MOVING POLYNOMIAL SURFACE MODEL FOR GENERATION DTM AND DSM FROM AIBORNE LASER SCANNING DATA

Grzegorz Jóźków[1]

Abstract

Airborne laser scanning delivers the discrete geometrical information about ground surface and objects existing on it. In the data processing the main issue is the identification of points belonging to the proper surfaces. Another way is direct generated models of these surfaces from original laser scanning data. Precise DTM and DSM can be used in many domains, for example: environment monitoring, orthorectification of photogrammetric pictures, land engineering. The algorithm of generating digital terrain model and digital surface model has been presented in this paper. For generation DTM the method of hierarchical classification of terrain points was used. This algorithm based upon the approximation of measuring data in regular grid using moving polynomial surfaces model. Parameters of surfaces were determined by robust estimation. Weighting function depended on distance measured data from grid points. In the work few asymmetrical damping functions as M-estimators were tested. Precise digital terrain models and digital surface models were created from the real airborne laser scanning data captured with ScaLARS system. Coordinates of these points were converted to national Polish coordinate system PUWG 1992.

Key words

Digital terrain model (DTM), digital surface model (DSM), laser scanning, moving polynomial surface, robust estimation, weighting function.

1 INTRODUCTION

Within the last years airborne laser scanning has become the basic technology of acquiring information of terrain and objects on it. Development of new devices and processing technology delivers high resolution data faster and with better accuracy. Final airborne laser scanning products like DTM and DSM are used in many domains.

The main problem in data processing is the classification points to the proper surfaces. Modelling terrain and terrain surface requests points without errors like multipath reflections or reflections from flying birds. Reflections from objects existing on the terrain (for example: roofs and walls of buildings, forests or other vegetation) become errors in the process of DTM creation. Manual points classification is impossible – there is very large quantity of points in the points cloud. All solutions go to automatic classification points belonging to the proper surfaces. Another way is the automatic elimination of points not belonging to the modeling surface. This elimination is called filtration. Many authors are interested in this problem and they propose various solutions based upon:

- linear prediction [4], [7],
- adaptive TIN models [1],
- mathematical morphology (slope adaptive filtering) [10], [11],
- data clustering analysis [6],
- surface energy minimization (active shape models or flakes) [5], [2],
- wavelet domain [3].

Overview of filtering methods, their accuracy and restrictions can be found in study [9].

Filtering of laser scanning data gives only points for further processing or surface interpolation with commonly known methods:

- distance inverse,
- kriging,
- thin-plate spline,
- closest neighborhood,

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- triangulation with linear interpolation.

Interpolation terrain models from raw scanning data without filtering results in many differences between real and modeled surfaces. Based on the some filtering methods DTM or DSM interpolation can be executed too. In this work assumption of interpolating DTM and DSM from not filtered laser scanning data has been taken. Known method of moving polynomial surface was adapted to the interpolation. Surface of small rank polynomial were locally fitted to the measured data in interpolated grid point. Parameters of this polynomial were calculated using M-estimators of robust estimation. Method described in this paper has some characteristics which are important in laser scanning data processing:

- there is no data filtration before interpolation ,
- interpolation is executed using original data (without earlier data computing),
- modeled by the polynomials surfaces fit good to the local terrain structures,
- algorithm can take into consideration the break-lines (belonging to the break lines fixed points indication result in no robust estimation for this points),
- algorithm is almost full-automatic (operator define only filtration parameters),
- algorithm is not very complicated (this is important in laser scanning data processing, because there is large quantity of points, even 10^8 points).

In the next part of this paper the description of the algorithm and the DSM and DTM examples made from real laser scanning data captured above Widawa River valley will be shown.

Interpolation procedures have been implemented based on MATLAB ® (licence no.: 101979), within the processing time grant awarded by Wroclaw Centre for Networking and Supercomputing.

2 DESCRIPTION OF MOVING POLYNOMIAL SURFACE MODEL

2.1 MOVING POLYNOMIAL

In the $3D$ space every polynomial can be written as:

$$z(x,y)=\sum_{i,j} a_{i,j}\cdot x^i\cdot y^j\ , \qquad (1)$$

- $i,j=0,1,2,\ldots$,
- $a_{i,j}$ ……polynomial parameters.

