

LANDSCAPE AS A HISTORICAL OBJECT: 3D RECONSTRUCTION AND EVALUATION OF A RELIEF MODEL FROM THE 18TH CENTURY

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ABSTRACT:

The relief of Franz Ludwig Pfyffer, constructed between 1762 and 1786, is considered the world's oldest large landscape model and a pioneering work of Swiss cartography. Based on Pfyffer's own measurements, the 26 m² big work represents topographically an area of almost 4100 km². The relief, which served as a basis for several printed maps issued at the end of the 18th century, is now a subject of the first quantitative evaluation. Applying principles of aerial photogrammetry, a precise 3D model of Pfyffer's relief is created for the documentation of cultural heritage. As a main research aim, methods for the comparison of the virtual model with current map information are implemented: planar and spatial transformations of identical points and an analysis of digital surface models. In particular, a new procedure for the transformation of historical height and image data has been developed and evaluated. Suggested approaches consider object distortions in all three directions and allow making statements about relief accuracy as well as reconstructing Pfyffer's model building strategy.

1. INTRODUCTION

Old maps, charts and 3D models have traditionally been a subject of study by the historians. These masterpieces combining art and a great knowledge of surveying and cartography currently receive deserved attention of scientists as well. In particular, photogrammetry and digital image processing are being used to extract metrical and semantic characteristics of historical maps (for example see Fuse, 1998; Shimizu, 1999; Baletti, 2000 and Rickenbacher, 1995). This paper addresses the three-dimensional aspect of historical cartography and focuses on the image-based reconstruction and geometrical evaluation of one of the most remarkable landscape models in history – the relief of Franz Ludwig Pfyffer.

Historical reliefs can be considered a direct ancestor of present virtual models. At the end of the 18th century, the bird-eye view at a landscape in the form of a relief was a special, unique experience comparable with our today's enthusiasm for virtual reality. The fascination of exploring and analysing the third dimension of the mountainous area of Switzerland - once surely stimulation for the construction of Pfyffer's relief - has motivated this research.

2. PFYFFER'S RELIEF OF SWITZERLAND

Lieutenant general Franz Ludwig Pfyffer von Wyher (1716-1802) devoted 20 years of his life to the construction of a relief of Central Switzerland (Figure 1). The result of his surveying and cartographic work is a 6.7 x 3.9 m² big model of Lake Lucerne and neighbouring cantons with a maximal elevation range of about 30 cm. It displays as much as 1/10 of the country in a scale of about 1:11500. Finished in 1786, Pfyffer's relief attracted numerous visitors from all over Europe to Lucerne: *"One of the most impressive sights is to be seen in the general Pfyffer's flat; namely, a topographic representation of a big part of the federation, highly admired by experts. It is up to the*

last detail correct and contains all the mountains, lakes, rivers and villages, as well as each cottage, bridge and road; even every cross is accurately and clearly depicted." (Leu, H. J., 1788). This masterpiece is a significant improvement of existing maps at that time and as such it served as a basis for several printed works issued at the end of 18th century. A detailed study of Pfyffer's relief probably played an important role in the victorious battle of French troops against the Russian field marshal Alexander Suvorov in the mountainous St. Gotthard region in 1799. As a strategic cartographic object, the French commander Napoleon Bonaparte planned to buy the relief in 1805 (Imhof, 1981). Fortunately, at that time better map information was already available and the model stayed Swiss property. Today it is on display in the Gletschergarten Museum in Lucerne as the world's probably oldest large landscape model.



Figure 1. A view on the 26 m² large Pfyffer's relief

Unlike many latter gypsum models, the relief of Franz Ludwig Pfyffer is constructed from pieces of timber, bricks, charcoal and cardboard with a wax mixture as a top layer. Thin cords and chenille indicate roads, rivers and railway lines. Other landscape objects such as churches, houses and bridges are thoroughly modelled using coloured beeswax (Figure 2). The relief surface is painted with tempera and oil colours.



