Transformation of Cadastral Data between Geodetic Reference Frames using Finite Element Method

Dr. Alexander KOHLI, Lorenz JENNI, Switzerland

Key words: cadastre, geoinformation/GI, implementation of plans, transformation, finite element method

SUMMARY

The contents of scanned and vectorized cadastral plans have to be transferred to a modern reference frame often. Knowing that the situation within existing reference frames and networks are not homogenous a one - step transformation leads seldom to acceptable results. Regional transformations do not fit together too and lead to a 'mosaic' of locally fitting transformation areas. In the gaps an inhomogeneous situation is the result.

A satisfactory solution was therefore defined by the Swiss Federal Institute of Technology (SFIT) Zurich and SWISSTOPO Berne with the affine transformation within finite triangles (finite element - FINELTRA). This method was applied in case of the renewal of the graphical cadastre in Kosovo.

The paper shows the principle of the method, the work flow and approach as well as experiences with borderline effects and accuracies. Finally there are given some hints for the practical application.

ZUSAMMENFASSUNG

Die Inhalte von Katasterplänen, seien es analoge oder digitale Daten müssen oft in neue Referenzsysteme überführt werden. Im Bewusstsein, dass bestehende Referenzsysteme häufig nicht homogen sind, muss in den meisten Fällen von einer einfachen globalen Helmert-Transformation abgesehen werden. Das gilt insbesondere, wenn die Fixpunktesysteme niederer Ordnung im Laufe der Zeit erweitert wurden ohne eine vermittelnden Ausgleichung über das gesamte Netz zu vollziehen.

Vor diesem Hintergrund entwickelten die Eidgenössische Technische Hochschule (ETH) Zürich zusammen mit der SWISSTOPO, Bern unter Anwendung einer Affintransformation innerhalb von finiten Elementen (Dreiecke) eine befriedigende Lösung, welche eine homogene Transformation über den ganzen Betrachtungsperimeter erlaubt. Diese Methode wurde für die Erneuerung der Katastervermessung aus den 1980er Jahren im Kosovo verwendet.

Der Artikel soll die Anwendung der Methode, den Arbeitsablauf, den Umgang mit Effekten am Perimeter-Rand sowie die Erfahrungen aus der praktischen Anwendung aufzeigen.

Transformation of Cadastral Data between Geodetic Reference Frames using Finite Element Method

Dr. Alexander KOHLI, Lorenz JENNI, Switzerland

1. INTRODUCTION

When upgrading vectorized cadastral data from plans, the transfer from an old geodetic to a new geodetic frame is often needed. The key problem then is the choice of suitable transformation method to get homogenous data for further use. The problem occurs especially when the data originally was derived from several not perfectly connected campaigns with low neighborhood accuracy.

The transformation by Helmert with four, respectively seven parameters does generally not lead to a satisfactory result. Only the shift, the rotation and an eventual scale of the former network can be compensated. This means that some systematical distortions in certain areas cannot be reduced or even eliminated and gaps between locally applied transformations create inhomogeneous data sets. With the finite element method on the contrary a method can be considered as an appropriate method for homogenous and reversible transformations without gaps or distortions.

Doing the re-establishment of the cadastre in Kosovo (Kohli, A. 2004; Kohli, A. 2005) cadastral plans were based (geo-referenced) on the old geodetic reference frame with a different origin and where local distortions in the network are common. A transformation of vectorized cadastral data from the FRYREF30 coordinate system to the new distortion-free network within the reference frame KOSOVAREF01 was required. The new geodetic reference frame KOSOVAREF01 has been defined in 2001 by means of Global Positioning System (GPS) measurements (Kohli, A. et al., 2001; Wiget, A. et al., 2001). The network is highly homogenous and accurate. It meets the requirements of a modern network as ETRS89 - GRS80 Ellipsoid and ETRF[1] integration etc..

In general the workflow for the Kosovo transformation project can be defined as a process of five steps with an iterative approach for the establishment of the transformation base (Jenni, L., 2003):

1.	Provisional triangle network	Build up the provisional triangles and determine the points of the transformation base and checkpoints out of former triangulation and traverse points.
2.	Determination of distortion vectors	Determination of the used points by measurements in the new reference frame to calculate distortion vectors by a global Helmert transformation.

[1] European Reference Frame ETRF, Adjustment on EUREF Permanent GPS Network EPN

3.	Improvement of the transformation base	Design the pre-definite triangle network, transformation of the checkpoints and assessment of selected points of the transformation base, iterative improvement of the triangle network by reduction of the residual lengths for checkpoints.
4.	Transformation of cadastral data	Transformation of vectorized cadastral data by finite element method.
5.	Quality checks	Quality tests by area comparison of parcels and reporting of results.

2. TRANSFORMATION BY FINITE ELEMENT METHOD

The method requires a triangle grid covering the area of concern. The nodes of the triangles are the so-called Transformation Base Points (TBP) for which coordinates are available in the former as well as in the new reference system. All vector data within the finite element of the triangle is being transformed with a linear affine transformation where the corner points become exactly the values in the new system. The method shows the following advantages (Carosio, A., Plazibat, M., 1995) compared to other methods as Helmert:

- Each mesh of the triangle grid is a clearly demarcated area in which the transformation depends only of the coordinates of the TBPs.
- The transformation is continuous and due to be a linear function reversible. It permits also a continuous change from one triangle to another.
- Local improvements and densification of triangles can always be applied.
- Straight lines remain straight; parallels remain parallel, which is important especially for cadastral data.