Only small rank polynomials have an estimation properties. Through that second rank polynomial was used. It is called moving polynomial because every time it is matched to the closest neighbourhood of interpolated surface grid point. Used polynomial model:

$$z(x,y)=a_{00}+a_{10}\cdot x+a_{01}\cdot y+a_{11}\cdot x\cdot y+a_{20}\cdot x^2+a_{02}\cdot y^2\ . \qquad (2)$$

Parameters $a_{i,j}$ were computed separately in every grid point using least squares method:

$$\sum_{i=1}^{n} p_i\cdot v_i^2\rightarrow \min\ , \qquad (3)$$

where v_i were residues of polynomial surface and measured points:

$$v_i=a_{00}+a_{10}\cdot x_i+a_{01}\cdot y_i+a_{11}\cdot x_i\cdot y_i+a_{20}\cdot x_i^2+a_{02}\cdot y_i^2-h_i\ , \qquad (4)$$

- h_i ……height of measured point,

and p_i were weights of measured points heights. For DTM estimation these weights decrease when distance between measured and grid point increase. For DSM estimation weights increase when distance increase. The weights were calculated from formulas:

$$p_i=\left(\frac{c}{d_i}\right)^r \text{ for DTM,} \qquad (5)$$

$$p_i = \left(\frac{c}{d_i}\right)^{-r} \text{ for DSM}, \qquad (6)$$

- c ……empirical chosen parameters equal minimal or average distance between points in the whole measured points set,
- r ……empirical chosen parameter to adjust influence of measured points more distant from grid point,
- d_i ……distance of measured point from estimated surface grid point j :

$$d_i = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \;. \qquad (7)$$

Polynomial parameters were calculated from the set of equations which in the matrix notation looks as follow:

$$V = A \cdot X - H \;,\; P \;, \qquad (8)$$

- $V = [v_1 \quad v_2 \quad \dots \quad v_n]^T$,
- $X = [a_{00} \quad a_{10} \quad a_{01} \quad a_{11} \quad a_{20} \quad a_{02}]^T$,
- $H = [h_1 \quad h_2 \quad \dots \quad h_n]^T$,
- $P = diag\{p_1 \quad p_2 \quad \dots \quad p_n\}$,
- $A = \begin{bmatrix} 1 & x_1 & y_1 & x_1 \cdot y_1 & x_1^2 & y_1^2 \\ 1 & x_2 & y_2 & x_2 \cdot y_2 & x_2^2 & y_2^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_n & y_n & x_n \cdot y_n & x_n^2 & y_n^2 \end{bmatrix}$.

Using the least squares method this equation has solution:

$$X = (A^T \cdot P \cdot A)^{-1} \cdot A^T \cdot P \cdot H \;. \qquad (9)$$

2.2 ROBUST ESTIMATION

Laser scanning data has a lot of errors. Points that do not belong to the modeled surface are qualified as errors. Using least squares method polynomial parameters were calculated from bad points too. To avoid this situation robust estimation of polynomial parameters is necessary. In this method parameters were determined according to assumption:

$$\sum_{i=1}^{n} p_i \cdot q(v_i)^{(k-1)} \cdot v_i^2 \rightarrow \min \;, \qquad (10)$$

- $q(v_i)$ ……damping function,
- k ……iteration number.

Inserted function $q(v_i)$ is called function of loss. Values of this function were calculated in the iteration process in step k on the basis of residues v_i calculated in the step $k-1$. The foregoing assumption can be solved with least squares method, where heights of points in the closest neighbourhood get new weights:

$$u_i = p_i \cdot q(v_i)^{(k-1)} \;. \qquad (11)$$

After consideration modified matrix of weights (11), estimated polynomial parameters were calculated in step k of iteration process [8]:

$$X = (A^T \cdot U \cdot A)^{-1} \cdot A^T \cdot U \cdot H \;, \qquad (12)$$

- $U = diag\{u_1 \quad u_2 \quad \dots \quad u_n\}$.