Figure 2. A detailed view on Pfyffer's relief – the city of Lucerne by the Lake Lucerne



Figure 3. Image acquisition

Within a project supported by the Swiss National Science Foundation and local cultural authorities, the relief and its constructor Franz Ludwig Pfyffer are subjects of an interdisciplinary research. The Institute of Geodesy and Photogrammetry of ETH Zurich is involved with following tasks:

- 3D reconstruction of the relief for the documentation of the cultural heritage
- Analysis of the relief accuracy for the purpose of research in the history of cartography – a comparison of the reconstructed virtual relief with current map information (digital maps and terrain models)
- Investigation on Pfyffer's surveying and model constructing procedures (outside the scope of this paper)

3. 3D RECONSTRUCTION AND VISUALIZATION

The project objectives require a high quality 3D model of Pfyffer's relief in terms of accuracy. The overall height difference between the reconstructed model and the original may amount to a maximum of 1 mm. Represented by around 11.5 m in reality, this value approximately corresponds to the accuracy of available national DTM in alpine regions. Thus, a comparison of the historical and present terrain models in the analytical project phase (see Chapter 4) can bring reasonable results.

3.1 Data acquisition

The relief is situated in a narrow cellar room without natural light on a table about 65 cm over the ground. These conditions make the image acquisition as well as control point measurement rather difficult. From a 185 cm high construction, 87 analogue and 50 digital "aerial" coloured images were taken, both providing stereo overlap for the whole object (Figures 3 and 4, Table 1). Both cameras were calibrated using a close-range photogrammetric reference field. To avoid disturbing specular reflection of the shiny relief surface, spotlights in a combination with dispersion umbrellas were used for indirect illumination. In spite of this, particularly the digital images show up rather big reflection and worse radiometric quality than their sensitive film-based counterparts.

The three-dimensional position of 40 marked control points temporarily placed onto the relief surface was determined by theodolite measurements in a local coordinate system with an accuracy of 0.09 mm. Considering the unfavourable space conditions leading to flat and wide-angled rays this result is satisfactory and sufficient for further processing.



Figure 4. A part of an analogue image (scanned with 1270 dpi)

Camera	Analogue Rollei 6006	Digital DSC460c
Calibrated focal length	83.557 mm	28.871 mm
Number of images	87	50
Number of strips / number of images per strip	4/13 +35 additional images in mountainous areas	5/10
Image size	6 x 6 cm ²	3060 x 2036 pixel
Scale / Pixel footprint	1:23	0.6 mm

Table 1. Parameters of acquired images

3.2 Photogrammetric processing and visualization

For reasons of high quality requirements the analogue images were selected as a basis for the photogrammetric processing. The whole block was triangulated manually on an analytical plotter. The achieved accuracy of 7.62 microns corresponding to 0.17 mm in object space is good enough. Currently, the manual DTM measurement is in work. Using measurements of parallel profiles with a distance of 1 cm, about 280000 points have to be measured. Additionally, breaklines and extracted structured vector data (roads, rivers, lake outlines, settlements etc.) will be integrated into the DTM.

In the following the data processing and results achieved within a pilot project will be presented. In order to develop an optimal methodology for the reconstruction of the whole object, a part of the relief (180 x 130 cm², area of the city of Lucerne, Mt. Pilatus and Lake Lucerne) was reconstructed. Two independent

blocks of analogue images in a scale of about 1:25 (8 images in two strips) and 1:30 (5 images in one strip) respectively were acquired and processed as follows:

3.2.1 Aerial triangulation. After scanning of all 13 images with a resolution of 1200 dpi, both blocks were triangulated semi-automatically using several digital photogrammetric systems (Match-T, SocetSet, Phodis) as well as manually on the analytical plotter.

3.2.2 DTM generation. The DTM generation with 05 cm raster width was performed for both blocks automatically using several commercial systems. As a reference, a part of the model was measured manually on the analytical plotter. A comparison of the results shows that the automatic procedures do not bring required performance in this case. The height differences between automatically derived models and a manually measured reference rise up to 6 mm in a data set with a maximal elevation range of about 160 cm. However, using manual measurements, the theoretical accuracy of 0.3 mm (0.15% of the flight height above ground) can be expected. Main reasons for the problems of commercial image matchers are distinct height differences and the low contrast in the relief. As mentioned before, a very precise DTM is needed and therefore we distorted to manual measurements in the main project phase.