The definition of the triangles is the main task and must be done very carefully. The software used should provide a tool, which automatically does the consistency checks whether there are overlaps or holes. It should also provide the possibility to visualize the distortions (change of scale, dilation, torsions) inside each triangle.

The cadastre data should be transformed with an engine that does not loose topologies. A possible approach is to transform vector data in a system-independent form of an INTERLIS export file (SWISSTOPO, 1997), called ITF. Using the software GeosFin[2] (Thalmann, H., 2000) also line definitions, text and symbol positions are transformed. Data available in ITF format can be transformed fore- and backward whenever required. The method requires thus a documentation of the triangles and its distortion vectors at the different stages of the triangle network development in a persistent manner.

[2] The mathematical function of the transformation of GeosFin underlies exactly the algorithms used in the software FINELTRA developed at ETHZ Zurich.

3. ITERATIVE APPROACH TO THE TRIANGLE NETWORK DESIGN

3.1. Provisional Triangle Network – Design Criteria

The quality of the transformation depends on the one hand on the density of selected TBPs and on the other hand on the definition of the triangles (SWISSTOPO, 2003). It is possible to influence on the result of the transformation by the definition of the triangle topology depending on the following main criteria:

- Use stable points as TBPs which have not been changed since the original determination.
- Use preferably adjusted first and second order points that are former triangulation points. Use only points with measurements that fulfill the accuracy and reliability requirements.
- Use TBPs in the bottom of valleys with priority relative to points on hilltop.
- To provide that local city networks stay homogenous city areas should be included by a single triangle and checked by re-measured points near and within the city.
- Bigger triangles in mountain areas can be accepted.
- About 3 to 4 checkpoints must be available within a triangle to prove the correctness of the selected TBP. In urban areas more checkpoints must be available than in mountain areas of the border zone.

The definition of the triangles is an iterative process. The triangles are tested, improved and optimized step by step with several quality controls before being accepted finally. As evidence it shall be mentioned that for the Kosovo project the first draft of the triangle network contained only 54 triangles. The final triangle network was defined by 113 triangles.

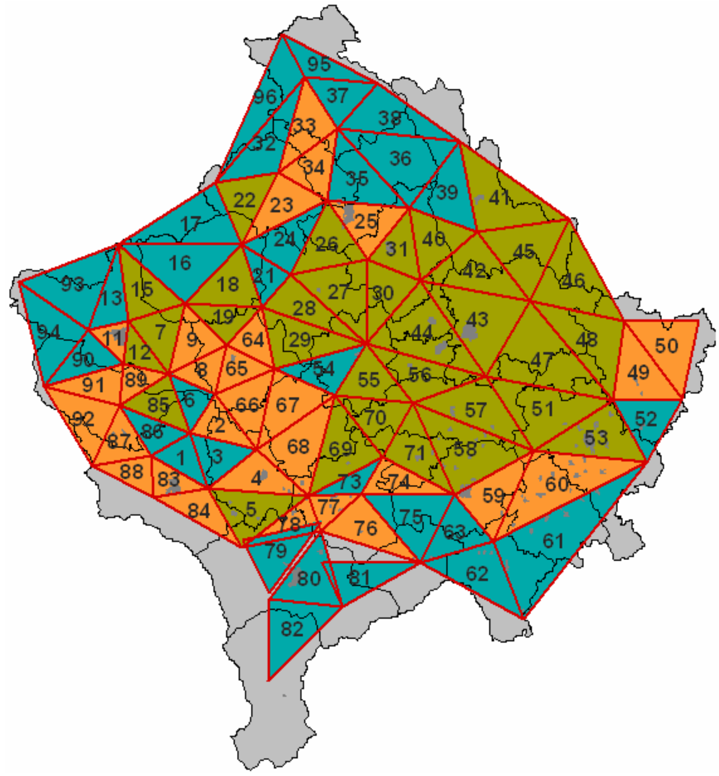


Fig. 3-1 *Map used for the planning of measurement campaign with provisional triangles, color distinctions according need for additional measurements.*

3.2. Provisional Triangle Network – Selection of Transformation Base Points

The first selection of TBPs was based on the residuals of a robust Helmert transformation of 26 well-distributed 1st order points, which were used as pass points. The parameters of this transformation were applied to all points, which are available in both reference frames; old FRYREF30 coordinates as well as new measured KOSOVAREF01 coordinates. The comparison of the transformed with the measured coordinates shows some systematical distortions in certain areas (Fig. 3-2).