Iteration process ends when parameters computed in step k are nearly the same as parameters computed in step $k-1$. This condition is realized when all differences between residues of the same points calculated in the steps k and $k-1$ are insignificant. Weights will be no more modified and the polynomial parameters do not changes anymore. Choose of right damping function is the main issue in the robust estimation. In the work three functions were used:

- Kraus function [7]:

$$q(v)=\begin{cases} 1, & |v|\le\sigma \\ \dfrac{1}{1+(\alpha\cdot|v-\sigma|)^{\beta}}, & |v|>\sigma \end{cases}, \qquad (13)$$

- α,β ……empirical chosen parameter to adjust power of weights modification,

- Gauss function:

$$q(v)=\begin{cases} 1, & |v|\le\sigma \\ e^{-(v-\sigma)^2/\sigma^2}, & |v|>\sigma \end{cases}, \qquad (14)$$

- Huber function:

$$q(v)=\begin{cases} 1, & |v|\le\sigma \\ \dfrac{\sigma}{|v|}, & |v|>\sigma \end{cases}, \qquad (15)$$

where in every case σ is the empirical chosen parameter to determine range of errors, usually equal scanning RMS error. Kraus (13) and Gauss (14) functions are asymmetrical opposite Huber (15) function. This characteristic seems to be better solution in surfaces interpolation from laser scanning data. Examples of these functions are presented on the figure 1.

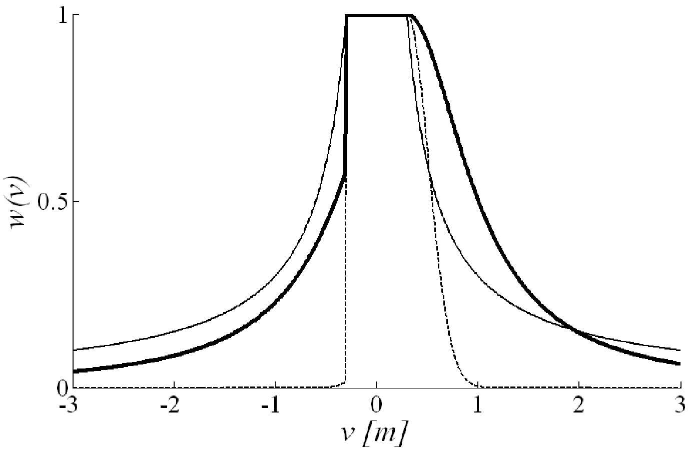

Fig. 1 Damping functions ($\sigma = 0.3\,m$): Kraus function ($\alpha = 2$, $\beta = 2$) – bold line, Gauss function – dot line, Huber function – normal line

3 NUMERICAL REPRESENTATION OF TESTING EXAMPLE

Example data comes from area where Widawa River comes into Odra River. Surfaces models were generated for area about 1 square km from raw scanning data coming from six scans and number of points is about 2 140 000 points. Models were generated in 1 m grid, but there is not 1 000 000 grid points, because DTM and DSM were created only for areas covered by the measured points. Surfaces were not generated for rivers (laser beam does not reflect from water), gaps or areas out of scanning range. The color coded projection of measured points is located on the figure 2. Modeled terrain has a forest, farm lands, dykes, rivers, embankments and other objects.