3.2.3 Orthoimage generation. For orthoimage generation and mosaicking the system SocetSet of LH Systems was used. The pixel footprint of 0.5 mm assures that even the smallest object details are clearly visible.

3.2.4 Extraction of 3D vector data. In order to get a vector data set for the accuracy analysis of Pfyffer's relief, significant relief features like roads, rivers, lakes and settlements were captured three-dimensionally.

3.2.5 Texture mapping and visualization. Mapping the orthoimage onto the DTM, a variety of visualization products were derived (Figures 5 and 6): anaglyph images, interactive VRML models and flyovers. A virtual flight over the reconstructed relief or an online navigation in the model is nowadays as fascinating as in the age of Franz Ludwig Pfyffer the relief itself.



Figure 5. The 3D texture-mapped model of the reconstructed part of the Pfyffer's relief

4. ACCURACY ANALYSIS OF THE RELIEF

In order to estimate the accuracy of Pfyffer's relief, the reconstructed model must be compared with current map information. Considering relief distortion in all three directions, various methods of planar and spatial geometric transformations

have been implemented and solutions are proposed in the following. In particular, a comparison of the historical terrain model with the current data represents a new problem in the historical cartography: rather than rectifying and georeferencing a planar old map, the 3D model has to be analysed. An important goal of accuracy analysis is a good visual presentation of the work; the methods and results must be easily understandable for project partners – historians with less technical background. As programming languages C and Matlab are used. The input data and all the results are georeferenced, maintained and visualised in ArcView GIS.

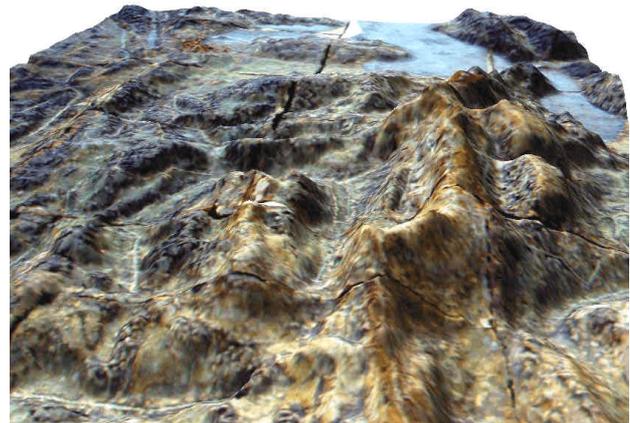


Figure 6. A detailed view on the reconstructed relief part

Two data sets are used for the comparison:

1. Historical data: results of photogrammetric 3D reconstruction within the pilot project, i.e. DTM of 0.5 cm grid width, orthoimage of 0.5 mm footprint (3570 x 2550 pixel) and structured 3D vector data. The data set covers an area of about 180 x 130 cm².
2. Current data: national DTM of 25 m grid width, digital map 1:25000 with 2.5 m footprint and vector data VECTOR25. The data set covers an area of about 25 x 25 km².

The accuracy analysis of Pfyffer's relief is based on a number of identical points selected according to principles of historical cartography. The described procedures include definition of identical points, determination of absolute relief accuracy and comparison of terrain models.

4.1 Definition of identical points

Identical points are objects in Pfyffer's relief, which in reality have been existing for centuries and which can reliably be found in both data sets: churches, crossings, mountain peaks, bridges etc. For each point, 3D coordinates x , y , z of historical data in the local system and X , Y , Z of current data in the national coordinate system are stored. Additionally, identical points are assigned to one of three categories according to their estimated reliability. In co-operation with historians, overall 57 well distributed identical points were defined in the used data set (Figure 7).

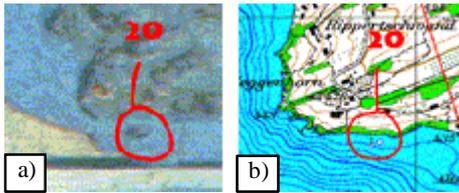


Figure 7. A chapel on a lake island as a reliable identical point: a) in Pfyffer's relief, b) in the 1:25000 map

4.2 Determination of absolute relief accuracy

To determine the absolute accuracy of Pfyffer's relief, identical points have been transformed using several coordinate transformations with weighted observations: planar Helmert (Equation 1), planar affine (Equation 2), spatial Helmert (Equation 3) and general spatial 9-parameter (Equation 4) transformation.