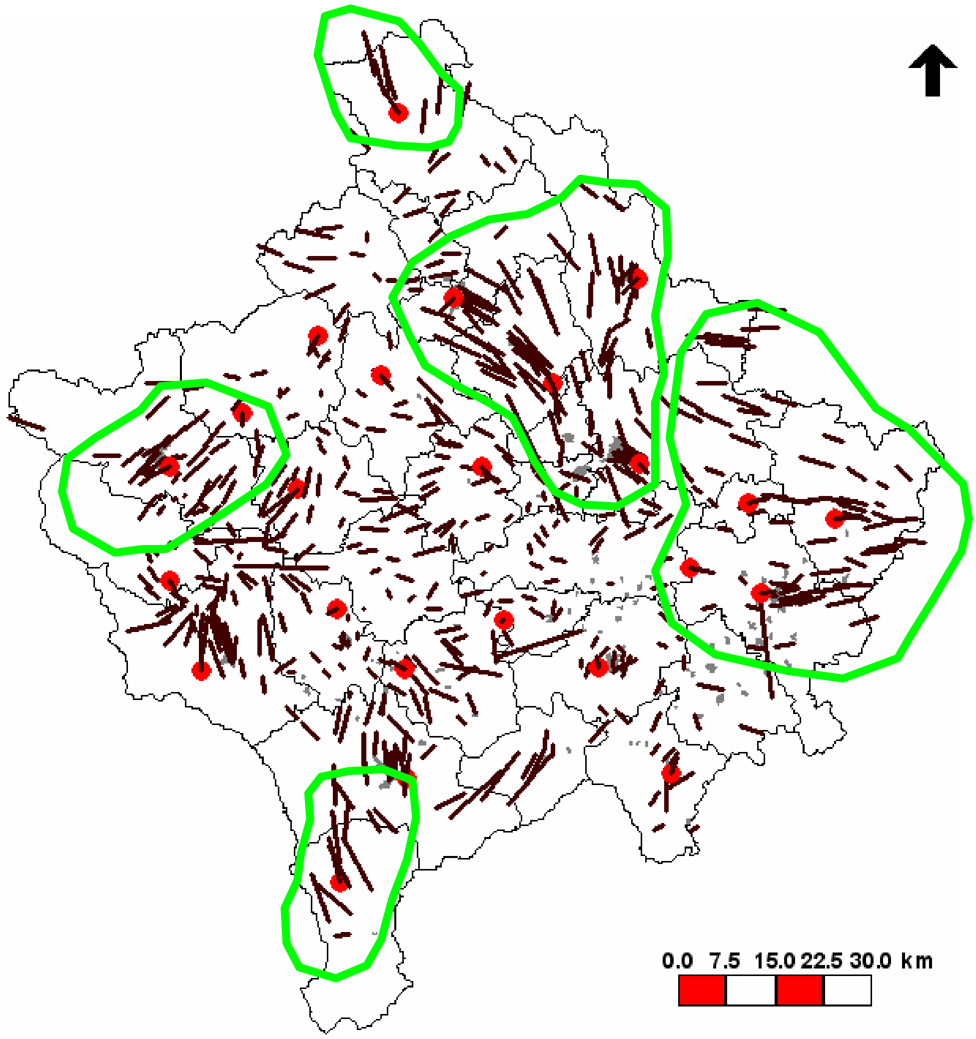


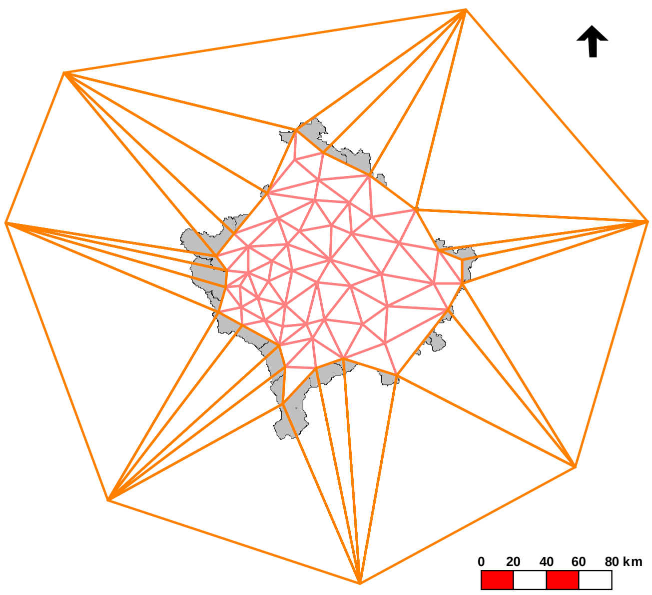
Fig. 3-2 *Map with residuals (brown) of a global Helmert transformation with 26 pass points (red) and areas with systematical distortions (green) which can not be adjusted with Helmert method.*

To improve the provisional triangle network the gross errors had to be eliminated. However some outliers remained. It cannot be expected that such outliers will be eliminated even by the finite element method. These points were not useful as checkpoints to evaluate the results achieved and were not taken into account. In case of too few relevant points further investigation could be necessary in the areas of concern. A detailed technical reporting is therefore needed.

Beside the above mentioned design criteria it was aimed to select TBPs with residuals similar to other vectors in its direct vicinity. Adjacent areas with relevant residuals in opposite directions should be defined as independent triangles. The dividing line of the triangles should go along these zones and not across. The big residuals should then be eliminated and not distributed linearly.