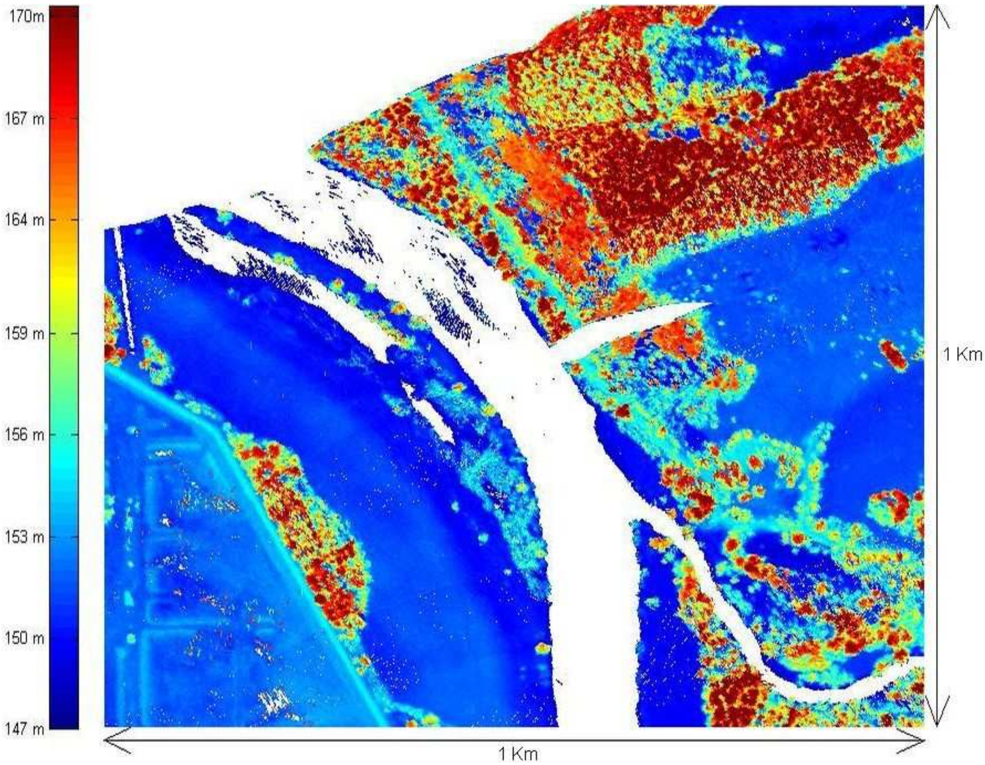

Fig. 2 Testing example – projection of measured points on the plane XY

There were no problems with generating DSM from the raw data. Local polynomials fit well to the terrain and objects on the terrain. Using weighting function as inverse of classic distance inversion function was helpful in better approximation polynomial surfaces near the break-lines. Problems appeared while DTM was creating. Using all measured points DSM instead of DTM was generated. In order to create DTM some kind of classification and removing points certainly identified as non-terrain points are necessary. It is possible through the hierarchical classification, described in: [4]. Figure 3 presents scheme of this classification.

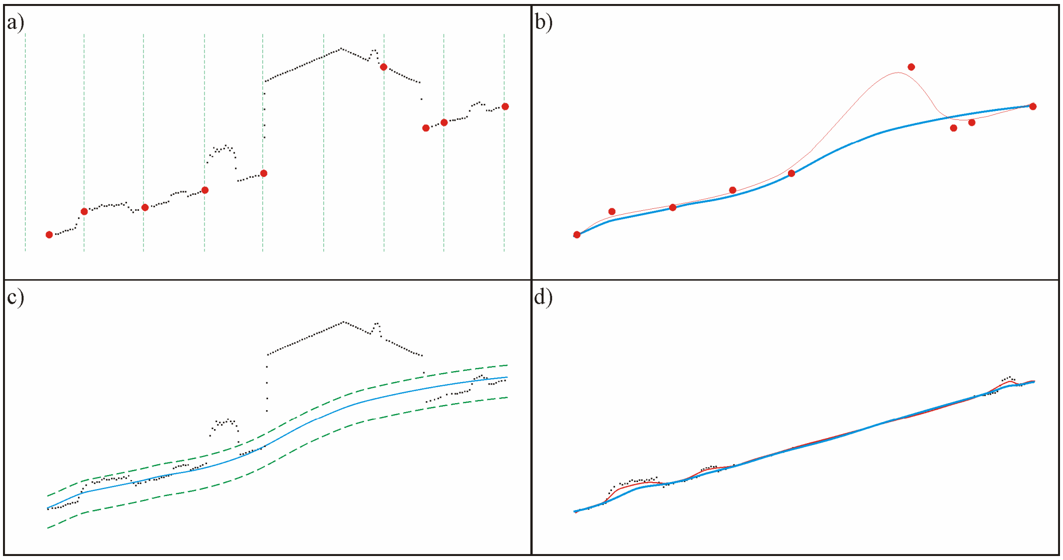

Fig. 3 Stages of hierarchical classification

Hierarchical classification is executed in 4 stages:

- partition whole area to the smaller sub-areas and chose for each sub-area one representative point (point with smallest height) (figure 3a),
- heights interpolation in each representative point using moved polynomial surface (figure 2b), the terrain trend (without human-made structures) is created,
- removing all points, that were not included in the cache of terrain trend (all local structures must be included in the cache) (figure 3c),
- heights interpolation in grid points using moving polynomial surfaces locally approximated to the non-removed points (figure 3d).