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} d_x \\ d_y \end{pmatrix} + m_{xy} \cdot R(\mathbf{a}) \cdot \begin{pmatrix} x \\ y \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} d_x \\ d_y \end{pmatrix} + \begin{pmatrix} m_x \\ m_y \end{pmatrix} \cdot R(\mathbf{a}, \mathbf{b}) \cdot \begin{pmatrix} x \\ y \end{pmatrix} \quad (2)$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} + m_{xyz} \cdot R(\mathbf{a}, \mathbf{b}, \mathbf{g}) \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix} + \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} \cdot R(\mathbf{a}, \mathbf{b}, \mathbf{g}) \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (4)$$

where x, y, z = coordinates in historical data set
 X, Y, Z = coordinates in current data set
 d_x, d_y, d_z = shifts in three coordinate directions
 m_x, m_y, m_z = scales in three coordinate directions
 α, β, γ = rotation angles
 R = rotation matrix

Starting with planar Helmert and ending up with general spatial transformation, additional unknowns were successively estimated in the transformation model. Visualisation of results has shown that orientation and amount of differences on identical points are of random nature. Therefore no polynomial transformations are applied: additional coefficients would perhaps decrease the residuals and improve the statistics, however, their use would deform the model what in this case would not be meaningful. We suppose that Franz Ludwig Pfyffer, constructing his relief at the end of 18th century without any reliable topographic base could be wrong in scales, rotations and shifts in three coordinate directions – and that is in accordance with parameters of the general spatial transformation. The implementation of the spatial projective transformation by adding two more parameters to the linear model is planned.

The best results were achieved with the general spatial transformation (Table 2). The 51 tested points deviate from the current map in average of absolute values about 180 m in the plane and 63 m in the height, corresponding to 1.6 and 0.5 cm within the object. Considering the conditions under which the relief was constructed – a definitely unfavourable age for landscape exploration and surveying, poor available maps and a very large area modelled in detail – Franz Ludwig Pfyffer's achievement is even from today's point of view admirable. Another surprising result of the accuracy analysis is the unity of relief scales in three coordinate directions (1:11420 in X, 1:11590 in Y and 1:11590 in Z): unlike previous assumptions the heights of the tested relief part are not magnified. For the visualization of residuals on identical points after general spatial 9-parameter transformation see Figure 8.

	σ_0	Average X	Average Y	Average Z
	in reality	in reality	in reality	in reality
Helmert 2D	220 m	198 m	161 m	-
	1.9 cm	1.7 cm	1.4 cm	-
Affine 2D	216 m	193 m	172 m	-
	1.9 cm	1.8 cm	1.5 cm	-
Helmert 3D	188 m	198 m	162 m	63 m
	1.6 cm	1.7 cm	1.4 cm	0.6 cm
General 3D	188 m	197 m	162 m	63 m
	1.6 cm	1.7 cm	1.4 cm	0.5 cm

Table 2. Absolute relief accuracy (results of transformation of identical points with weighted observations): sigma a-posteriori and average differences in absolute values

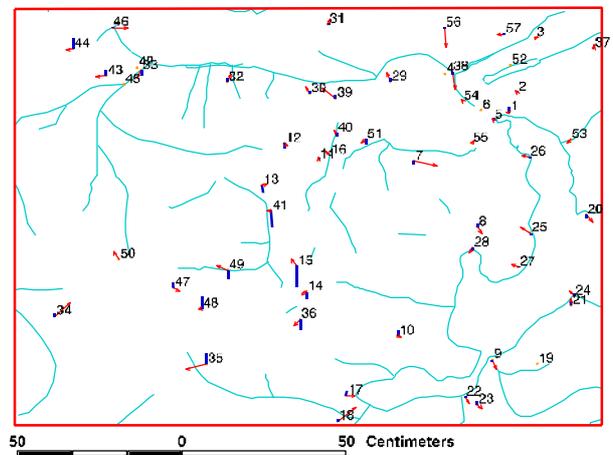


Figure 8. Result of general spatial transformation in historical data set: differences on identical points in XY direction (red arrows) and in the height (vertical blue bars, magnified 2x)