However the criteria cannot be applied one by one without assessing the local situations every time for each triangle. It is always necessary to consider the adjacent triangles. Knowledge about topography and geography is useful in most of cases. For example big residuals and few checkpoints in border zones and mountain areas were accepted due to lower accuracy requirements whereas settled areas were aimed to have smaller residuals and more checkpoints to reflect a more reliable image of real distortions.

3.3. Borderline Effects – Fictitious Transformation Base Points



During the planning of measurements of checkpoints and TBPs it was predictable that there are no measurements of points outside of Kosovo possible due to political and practical reasons. From the geodetic point of view this problem can be handled with so called fictitious TBPs with residuals equal null. Therefore TBPs are calculated far outside of Kosovo to be connected afterwards with the internal TBPs. The influence of these fictitious points can be minimized if the distance chosen is long (e.g. 100 kilometers) relatively to the opposite triangle side (Fig. 3-3).

Fig.3-3 *Map with Fictitious Triangles (orange), used to cover the border area of Kosovo (gray).*

3.4. Transformation of Checkpoints

The quality of the TBPs selected is to be assessed by the quality of the distortion vectors of the checkpoints located within the provisional triangle definitions. As distinct from the approach for the (preliminary) detection of the distortion vectors of the TBPs the vectors for the checkpoints are derived by applying the finite element method using the provisional triangle network.

The residuals of the transformed former points to the measured checkpoints show that the systematical distortions in some areas were reduced significantly. The vectors show different, local and non-systematical directions and are shorter. Most outliers already detectable with the Helmert transformation (Fig. 3-2) remained.

The average of the residual vectors of all transformed checkpoints reached is 0.19m with a mean deviation of 0.10m. The triple length of the average vector (0.57m) was used to set a tolerance for the detection of gross errors. The results show that the method cannot eliminate blunders but can even detect other local distortional residuals (Tab.3-1). This effect is confirmed by Steffen and Schütz (Steffen, B., Schütz St., 2002).

ID	Δ E [m]	Δ N [m]	Δ Total [m]
ST26	1.43	0.20	1.44
660245	-1.41	0.07	1.41
DR21	0.49	-0.70	0.85
60207	-0.85	0.01	0.85
620088	-0.11	-0.83	0.84
750159	-0.80	-0.05	0.81
Pris1714	0.10	-0.71	0.72
730144	0.22	-0.68	0.71
BP0173	0.41	0.47	0.62
PZ28	0.38	0.47	0.61
380215	-0.05	-0.59	0.60
380205	-0.13	-0.56	0.58

Tab. 3-1 *Outlier residual vectors for checkpoints, whereas E equals Easting and N equals Northing. - Several outliers go beyond the tolerance (> 0.57m) set.*

3.5. Modification of Triangles

The iterative determination of the triangle network was realized by several variants. The best approach to assess the result of these transformations turned out to be a visual judgment on a printed map of the residuals in scale 1:200'000. On the basis of this review the selection of TBPs was varied in several areas but mainly in the NW region of Kosovo. Due to these changes most of the residuals within the triangles in question could be reduced significantly.