This way suitable DTM was created without objects existing on bare earth. Algorithms of interpolating height in each grid point for digital surface or digital terrain models were executed according diagram shown on figure 4.

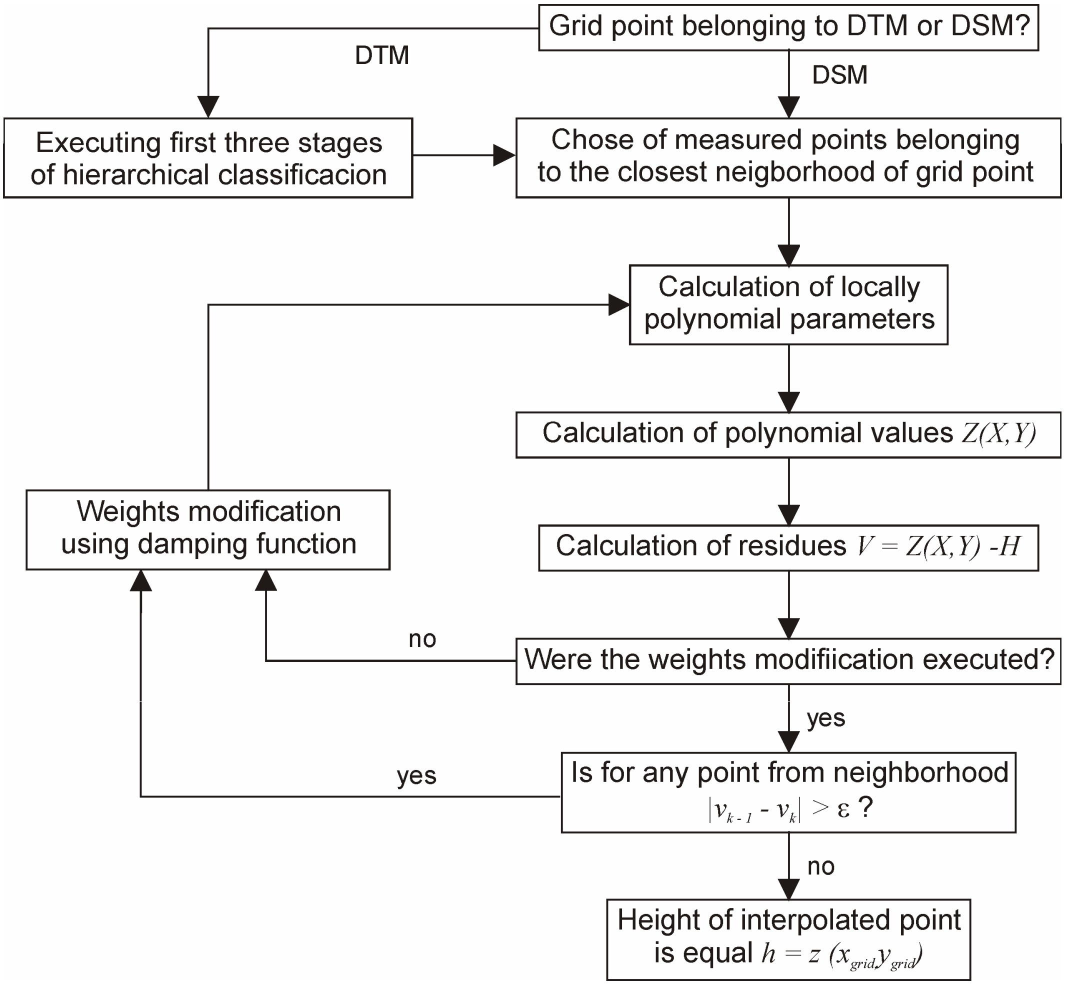

Fig. 4 Diagram of height interpolation in one grid point of DTM or DSM

In the presented test example square 10 m x 10 m was chosen as local neighbourhood to approximate moving polynomial. The other parameters were as follow:

