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Digital terrain model of the Second Military Survey.  
Two model territories: the surroundings of the town Rokycany and part of the military training area Brdy.

Keywords: Digital terrain model; hachure; spot height; hypsometry; Second Military Survey.

Summary
The Second Military Survey (ordered by Emperor Francis II) in the territories of the former Austrian-Hungarian Monarchy progressed between 1806 and 1869. The territory of Bohemia was surveyed from 1842 to 1852 (267 handwritten colour sections 1:28 800) and Moravia and Silesia from 1836 to 1840 (146 handwritten colour sections 1:28 800). The aim of the paper is to propose and describe the methodology of creating the digital terrain model (DTM) from the Second Military Survey hypsometry and to analyze its accuracy. A part of the longstanding military training area Brdy and the surroundings of the town Rokycany were chosen as model territories. The two resulting DTMs were compared with the recent reference digital ground model – DMR ZABAGED®. The conformity of terrain relief forms and elevation accuracy of the DTM derived from the Second Military Survey hypsometry were also investigated. New methodology of creating the DTM from the hypsometry of the Second Military Survey makes it possible to create a digital terrain model of the original relief of the landscape dating back to the time of the completion of the respective map sheets (the first half of the 19th century).

The Second Military Survey
The fundamental characteristics of the Second Military Survey Maps

The Second Military Survey was launched on 2nd April 1806 by a decree of Emperor Francis II (Hofstätter 1989: 61). The Second Military Survey in the territories of the former Austrian-Hungarian Monarchy progressed between 1806 and 1869. In the territories where the cadastral survey was completed (including Bohemia, Moravia and Silesia), the outcomes were exploited for the military survey. Reduced and generalized planimetric content from the cadastral maps and cadastral triangulation was used to outline the planimetric content of the Second Military Survey. This assured an improved positional accuracy and better work economy.

The territory of Bohemia was surveyed between 1842 and 1852 and Moravia and Silesia between 1836 and 1840. Original map sections in scale 1:28 800 for Bohemia (267 handwritten colour sections), Moravia and Silesia (146 handwritten colour sections) are kept in the map collection of the Austrian State Archives – Military Archive in Vienna (Österreichisches Staatsarchiv – Kriegsarchiv Wien), (Vichrova and Cada 2010: 606 - 607).

The Second Military Survey provides a complex image of the Czech Republic before the peak of industrial and agricultural revolution. The map sheets of Bohemia, Moravia and Silesia were completed within only 16 years. Such a quick process of mapping was possible thanks to changes in technology, especially by taking over the results of cadastral triangulation and ongoing or

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completed cadastral survey. The fundamental characteristics of original and modified technologies of surveying in Bohemia, Moravia and Silesia are shown in Figure 1.

<table>
<thead>
<tr>
<th>Original concept</th>
<th>Characteristics</th>
<th>Modified Concept</th>
</tr>
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<tbody>
<tr>
<td>military</td>
<td>triangulation</td>
<td>cadastral</td>
</tr>
<tr>
<td>St. Stephen</td>
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<tr>
<td>topographic survey with a plane table</td>
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<td>use of cadastral planimetry</td>
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<tr>
<td>original</td>
<td>section indexing</td>
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</tr>
<tr>
<td>63 x 42 cm</td>
<td>size of one map sheet</td>
<td>52,7 x 52,7 cm</td>
</tr>
<tr>
<td>221 km²</td>
<td>area displayed in a map sheet</td>
<td>230 km²</td>
</tr>
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</table>

Figure 1. Fundamental characteristics of original and modified technologies of surveying.

**Hypsometry on the Second Military Survey Maps**

The Saxon topographer Johann Georg Lehmann defined, described and unified the theory, which was subsequently published in the articles: *Darstellung einer neuen Teorie der Bezeichnung der schiefen Flächen im Grundriß oder der Situationszeichnung der Berge* (Lehmann 1799) and *Darstellung einer neuen Teorie der Bezeichnung der schiefen Flächen im Grundriß oder der Situationszeichnung der Berge* (Lehmann 1812).

Johann Georg Lehmann chose for the 2D representation of terrain shapes black hatches on a white background. The width of the hatches (the amount of black) on the surface was directly proportional to the value of the slope; the direction of hatches was analogous to the water flow on the surface of an elevated terrain shape. For the convenience of the topographer’s work and map reading, out of the slope from the map Lehmann prepared the tables with the ratios of black and white and the corresponding value of the slope between 0° – 45°, in increments of 1° (Lehmann 1799: 102-103) and of 5° (Lehmann 1812: 25). The final table allowed for the estimation of the slope angle in an assigned locality by a naked eye (Fig. 2).