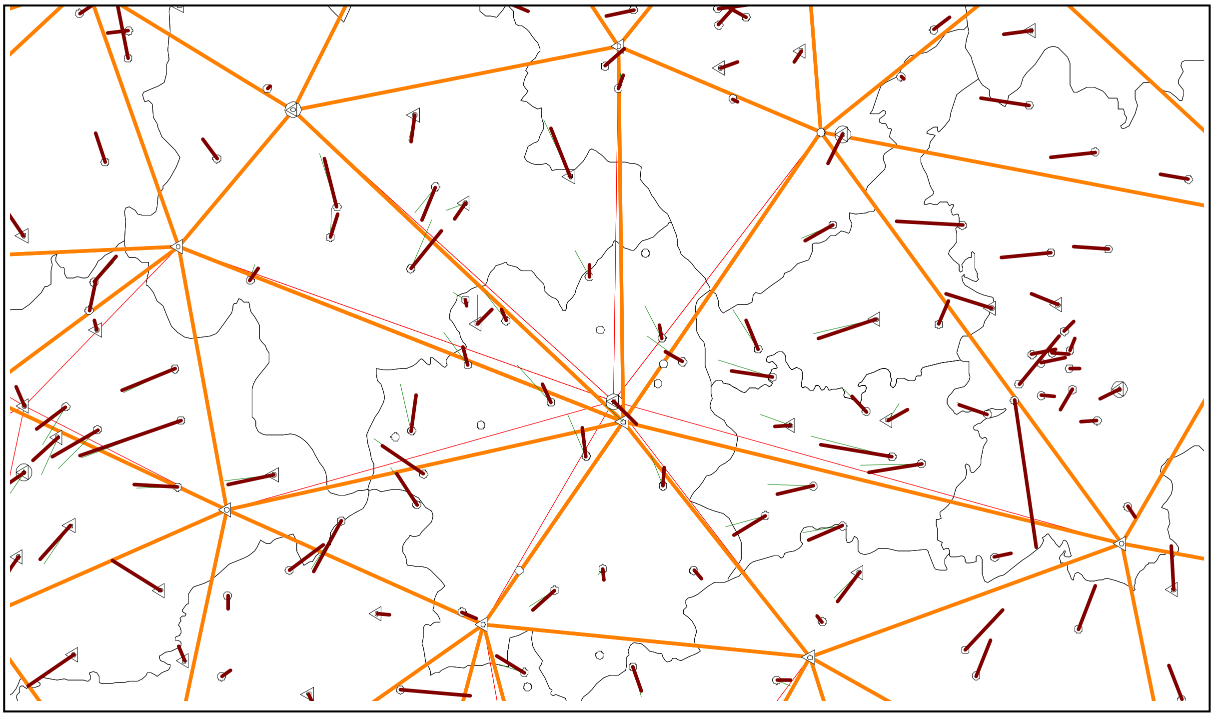


Fig. 3-4 *Map with changed TBPs to get smaller, unsystematically distributed residuals in the concerned area; orange: new triangle with brown: new residuals, red: old definition with green: residuals of old definition.*

3.6. Final Triangle Network Residuals

The iterative improvement of the triangle network of TBPs produced acceptable results. Local distortions were mostly reduced. Checkpoints that did not fit into the areas (quality of distortion) are significantly visible (compare Fig. 3-5 and 3-2).

	Average Vector length [m]	Average Deviation [m]	Number of Checkpoints out of Tolerance
Helmert Transformation	0.36	0.15	84
First Version / Pre-definite Triangles	0.19	0.10	14
Final Version / Definite Triangles	0.18	0.10	12

Tab. 3-2 *Residual vectors of checkpoints and quality over different stages of transformation.*

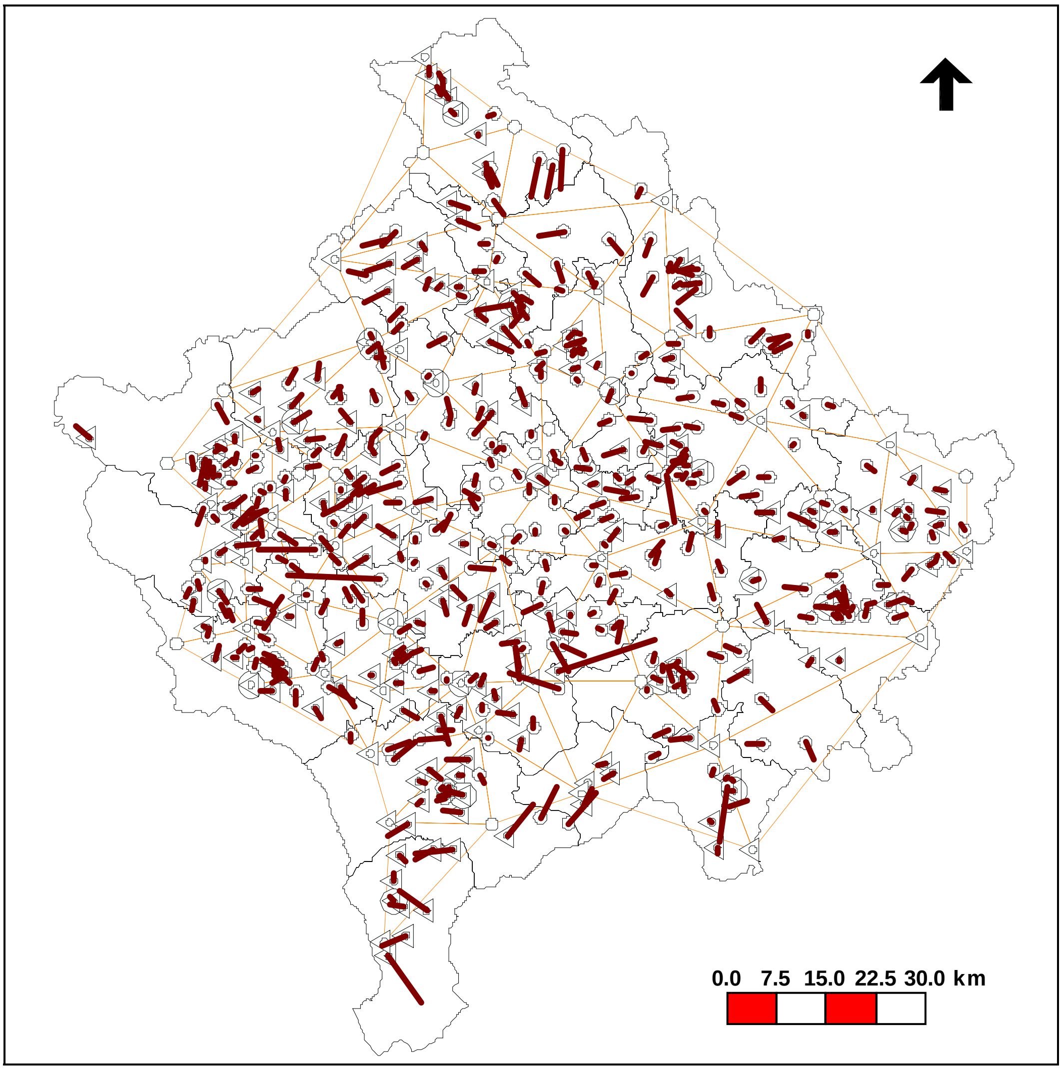
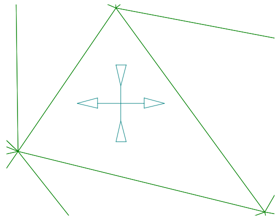
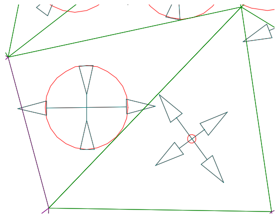