- to the hierarchical classification square 40 m x 40 m as sub-area was chosen,
- cache 6 m above and 3 m below trend (embankments and dykes held whole in the cache),
- in weighting function parameters $c = 1$ and $r = 0.5$,

- scanning RMS error $\sigma = 0.3\,m$,
- as damping function Kraus (13) function with parameters $\alpha = 2$, $\beta = 2$ was chosen (Gauss (14) and Huber (15) functions were tested too, but Kraus function is more elastic due to the free choice of parameters),
- relevant residue $\varepsilon = 0.3\,m$,
- maximal number of iteration were 20, iteration process were not executed after 20 iteration, although residues were bigger than relevant residue, but polynomial parameters were quite good estimated and the interpolated height was correct.

Figure 5 shows generated DTM and figure 6 presents generated DSM. Models are created of 772 426 points in regular 1 m grid. Nevertheless interpolation is possible in irregular grid too.

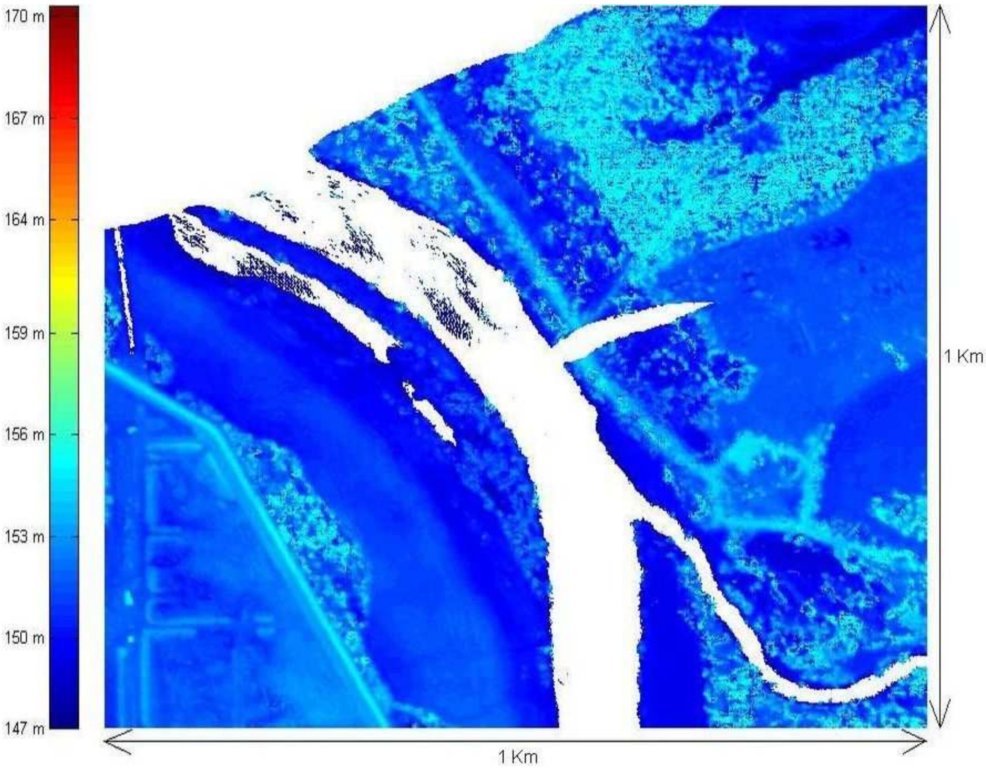

Fig. 5 Digital terrain model (color coded)