![Figure 2. Original Lehmann’s table with ratios of black and white for the slope between 0° and 45° (Lehmann 1812: 25).](image)

Elevated terrain forms were surveyed from the lowest place towards the highest. At first, the horizontal lines were staked out in the terrain and then drawn into the map from the foot towards the
top. Then values of the slope were recorded. Afterwards, the hachures were drawn and auxiliary drawings (horizontal lines, values of the slope) were removed in the office, (Vichrova and Cada 2011).

The hachures in the maps of the Second Military Survey were created by means of the modified Lehmann’s scale. They portray not only the direction of the maximum gradient but also the slope of the terrain. The slope is portrayed by the functionally dependent length and thickness of the hachures, and the distances between them are according to the precise scale (Vichrova and Cada 2011). The representation of the landforms in the maps of the Second Military Survey was accomplished by spot heights chosen mostly from points of geodetic control. The heights in the map sheets of Bohemia, Moravia and Silesia are produced according to the modified technology in units of Viennese fathoms with an accuracy of two decimal points (Fig. 3). In the map sheets that represent a part of South Bohemia – Vitorazsko, which were made according to original technology, no spot height is available.

The representation of the terrain in maps using hachure gives a true plastic image of the terrain, as well as objective and visual information about the permeability of the area. The disadvantage of this method is a high graphical load of the map sheet.

**The methodology for creating the DTM from hypsometry of the Second Military Survey**

The methodology for creating the DTM from hypsometry of the Second Military Survey comprises the four following steps:

- Identification of the horizontals and skeleton elements of terrain relief in existing hypsometry,
- fragmentation of areas with a constant slope of terrain relief,
- determination of elevations of horizontal lines using the least squares method,
- creation of the digital terrain model.

**Identification of horizontals and skeleton elements**

The skeleton elements of the terrain for the whole of the model territory (the ridge lines, fall lines, valley lines and the valley lines as a water flow) were identified and digitalized in the map. Next, the boundary lines of hachure layers, recognized as the horizontal lines were digitized (Fig. 4).
The fragmentation of areas with a constant slope of terrain relief comprises the following steps:

1. Transfer of the map drawing from colour to grayscale expression.
2. Adjustment and colour correction of the map drawing (with removal of some planimetric objects and descriptions from the map): the planimetric objects were removed from the map and these objects were replaced by hachures similar to those in the vicinity of the object. The descriptions were removed from the map too, because they were represented in black colour and would substantially skew the areas of constant slope (Fig. 5). It was also necessary to take the colour of the background into account. Using colour histograms the background colour was set as white and the colour of hachure as black. It is obvious that leaving the planimetric objects and descriptions in the map drawing and omitting the colour correction would reduce the accuracy of the areas of constant slope and the resulting digital terrain model as well.
3. Blurring of the map drawing.
4. Setting of limits for grayscale intervals, see Muster-Blätter, 1831-1840, sheet 8.
5. Fragmentation of areas of constant slope, in increments of 5°.
6. Choice of colour scale.

Points on the borderlines of hachures (where value of the slope has changed) were identified on selected line elements of the terrain skeleton. Between such points height differences on the ridge lines, fall lines and, where necessary, on the selected valley lines were calculated using a rectangular triangle. The valley lines passing the ravine were suitable for calculating the height difference, because they respect the direction of hachure as parts of fall lines. The valley lines passing through the narrow valley, often with water flow and rocky watersides, were unsuitable for calculating the height differences (Vichrova and Cada, 2011).
In view of the potential for discoloration or other colour changes of map drawings and background papers of old maps, it was very important to take into account the relative relations between hachure layers when determining the slope values. Hereafter it was very important to take into account presence of rocks and detritus fields, because these objects disturbed the areas of constant slope. Considering the local changes of hachures caused by removing some planimetric objects and descriptions from maps, it was very important to consistently follow the falling and climbing of the terrain, especially on the top parts of mountain ridges.

In the next step the partial height differences were calculated between the points on the lines of the terrain skeleton on the boundary of hachure layers. Then the height differences between nodal points of the network were calculated by summarising partial height differences. The complete network was adjusted by a minimum square method so that determination of the nodal point heights was not independent of the calculation mode.