Fig. 3-5 *Residuals of checkpoints after transformation with final triangle network definition.*

Taking into consideration the comparison of residual lengths and the quality by tolerance the biggest improvement was achieved after the first version of transformation by finite element method. The improvements of the second version seem to be less significant. This is showed on the map (Fig. 3-5). The relatively big standard deviations come from the outliers that remained in the calculation for documentations purposes.
The results show furthermore that a complete elimination of local distortions is not possible with the finite element method. A better result could only be found if much more points were measured in both systems and if the triangle network would have a much bigger density.

3.7. Distortions within Triangles

The indicators of extreme distortions within a triangle are another source of analysis of the quality of performed transformations. As a relevant set of indicators the graphs of the *Main Axis of Distortion* and *Dilation* were chosen:

Main Axis of Distortion:	Represents the extreme differences in scale within a triangle - Positive values indicate stretching/expansion - Negative values indicate compression	 ***Fig. 3-6*** *Triangle with stretching in east-west and compression in north-south direction.*
Dilation:	Represents mean change of scale within a triangle - Positive values indicate stretching/expansion - Negative values indicate compression	 ***Fig. 3-7*** *Triangles where the red circle of dilation indicates bigger or fewer change of scale.*

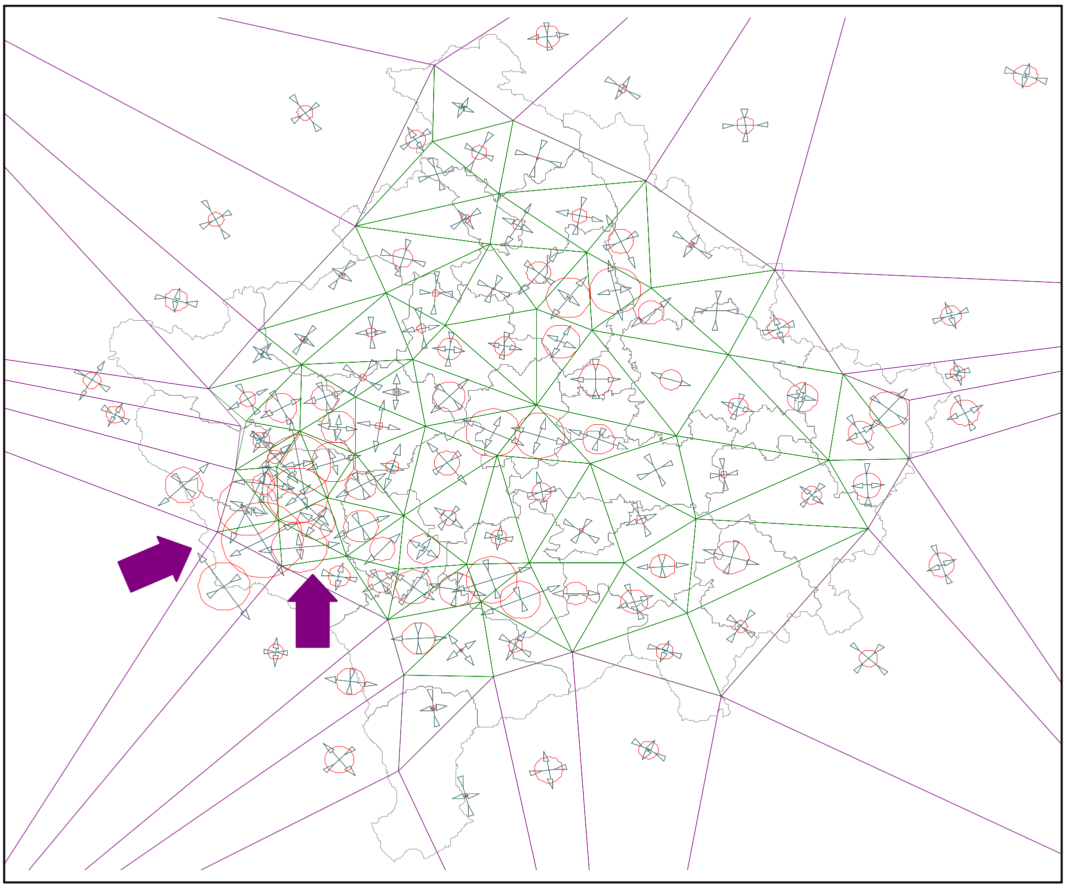


Fig. 3-8 *Map with distortion components of stretching/compression (blue) and dilation (red), area of heterogeneities marked by arrows (⇨).*

A graph of distortion components for each triangle is useful to detect heterogeneities within the triangle network. The map (Fig. 3-8) shows the distortion components off all triangles. Distinctly detectable are the heterogeneities in the Gjakova-Deçan (West Kosovo) region where also the biggest distortions exist in the TBPs. Although split in quite small meshes the triangle grid does still not show a homogenous change in this area. The practical approach to reduce these tensions should be the continuous improvement of data within the reconstruction process of the maintenance of the cadastre. Assuming that no further improvements by triangle adjustment can be reached the triangle network is ready to serve as transformation base of the cadastre data.