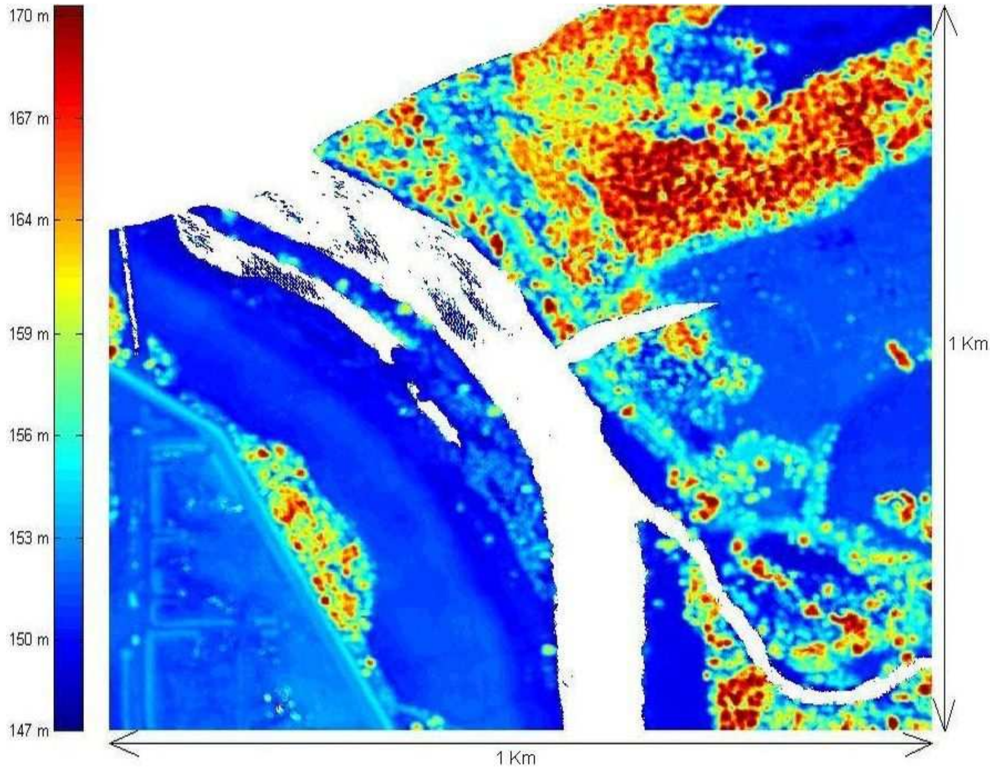

Fig. 6 Digital surface model (color coded)

Whole digital surface model is well created. Digital terrain model in some places have small errors – where dense forests were removed from terrain model. Other areas were modeled correctly.

4 CONCLUSION

In the work interpolation DTM and DSM method has been presented. All heights of points of regular grid were calculated from the equations of polynomials surfaces approximated to the measured points. Polynomials parameters were determined using robust estimation and the best result gave Kraus function.

Creating terrain surface model (bare earth and objects on it) was easier than creating terrain model (bare earth). The reason for this is that, because in some places (buildings, forests) there were no points or very few points reflected from terrain. In these situations more points were reflected from objects existing on the terrain. In this case hierarchical classification is helpful and necessary. In this way points certainly identified as non-terrain points were eliminated and the quantity of terrain points become larger than quantity of non-terrain points. When there were more points reflected from bare earth local polynomial surface matched better to the real terrain and the interpolation results in better effect. Nevertheless there are still problems with good DTM creating on the forests areas, because a lot of "good" points are needed to determine correct polynomials parameters. The method to avoiding this situation will be point of next research. Problems happens with small vegetation, but it is due to scanning resolution. It is very hard to recognize if point was reflected from grass or from terrain, because height of grass is in range of scanning RMS error. Beside these shortcomings, digital models were created correct. Break-lines like embankments or dykes exist on the created DTM too.

When DSM and DTM are generated it is very simple to create DEM (digital elevation model). DEM is the difference between surface and terrain models. Digital elevation model can be applied in various domains same as DTM and DSM.

Interpolation with use of moving polynomial surface model is an easy method for generating DTM and DSM from raw airborne laser scanning data. To make this algorithm more efficient it is possibility to use additional information as total-station measured points and adding it as fixed points to the points cloud. Moving polynomial surface method can be used for filtering airborne laser scanning data.

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