The network contained trigonometric stations with fixed value of their heights, unknowns (heights of the nodal points) and especially the corrections \(v_i\) for each height difference were solved for the calculation of the mean error of adjusted height difference \(m_{0v}\), according to:

\[
m_{0v} = \sqrt{\frac{v^T \cdot v}{r}} \quad \text{(Equation 1)}
\]

where

\[\vec{v} = A \cdot \vec{dh} + \vec{L} \quad \text{is the vector of height difference corrections,}\]
\[v^T \quad \text{is the transposed vector,}\]
\[A \quad \text{is the matrix of determined height difference directions,}\]
\[\vec{dh} = - (A^T \times A)^{-1} \times A^T \times \vec{L} \quad \text{is the vector of corrections of the approximate heights of nodal points,}\]
\[\vec{L} \quad \text{is the vector of height differences of nodal points,}\]
\[r \quad \text{is the difference between number of equations and unknowns.}\]

The partial height differences summarized between the layers of hachures (on the border lines of the constant slope areas) were adjusted proportionally to the values of partial height differences. Then (proportionally to the value of slope) the height was matched to each horizontal line or a part of horizontal line that intersects the line of terrain skeleton in a concrete area.

Creating the digital terrain model (DTM)

Horizontal lines and parts of horizontal lines with calculated heights were used for the creation of the digital terrain model derived from the Second Military Survey maps. Heights displayed at trigonometric stations were applied as well. The digital terrain model derived from the Second Military Survey maps was computed by means of MicroStation V8i – InRoads Suite. At first the triangulated irregular network (TIN) was generated and edited and then the digital terrain model (DTM) was created.
Digital terrain model of the Second Military Survey

Two model territories were selected for creating the DTM from the Second Military Survey.

1. Surroundings of the town Rokycany (total area 50.7 km$^2$, parts of map sheets W_III_10 and W_III_11), see Figure 6. The territory was chosen deliberately as an example of area with settlements and significant changes in the terrain caused by human activities.

2. Part of the military training area Brdy (total area 124.1 km$^2$, a part of the map sheet W_II_11). This territory (Fig. 6) is situated in surroundings of the ponds called “Padrtske rybníky” and to north-east of them. The chosen model territory has been part of the military area Brdy for a long time and is very sparsely populated for that reason. The territory was chosen deliberately because there are no significant changes in the terrain caused by human activities. The terrain is very diverse with some interesting morphological shapes.

![Figure 6. The Model territories: blue - surroundings of the town Rokycany (parts of map sheets W_III_10 and W_III_11), green- part of military training area Brdy (a part of map sheet W_II_11).](image)

**DTM - surroundings of the town Rokycany**

For the creation of the DTM – surroundings of the town Rokycany 63 equations were generated for the adjustment of the network. The network contained 5 trigonometric stations (Čilina B., Kotel B., Na Wrchu, Wossetzkei Wrch, Zdiar B.) with fixed value of their heights. 38 unknowns (heights of the nodal points) and especially the corrections ($v_i$) for each height difference were solved for the calculation of the mean error of adjusted height difference according to Eq. 1:

$$m_{\text{Rokycany}} = \sqrt{\frac{v^2}{r}} = 2.06 \text{ m}$$

Horizontal lines and parts of horizontal lines with calculated heights were used for the creation of the digital terrain model derived from the Second Military Survey maps, heights displayed at 5 trigonometric stations were applied as well. The digital terrain model derived from the Second
Military Survey maps was computed by means of *MicroStation V8i – InRoads Suite*. Initially, the triangulated irregular network (TIN) was generated and edited and then the digital terrain model (DTM) was created (Fig. 7).

![Digital terrain model of the Second Military Survey - surroundings of the town Rokycany.](image)

*Figure 7. Digital terrain model of the Second Military Survey - surroundings of the town Rokycany.*

**DTM - part of the military training area Brdy**

For the creation of the DTM – part of the military training area Brdy 133 equations were generated for the adjustment of the network. The network contained 10 trigonometric stations (*Brag B.*, *Brda B.*, *Hlawa B.*, *Kamenna, Kocka B.*, *Korona, Na Skalach, Pacir, U Svatyho Jana, Tock*) with fixed value of their heights. 81 unknowns (heights of the nodal points) and especially the corrections ($v_i$) for each height difference were solved for the calculation of the mean error of adjusted height difference according to Eq. 1:

$$m_{Brdy} = \sqrt{\frac{v^2}{r}} = 4.84 \text{ m}$$

As before, horizontal lines and parts of horizontal lines with calculated heights were used for the creation of the digital terrain model derived from the Second Military Survey maps, heights displayed at 10 trigonometric stations were applied as well. The DTM (Fig. 8) was created following the procedure described in the previous.
Comparing the digital terrain models of the Second Military Survey with the reference model

The reference model ZABAGED

Both digital terrain models of the Second Military Survey were compared with the recent reference digital ground models – DMR ZABAGED®. The Land Survey Office in Prague provided the reference data DMR ZABAGED for the model territory surrounding of the town Rokycany (2D contour lines with basic interval i = 2 m, format *.shp) and for the model territory part of the military training area Brdy (3D spatial contour lines with basic interval i = 5m, format *.dgn).