4. TRANSFORMATION OF CADASTRAL DATA

4.1. A Priori Accuracy Considerations

Prior to define quality requirements of the transformation and further actions, some a priori reflections were made in order to classify the results to be expected. It shall be pre-estimated of what influence the transformation compared to other errors of cadastral data will be on the overall error.
Following general error sources and its values were derived considering the applied technology and the results of two pilot projects in Gllogovc and Klina municipality in Kosovo (Tab. 4-1).

Error Sources of Basic Cadastral Data	Values for Map Scale 1:500
Quality of Basic Surveying (Photogrammetry or Conventional)	+/- 0.30m
Drawing of Plans	+/- 0.05 – 0.25m
Printings from the Original Plans	+/- 0.10m
Vectorization of Scanned Plans after Georeferencing	+/- 0.05 – 0.20m

Tab. 4-1 *Error sources of basic cadastral data.*

The maximum error coming from the above mentioned influences for cadastral data of a plan in scale 1:500 expected is therefore according to the Gaussian error formula:

$$\sigma_{\max} = \sqrt{\sigma_{surveying}^{2} + \sigma_{drawing}^{2} + \sigma_{printing}^{2} + \sigma_{vectorization}^{2}} = \underline{\sim 0.50\text{m}}$$

In the case study of the Gllogovc pilot, where transformed coordinates were compared with new measured coordinates, an average difference of 0.001 – 0.0015m could be detected. These differences are of two orders of magnitude smaller than the overall accuracy of the data to be transformed and lead to the assumption that the influence of the transformation on the overall accuracy of data is to be expected a neglecting part.

4.2. Parcel Area Comparison of Transformed Data

Some cadastral zones of Municipalities distributed over Kosovo were transformed to check the influence of transformation on the parcel areas. The transformation was performed using the tools mentioned in section 2 of this paper. The area of every parcel was calculated in the GIS package GeoMedia from INTERGRAPH by applying the function *Analyze Geometry*.

Cadastral Zone - Municipality	No. Triangles	Parcel Area [km^2]	Avg. Δ / Parcel [m^2]	Max. Δ / Parcel [m^2]	σ_{area} [m^2]
Berkove - Klina	1	0.025	0.015	-0.23	0.011
Shaptej - Gjakova	2	0.200	0.412	25.07	0.397
Shajnovc - Dragash	1	0.900	0.012	7.92	0.008
Strpce - Strpce	4	9.900	0.176	320.61	0.221
Pogragje - Gjilan	5	1.600	0.182	72.95	0.207
Lluge - Podujeva	2	0.013	0.022	0.32	0.018

Tab. 4-2 *Effects (σ_{area}) of transformation on areas of parcels.*

The results of the table 4-2 show that the effect of transformation on the areas of parcels is neglectable relative to the errors of vectorization, original surveying data, drawing and distortion of cadastral plans. Even in areas where residuals remained big and distorted after transformation, the relatively small area of parcels was not affected. The apparently big maximum area residual of 320.6m^2 of a parcel in the cadastral zone Strpce in Strpce municipality is relatively small compared with the size of this rural parcel of 9.9km^2.

5. EXPERIENCES AND CONCLUSIONS

5.1. General

Using the finite element method proposed the result is a homogenous, accurate and gapless data set over the whole area of concern. The transformation method is ideal for changing the reference frame as well as only for changing the projection system. Local and systematical distortions can be reduced comprehensively in developed countries as well as in countries in transition with existing networks.
Generally the efforts and the costs of the method are reasonable. Especially the efforts of increasing the density of the triangle network must always be reflected under the fact that the error of transformation compared with the errors out of vectorization, original measurements and distortion of cadastral plans is proportionally very small. There is almost no influence on the areas of the parcels if local effects are detected.

5.2. Establishment of the Triangle Network (Transformation Base)

There would be much more checkpoints needed to get an image of 'real' distortions. Big triangle meshes have a small effect. Small triangles however require a huge effort of measurements on available 'former' points, which was not an issue for the special circumstances in Kosovo.
It is not possible to derive a general tolerance for the evaluation of the residuals of checkpoints in order to prove the selected TBPs. It is rather applicable to use a common sense for the selection – consider mountain areas, achievable overall accuracy of vectorized data etc. Knowledge of the local geographic and topographic characteristics is therefore of an advantage. Nevertheless as a general rule the average vector values achieved can be applied:

1. Points with vectors longer than 0.5m are assessed and marked in the map.
2. Evaluation whether it is an outlier or not, eventually redefinition of the triangle.

A visual evaluation of residuals after every transformation step is therefore absolutely required. With some experience the behavior of residuals after changing a TBP in an area can be predicted.

5.3. Limitations of Application

Not detected local data sets within bigger triangles with different distortion can become a problem. Such data must be implemented by another transformation project. The triangle network must be consolidated by additional triangles covering the local distortion effects. Especially city networks should therefore be taken into account. The re-transformation of the data has to be done within the specific triangle.
As the handling of a triangle network and its improvements needs experience the maintenance of the transformation base has to be the responsibility of one single institution/authority within a country. That means the private sector has to request and cooperate for data transformation as well as for triangle network improvements.

