point,

a_{ij} are coefficients of the local polynomial.

The coefficients of the local polynomial are calculated using the least squares method:

$$\sum_{i=1}^{n} p_i v_i^2 \rightarrow \min, \tag{2}$$

$$v_i = a_{00} + a_{10}x + a_{01}y + a_{11}xy + a_{20}x^2 + a_{02}y^2 - h_i, \tag{3}$$

where:

p_i are weights of points that belong to the surrounding of the interpolated point and depend on distances to the interpolated point,

v_i are deviations on the points that belong to the surrounding of the interpolated point,

h_i are points' elevations that have been measured.

Points which are reflections of the laser beam from non-terrain objects are considered gross errors in this approach. Robust approximation of the local polynomial coefficients (a_{ij}) depends on modification of weights p_i of survey points depending on residues v_i between the elevation interpolated from the polynomial and indicated as z and the measured elevation indicated as h. Robust approximation of the polynomial coefficients is carried out iteratively. The algorithm also uses the idea of hierarchical filtration which relies on gradual elimination of points (BRIESE et. al. [4]). Every next step involves removal of points situated in the closer distance to the surface, where these points are still non-terrain points. It was evaluated that the efficiency of filtration in the applied algorithm was 98% (BORKOWSKI and JÓŹKÓW [3]). Sets of points selected with automatic filtration were checked and adjusted manually. In this process we benefited from facilities of the digital photogrammetric workstation ImageStation software (such as stereometric measurement on the aerial photographs whose scale is 1: 26000).

As a result of the automatic verification of ALS data filtration, for each test area we obtained sets of points, which were later used to generate DTM.

DTM was generated on the photogrammetric station ImageStation as a TIN consisting of laser scanning points. DTM presented in the form of the TIN is the simplest method of linear interpolation. Even though this method does not reconstruct the surface faithfully, due to the high density of laser scanning points (about 2 points per square metre), the generated model is considered as very detailed.

Owing to a varied accuracy of the raw laser scanning data obtained for different land categories, the accuracy of DTM was determined separately for each category

(GOŁUCH et. al. [7]). The set of points measured with surveying methods was divided into subsets representing each of the land categories. Table 2 presents the number of terrain points for land categories in each of the test areas.

Table 2

Number of points measured with surveying techniques for various land categories

Type of landcover	Number of points				
	Overall	Test areas			
		Krzywoustego	Sołtysowice	Paniowice	Szewczenki
Area covered with forest and woodlot	730	65	34	110	521
Area covered with thicket and high grass	753	213	540	–	–
Meadows and arable fields	574	159	172	243	–
Roads	50	32	18	–	–
Total	2107	469	764	353	521

In every point measured with classical methods, we calculated the difference between the elevation that was interpolated from DTM and the elevation that was actually measured. We assumed that the DTM accuracy (m_{NMT}) would be indicated by the mean error calculated for all $dz = Z_{NMT} - Z_{Ter}$ elevation differences in each land category separately,

$$m_{NMT} = \sqrt{\frac{\sum dz^2}{n}}\,, \tag{4}$$

where n is the number of control points.

Table 3

DTM accuracies depended on the landcover

		Type of landcover			
		Area covered with forest and woodlot	Area covered with thicket and high grass	Meadows and arable fields	Roads
Quantity n		730	753	574	50
Median dz	[m]	0.12	0.32	0.23	0.14
Mean value of dz	[m]	0.07	0.29	0.22	0.12
Absolute mean value of dz	[m]	0.37	0.37	0.23	0.15
Accuracy of DTM m_{NMT}	[m]	0.46	0.44	0.27	0.17
Accuracy of LIDAR data	[m]	0.33	0.33	0.23	0.16

Table 3 presents the obtained accuracies. The bottom row of the table gives ALS data accuracies for individual categories of land cover obtained from the paper (GOŁUCH et. al. [7]). These accuracies were calculated using the survey data. By comparing the last two rows in the table, we can notice that DTM accuracy is slightly lower than ALS data accuracy. The accuracy of the latter determines DTM accuracy. The median and mean *dz* values given in Table 3 suggest a systematic error. DTM generated on the basis of laser scanning data "lies" a dozen up to several dozen centimetres above the actual surface. This difference is caused by the surface roughness.

4. APPLICATION OF ALS DATA IN HYDRODYNAMIC MODELLING

Many computer systems have been developed for hydrodynamic modelling of water discharge. These are usually software packages which can be used for any river segment to solve the problem of water flow. The modelling task depends on selection of the appropriate mathematical model and the structure of the database that will be relevant for the computer model. It also requires appropriate definitions of the boundary conditions in the modelling process. Data which is essential for discharge modelling includes, inter alia, information on the shape of the discharge area and the hydraulic roughness value which depends on the land cover (EWERTOWSKI [5]).

The detailed information about the terrain is crucial for currently developed, high-quality software packages which are 2D models. ALS data features high density of points (a few points per square metre) and accuracy of around a dozen to several dozen centimetres depending on the land cover. These data refer to the "dry" area of the river valley. The riverbed is modelled using the raw survey data (e.g. from tachymetric measurements) or using the modern sonar technique.