According to Sima (2009: 218), the accuracy of DMR ZABAGED hypsometry (1994 - 2000) is defined with the mean error of height:

- 0.7 – 1.5m in the uncovered terrain
- 1 – 2m in the built-up area
- 2 – 5m in the continuous forested area

The DMR ZABAGED improved hypsometry (since 2005) has the same parameters, but with more details. More information about accuracy of DMR ZABAGED is available in Brazdil (2009).

Using the DMR ZABAGED hypsometry data, the reference digital terrain models in MicroStation V8i – InRoads Suite were derived as a generalized and edited triangulated irregular networks (TIN). When comparing the reference DMR ZABAGED and digital terrain model of the Second Military Survey, it was established that both models are identical in basic forms. It is possible to see some differences in details caused by the different scale of both products (ZABAGED 1:10 000, the Second Military Survey 1:28 800) and the different representations of hypsometry on the maps. Especially the rock forms at top of elevations and terrain steps on the
hillsides are represented in the maps of the Second Military Survey only schematically by hachures according to the modified Lehmann’s scale and often by a map symbol.

*The differential digital terrain models*

The differential digital terrain models (DMR ZABAGED minus DTM of the Second Military Survey for both model territories) were created using *MicroStation V8i – InRoads Suite*. The height differences were displayed by means of colour scale with 3m (Fig. 9, Fig. 10).

![Figure 9. Differential digital model – surroundings of the town Rokycany (extremes).](image)

The local extremes are squared off with brown lines and are numbered:
1. Local extremes caused by the positional error and especially by differences in terrain forms,
2. local extremes on the top part of the elevation caused by the incidence of rocks,
3. local extremes in the valley; it was very difficult to identify extremes from horizontal lines (the boundary lines of hachures) and to determine the slope on the lines of the terrain skeleton with sufficient accuracy because valley lines were unsuitable for such a task,
4. Local extremes in places where the wrong value of the slope was determined. Probably hachures for other slopes were drawn in this place, or the wrong value of the slope was read out in the course of processing.

5. Local extremes caused by wrong quality of map drawing, it was very difficult to identify the horizontal lines and the direction of hachure.

It is evident that the reasons of presence of local extremes could combine.

Using both differential digital models, total areas for each interval of height difference were computed. The generation of the graph for model territory surroundings of the town Rokycany followed (Fig. 11). The maximum values of areas belong to intervals (-3; 0) and (0; 3). In addition, Figure 11 illustrates that the set of values is not conformal with normal distribution.
The generation of the graph for model territory part of military training area Brdy followed (Fig. 12). The maximum values of areas belong to intervals (-6; -3) and (-3; 0). The existence of a systematic error in this data set is evident. In addition, Figure 12 illustrates that the set of values is conformal with normal distribution.

![Figure 12. Areas of differential digital model for corresponding height interval in square metres (part of the military training area Brdy).](image)

**Conclusion**

The Second Military Survey maps of Bohemia, Moravia and Silesia provide a complex image of the countryside before the peak of the industrial and agricultural revolutions at a time when the country was not so much influenced by human activities. All these influences and many others influenced the image of the country and the content of the maps of the Second Military Survey. These maps are very valuable and unique sources of information and are a valuable source of information for professional historians, archaeologists, geographers, landscape ecologists, planners, and more.

The described methodology of creating the digital terrain model of the Second Military Survey makes it possible to create a digital terrain model of original relief of the landscape dating back to the time of the completion of the respective map sheets (the first half of the 19th century). The method of creating the DTM of the Second Military Survey allowed us to obtain a digital model of the “previous landscape relief” anywhere in the Czech Republic that can be reliably used by many experts including geographers, landscape ecologists, historians and archaeologists.

This new method of creating the DTM of the Second Military Survey can be also used in territories where the terrain was represented only by hachures according to the modified Lehmann’s scale and no heights of triangulation stations are at disposal. In such a case it is necessary to supplement the heights from other available sources (e.g. spot heights in maps of the Third Military Survey or DATAZ – Database of trigonometric a densification points, [http://dataz.cuzk.cz/](http://dataz.cuzk.cz/)). In the case of an insufficient number of trigonometric points in the area of interest it would be necessary to determine identical points in the terrain which could be considered as position- and height- invariant since the time of creating the Second Military Survey maps.

DMT derived from hypsometry of the Second Military Survey can be exploited in projects of revitalization of areas significantly affected by human activities such as those affected by surface mining, currently flooded areas or built-up areas, for implementation of landscape treatment, for
landscape planning and landscape protection. This product may be useful for archaeologists, historians, landscape environmentalists and other specialists.

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