AKNOWLEDGMENTS

The authors wish to thank Markus Schreier for his project work. The Swiss Agency for Development and Cooperation (SDC), Grant Number S.20.11 KOSGSO, 7F-01067.01-04, funded the BSB + Partner project unit at KCA. Special thanks go to the Swiss Federal Office of Topography, especially to Dr. F. Wicki for his advice and cooperation.

REFERENCES

Carosio, A., Plazibat, M. 1995, *Lineare Transformation mit finiten Elementen.* Geomatik Schweiz, Geoinformation and Land Management (former VPK), Vol. 94 (4): 192-194, Switzerland.

Jenni, L. 2003, *Kosovo Cadastre Support Programme, Transformation of Cadastral Data from FRYREF30 to KOSOVAREF01 Geodetic Reference Frame*, Project Report No. 040-029, KCA, Pristina, Kosova.

Kaufmann, J., Steudler, D. with Working Group 7.1 FIG Commission 7. 1998, *Cadastre 2014*, A Vision for A Future Cadastral System, FIG Booklet, http://www.swisstopo.ch/fig-wg71/cad2014.htm.

Kohli, A. 2002, *Renewal of the Network and the Realization of Orthometric Heights using GPS in Kosovo*, 22nd FIG International Congress and ACSM-ASPRS Conference, Washington DC, USA.

Kohli, A. 2004, *Reconstruction of a GIS-Cadastre in a developing Country*, GeoSpatial World 2004 Congress, INTERGRAPH, Miami Beach, Florida, USA.

Kohli, A. 2005, *Wiederaufbau des Katasters in Kosovo*, Geomatik Schweiz (former VPK), Vol. 103 (11): 613-616, Switzerland.

Kohli, A., Krasniqi, R., Heer, H.P. 2001, *Reference Network 1st order KOSOVAREF*, Project Report Nr 020-001, KCA, Pristina, Kosova.

Steffen, B., Schütz St. 2002, *LV03 – LV95, Optimierte Dreiecksvermaschung*; Diploma Thesis at the Basel University of Applied Science, FHBB, Muttenz, Switzerland.

SWISSTOPO, 1997, *INTERLIS - A Data Exchange Mechanism for Land-Information-Systems*, http://www.interlis.ch/interlis1/docs/iref11_e.pdf, SFOT, Wabern, Switzerland.

SWISSTOPO, 2003, *Leitfaden für die Anwendung geometrischer Transformationsmethoden in der Amtlichen Vermessung*, Handbook, SFOT, Wabern, Switzerland.

Thalmann, H. 2000, *Description of a Solution for the Transformation of Interlis described Cadastral Data from LV03 to LV95 Geodetic Reference Frame*, a/m/t software service AG, Winterthur, Switzerland.

Wiget, A., Brockmann, E., Marti, U. 2001, *GPS Network Kosovo, Processing with Bernese GPS Software Version 4.2*, Mandate Report for the Swiss Agency for Development and Cooperation SDC in cooperation with BSB + Partner, Report SFOT, Wabern, Switzerland.

BIOGRAPHICAL NOTES

Dr. Alexander Kohli, born in 1967, graduated in surveying engineering in 1995 from the Swiss Federal Institute of Technology (ETH Zurich). In 1995 he started his PhD at the Versuchsanstalt für Wasserbau (VAW), Swiss Federal Institute of Technology (ETH Zurich) on BUILDING SCOUR IN FLOOD PLAINS under the supervision of Prof. Daniel Vischer. After the PhD in 1998 he started as surveying engineer and geomatics expert in the Swiss engineering company BSB + Partner, Ingenieure und Planer. In 1999 he earned the Swiss license for licensed land surveyor. Since he became partner with BSB + Partner he runs a special department for Cadastral Surveying and Consulting working for public and private organizations in the fields of Cadastre and Geomatics in Switzerland and in the Balkan States.

Lorenz Jenni, Lorenz Jenni, born in 1972, earned his BSc in surveying engineering in 1995 from the Basel University of Applied Sciences (FHBB) Switzerland. After the graduation he started at Ammann AG Vermessung as surveying engineer. In 2000 he joined the team of BSB + Partner, Ingenieure und Planer. In 2004 he earned his MSc at the Universitat Politècnica de Catalunya in Geographic Information Systems. Since 2001 he contributed with BSB + Partner and other consulting companies in several development projects within the field of Land Management and Land Administration in Kosovo, Central and South America.

CONTACTS

Dr. Alexander Kohli
BSB + Partner, Ingenieure und Planer
Dammstrasse 14
CH-2540 Grenchen
SWITZERLAND
Tel. +41 76 393 01 21
Fax + 41 32 654 59 31
Email: alexander.kohli@bsb-partner.ch
Web site: www.bsb-partner.ch

Lorenz Jenni
SIGISconsult
Bürenstrasse 16
CH-2504 Biel
SWITZERLAND
Tel. +41 79 475 45 87
Email: lorenz.jenni@sigis-consult.org
Web site: www.sigis-consult.org