In the experiment we used 2D hydrodynamic models obtained in the **SMS** (Surface-water Modeling System) environment on the basis of 2D finite element meshes created in the **Mesh** module. The hydrodynamic module of the **SMS** model facilitates simulation of the river valley during the analysis of water flow using the feature that depends on flooding elements of the discretization grid. The set of equations and type of digital diagrams applied in **SMS** imposes application of a boundary condition in the extreme cross-sections of the given grid in order to solve these equations:

– in the start nodes of the mesh – river stage hydrographs $H(t)$,

– in the end nodes of the mesh – flow $Q(t)$ or stage hydrographs $H(t)$.

The surface roughness coefficients and longitudinal turbulence element coefficients (τ_{xx}) are model coefficients. Conformity of the measured river stages with the calculated river stages and velocity of water discharge in various spots of the investigated area were used to assess the simulation accuracy.

The numerical realisation of the model relies on the principle that the topographic structure of the network is described by means of the grid consisting of segments and nodes (EWERTOWSKI [5]). Computation of the model relies on linearization on the segmental differential equations by "double calculation" of all network segments. It is followed by reducing the border system to the node system, which is solved by Gauss method. As the result, we get the solution of all segments' "interiors" and updated geometric parameters.

Appropriate preparation and definition of geometry of the water discharge area is very important for 2D hydrodynamic modelling (GOŁUCH [6]). Our project benefited from the highest quality of data (as far as the acquisition of data for large areas is concerned) acquired from laser scanning. ALS data allowed for generation of the detailed DTM for the "dry" part of the Widawa river. DTM was accompanied by data which delineate the riverbed and which were obtained from direct tachymetric measurements of cross-sections. DTM generated in such a way was directly imported to the hydrodynamic model. In the **Mesh** module, the network of elements was built on the basis of imported points and using the triangulation method. The grid was then verified with the software functions (e.g. in order to connect triangles, change the division edge of the rectangular element into two triangular elements or to remove elements). Figure 2 illustrates a mesh of finite elements generated in the **Mesh** module of the **SMS** environment.

The mesh was built of 34,573 points of DTM, consists of 47,332 nodes and has 23,317 triangular or rectangular elements. When the discretization grid is made of DTM in the TIN form, the verification process is more laborious but the DTM with such a structure includes information on the terrain morphology, which is important for water flow modelling (e.g. flood embankments). We also have to notice that DTM which has the TIN structure includes fewer points than DTM which has the GRID structure (particularly in the areas that are flat). We also have to bear in mind that time required to obtain the outcome in the 2D hydrodynamic modelling is proportional to the square of the number of the grid points.

The areas with different land-use types and roughness coefficients for these land use-types were determined on the basis of remote sensing data (orthophotos, Digital Land Cover Model and intensity of the laser pulse reflection). The detailed description of this problem is presented in the paper (TYMKÓW et. al. [11]).

We modelled the discharge of $Q = 130$ m^3/s, which was used by Germans to design the capacity of the Widawa river valley. Such a discharge means that water leaves the riverbed and flows in the region between embankments. Figure 3 illustrates the distribution of flow trace obtained from hydrodynamic modelling. The calculation outcomes are similar to results obtained from alternative modelling processes and measurements taken during the flood in 1997 (PARZONKA [9]). The generated model additionally enables to determine the water flow velocity with vectors that indicate the flow direction in any point of the hydrodynamic model.

Fig. 2. 2D finite element meshes generated on the basis of DTM

Fig. 3. Flow Trace at the modelled discharge $Q = 130\ \mathrm{m^3/s}$

5. SUMMARY

The first part of this paper presents the outcomes of the accuracy evaluation for DTM interpolated with ALS data obtained from ScaLARS system. Elevations from DTM were compared to elevations of points measured with traditional surveying techniques, where the latter ones were considered reference elevations. On the strength of this information, the accuracy of DTM was established. This accuracy depends on the lay of the land and land cover and was between 17 and 46 cm. The accuracy of primary laser scanning data, which differs for various land categories, had the greatest impact on the DTM accuracy. The accuracy of DTM for the flat areas with no land cover (particularly with no vegetation, e.g. roads) was 17 cm. The DTM accuracy decreases compared to the accuracy of the primary data when the elevation of the land rises and when the vegetation becomes denser.

In the second part of the paper we discuss the application of DTM for the description of the geometry of the water flow area in the 2D mathematical hydrodynamic model **RMA2**. We could use the 2D hydrodynamic model only because we held high quality data (numerous and dense points) from ALS. The detailed DTM was built on the strength of ALS data and for the riverbed it was complemented with data from traditional measurements. DTM was used in the **Mesh** module of the **SMS** environment to generate the mesh of finite elements. The mesh built in such a way was used for modelling the water flow velocity (v_x, vy) and the surface water elevation (H_w). In this project, we also found that remote sensing data was very useful to determine the flow roughness coefficients and areas with different land-use types (TYMKÓW et. al. [11]).

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