4.3 Comparison of digital terrain models

DTM analysis of historical reliefs addresses the question of comparing two 3D models with differences in all three directions. The historical reliefs are distorted and their height scale is often magnified on purpose. Before comparison of Pfyffer's relief with the current DTM, the historical data set must be transformed to the national coordinate system. Two approaches are applied to solve this problem: transformation of historical data using global spatial parameters (4.3.1) and a mesh-wise transformation using local parameters (4.3.2). To be

able to evaluate these two methods and propose the appropriate solution (4.3.3), both height and image data of the historical data set have been transformed.

4.3.1 Transformation using global spatial parameters. 9 parameters of the general spatial transformation of identical points ($d_x, d_y, d_z, m_x, m_y, m_z, \alpha, \beta, \gamma$) allow the transformation of the historical data to the national coordinate system with global validity for each point/pixel of the transformed data set. To avoid the creation of holes, both height and image data are transformed using the indirect method.

Height data. For each node X, Y of the new regular DTM the following algorithm is applied:

1. Take X, Y of the node and an initial Z value
2. Calculate x, y from Equation 4
3. Find z' value of the nearest DTM node in the historical data set (nearest neighbour interpolation)
4. Calculate X', Y', Z' using x, y, z' (Equation 4)
5. Repeat steps 1-4 for X', Y', Z' until the differences $|X-X'|$ and $|Y-Y'|$ do not change significantly
6. Take Z' value as transformed height for X, Y

Image data. For each pixel U, V of the new texture image an algorithm similar to the orthoimage rectification procedure is applied:

1. Using georeferencing information (pixel footprint and coordinates of image corners), calculate X, Y
2. Find Z' value of the nearest DTM node of the transformed historical data set (nearest neighbour interpolation)
3. Calculate x, y for X, Y, Z' from Equation 4
4. Calculate corresponding pixel u, v of historical image using georeferencing information
5. Take grey values of u, v as transformed radiometric information for U, V pixel of the new image

As a result, both DTM and orthoimage of the historical data set are in national coordinates now and thus can be overlaid with current vector data (Figure 9) or transformation residuals on identical points (Figure 10). The latter allows correction of obviously wrong defined identical points in the historical data set.

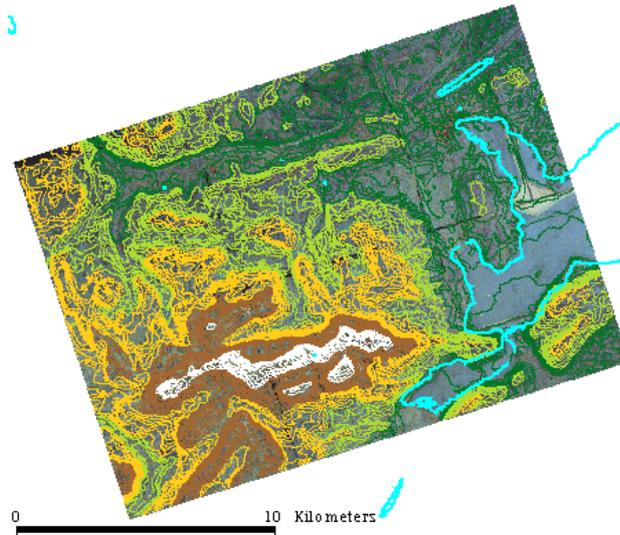


Figure 9. DTM and orthoimage of Pfyffer's relief in national coordinate system, transformed using global parameters. In blue an overlay with current lake outlines is depicted.

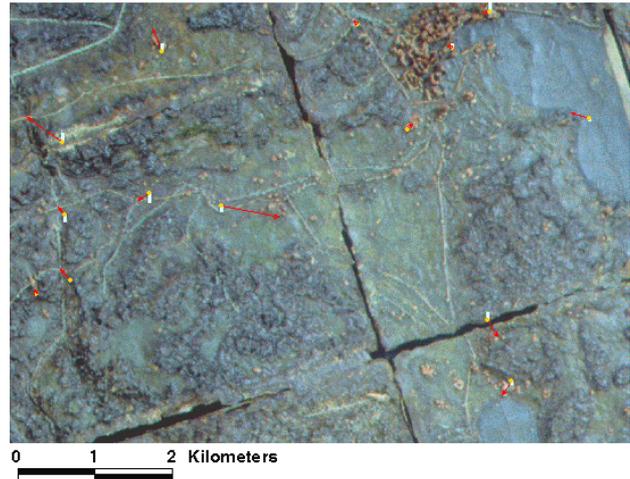


Figure 10. Result of general spatial transformation in transformed historical data set: differences on identical points in XY direction (red arrows) and in height (vertical blue bars, magnified 2x)

A comparison of transformed DTM of Pfyffer's relief with the national DTM is now a simple task of comparing two regular rasters. The average height difference of Pfyffer's relief DTM points is 107 m in absolute values, corresponding to 9.2 mm in the relief (Figure 11).

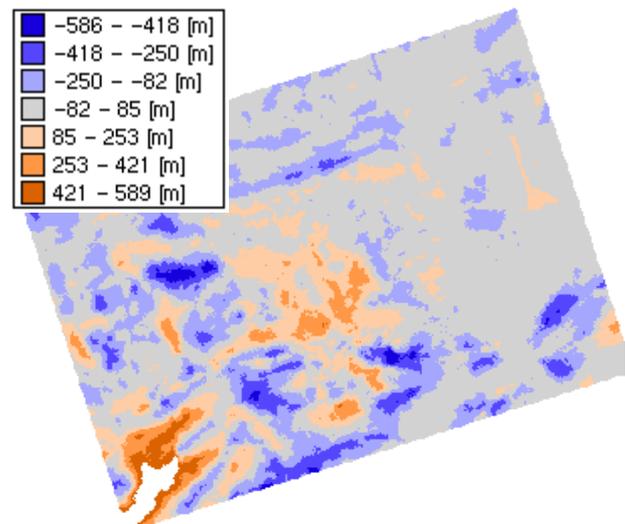


Figure 11. Difference DTM of Pfyffer's relief and DHM25

4.3.2 Mesh-wise transformation using local parameters. The mesh-wise transformation using local parameters is an often used method for the geometrical correction of historical maps (Fuse, 1998; Shimizu, 1999; Baletti, 2000). First a Delaunay triangulation mesh is created on identical points. All nodes/pixels of the historical DTM/orthoimage situated within a triangle are transformed to the national coordinate system using triangle vertices as reference. The parameters of the planar affine transformation have local validity within a particular triangle only. The advantage of this method is that the position of identical points is not influenced by the transformation. The algorithm of transforming height and image information is similar to the one described in 4.3.1 with the difference, that Equation 2 instead of

Equation 4 is used for the transformation of DTM nodes/pixels within each triangle. The DTM and orthoimage transformed using local parameters, including overlay with Delaunay triangulation mesh are depicted in Figure 12.

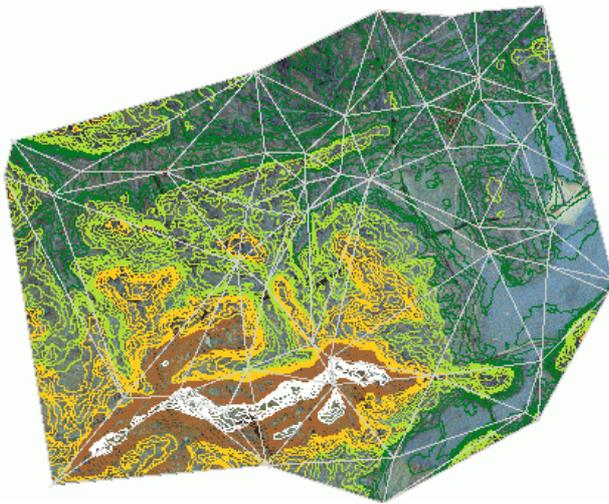


Figure 12. DTM and orthoimage of Pfyffer's relief in national coordinate system, transformed using local parameters

A comparison of the transformed DTM with the national one is in this case not that simple task as in 4.3.1. The reason is that now the DTM as well as the orthoimage were transformed using parameters of affine transformation *in the plane* (there are 3 vertices as identical points for each triangle so a maximum of 6 unknowns is possible). For a comparison of the transformed DTM with the national one an appropriate scale in Z direction is needed. Using a scale of 1:11590 as the result of general spatial transformation, the average height difference between tested two data sets is in absolute values 117 m. A statistically better result (98 m) can be achieved by computing the height scale for each triangle individually as an average height scale of the triangle vertices. However, the latter is not reasonable, because the difference DTM contains big height shifts between adjacent triangles.

4.3.3 Evaluation of methods and proposal. A question is, which one of two above described methods is more suitable for the comparison of a texture mapped historical terrain model with reference data.

As the parameters of the mesh-wise affine transformation have only local validity, it is impossible to compare the two used methods statistically. Therefore 14 additional identical points were defined as checkpoints. Their 3D coordinates were measured in both transformed data sets (planar coordinates taken from the transformed orthoimage and heights interpolated from the transformed DTM). The "to-be" reference coordinates of checkpoints were measured in current data set. The differences between "are" and "to-be" coordinates of checkpoints show a surprising result: an often-used mesh-wise transformation causes for a majority of checkpoints bigger planar differences than the transformation using global spatial parameters (Figure 13). A similar result was achieved by the comparison of heights. Also when handling the historical orthoimage as a planar map and transforming it using global parameters of Equation 2, the residuals on checkpoints are smaller than by using the mesh-wise transformation.

Considering these results as well as the known negative effect of mesh-wise transformation (deformed straight linear features between adjacent triangles, Shimizu, 1999) the transformation of texture mapped DTM using global spatial parameters is proposed for the comparison of historical and current data.

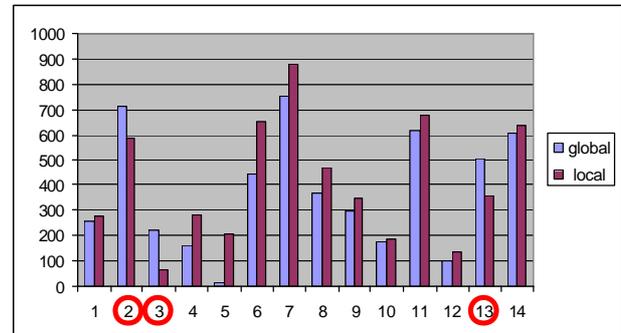


Figure 13. Planar differences of 14 checkpoints in [m]. Only in three marked cases the transformation with global parameters achieves worse results than the one using local parameters.

5. CONCLUSIONS

On the example of the relief model of Switzerland, constructed by Franz Ludwig Pfyffer in 1762-1786, methods for 3D reconstruction and accuracy analysis of historical reliefs were shown. A remarkable feature of the photogrammetric part of the project is the unusual combination of aerial and close-range applications: a big landscape mapping process is performed in an artificial environment of the cellar room of a museum. Since a very precise DTM is required, manual measurements of the surface are applied.

For the first time the relief of Franz Ludwig Pfyffer has been quantitatively evaluated. The a-posteriori standard deviation of spatial vectors on identical points, reaching 1.6 cm within the 26 m² big relief as well as the overall average height error less than 1 cm show a surprising accuracy of the relief constructed long time before the first Swiss national triangulation network was established. Moreover, these numbers consider not only the accuracy of Pfyffer's surveying, but also include an influence of model construction. The suggested approaches of accuracy analysis allow a meaningful evaluation of old 3D models, taking into account a probable way of their creation according to research in history of cartography. In particular, new methods for the comparison of historical terrain models with current data have been developed and evaluated. The transformation of height and image data using global spatial parameters is proposed as the appropriate solution.

After finishing the photogrammetric reconstruction of the overall Pfyffer's work, the developed methods for accuracy analysis will be applied. Further project steps include deeper investigations on the surveying process for the relief construction. Finally, procedures for visibility analysis of preserved topographic sketches of Franz Ludwig Pfyffer will be implemented.

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