ISSUES OF INTERSYSTEM TRANSFORMATIONS IN THE CZECH REPUBLIC

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Introduction

Point coordinates determined by means of GNSS technology must often be converted or transformed into one of the obligatory plane reference systems specified in the Czech Republic in "Government Decree on the determination of geodetic data and state map series obligatory within the state boundaries and their application policy" No. 430/2006 Coll. For example, this system may be S-JTSK (Datum of Uniform Trigonometric Cadastral Network) or St. Stephen Datum of Cadastre Coordinates, a formerly used cadastral coordinate system in Moravia and Silesia with possible connections to verticals in Bpv (Baltic Vertical Datum – after adjustment).

Transformations between the system of ETRS89 and St. Stephen Datum is dealt with via an intertransformation using JTSK system, in a way that the coordinates in St. Stephen Datum are transformed into S-JTSK and later into the European Terrestrial Reference System – ETRS89. The choice of identical points necessary to determine the transformation parameters then remains an important matter. Accuracy and choice of identical point determination, including identity analysis, is discussed in e.g. [1].

An experiment was carried out in Brno and its environs to directly transform between St. Stephen Datum and ETRS89 system, i.e. without a transition via JTSK system. A set condition was to proceed from the points of an observation grid and thus, for the St. Stephen Datum, points of cadastral triangulation were used (1822-1829) of order I-III within the Brno region, in case of which the sources and accuracy of their origin were possible to document. A part of the project was an analysis of the selected identical point identity, the results of which are available in [1].

Land registry Stable Cadastre

The land registry was founded on the territory of the present Czech Republic at the beginning of 19th century. This registry, named Stable Cadastre (1817–1869), was founded on a new surveying basis of large scale maps in Cassini –Soldner projection. Cassini – Soldner projection is transverse cylindrical projection maintains scale along the central meridian and all parallel to it and is neither equal are nor conformal. It is most suited for large – scale mapping of areas predominantly north – south extent. Distortion in area and shape increases with distance from the central meridian. This projection used for the Ordnance Survey of Great Britain and some German states in the 19th century and also in Cyprus, former Czechoslovakia, Denmark, Malaysia and former Federal Republic of Germany. Stable Cadastre registry became the fundamental tool for meeting the fiscal policy of the state and beginning in 1874 was utilized as technical foundation for filing the new Land Book of the Czech Lands, as it guaranteed unmistakable and simple individualization of land as an object of the law. More about this issue can be found in [2].

History of S-JTSK Construction, Reasons and Origins

Cadastral networks of trigonometric points of different origin and accuracy existed at the territory of the Czechoslovak Republic In 1918.

In these times, *Cadastral Networks in Bohemia, Moravia, and Silesia* were not in compliance with their purpose thanks to both their diversity and accuracy.

In Slovakia and in Carpatho-Russian region *Hungarian cadastral network* was applied, related to the initial point located in Gellertégy. This network was impossible for studying, since Hungarian government did not provided Czechoslovakia with triangulation documentation. However, it was obvious from their instructions, that in the above mentioned countries was used a trigonometric network in three projections, i.e. portrayal without mathematical projection, in stereographic projection, and in conform cylindrical projection.

Other separate part of the cadastral network was mathematically projected *trigonometric network related to initial point Pšov in Prussia* interfering to the region of town of Hlučín. However, this network had to be remade, since instructions of Prussian cadastre did not correspond to our ones.

Military network of the I[st] order dated 1860-1898 related to the basic triangulation point Hermanskogel by Vienna was processed on Bessel ellipsoid. In contrast to the position of trigonometric points, identified in rectangular coordinates of appropriate coordinate systems, the positions of military trigonometric points were identified in geographical latitude and longitude. Average triangle size was of about 50 km that is why it did not suit for local triangulation; furthermore this network was not established for great part of Slovakia, nor at the part of Moravia around Brno.

Triangulation office of the Ministry of Finance was authorized to evaluate these networks. Its task was to perform a new triangulation to be used for establishment of future uniform network.

Triangulation for the basic network of trigonometric points was done in 1920 – 1926. In 1920 was established project of a new trigonometric network for North – Eastern Moravia, Opava (Troppau) region, and North – East part of Slovakia. Two years later for the residual part of Moravia with connection to the boundary trigonometric points of the I[st] order in Austria. In 1923 was elaborated a project for enlargement the network in Slovakia.

For compilation new cadastral maps the Ministry of Finance stipulated principles for new projection method. Said was to follow these properties:

1. uniformity for the entire state territory;
2. it was to follow longitudinal shape of our at the time Czechoslovak Republic;
3. it was to be conform;
4. angle deformation in a triangle having the sides up to 5,000 m was not allowed to exceed the value of 1″;
5. scale error value was to be of 1 : 10000;
6. the whole territory of the Czechoslovak Republic was to be depicted in a single quadrant;
7. calculation of direction adjustments was to be as simple as possible;
8. Gaussian sphere was to be applied for projection to simplify the calculations.

More authors discussed the choice of projection, however the proposal of Ing. J. Křovák had been chosen, since said had met all the 8 above mentioned preconditions.

ETRS89 Performance in the Czech Republic

For processing the GPS campaigns being done at the territory of the Czech Republic the EUREF subcommission recommend to apply the ETRS89 geocentric coordinate system.

ETRS89 (European Terrestrial Reference System) creates a uniform geocentric coordinate system. As per [3] it is defined thru a system of constants, algorithms, and reference frame ETRF (European Terrestrial Reference Frame), being executed using coordinates of stabilized points at the terrestrial surface.

In the Czech Republic, the ETRS89 is determined thru the adjustment of EUREF-CS/H-91campaign results, which took place in 1991. Within the framework of this campaign, at the territory of the Czech and Slovak Republics, total 6 points were surveyed being identical with AGS points (Astronomic geodetic network), and 5 points in Hungary.

First concentration represented a network of 6 points of the zero order, which at the territories of Czech and Slovak Republics consists of 19 points as a whole. This network bears the name NULRAD (Network of Zero Order). Processing of the campaign is described in details e.g. in [3].

Decision was made in 1993, to concentrate the network such way, that average distance of the points determined thru GPS method, was of about 25 km. Name DOPNUL was accepted for this concentration of the NULRAD network.

DOPNUL network (amendment the zero order) was executed in 1993 and 1994, using the GPS technology exclusively. Total 176 points were surveyed, identical with trigonometric points of the JTSK system.

Point concentration of the DOPNUL reference network (average 1 point per 450 km^2) was in sufficient for most of geodetical works. That is why it was necessary to build up a reference system, which would meet following requirements [4]:

– direct utilization of GPS technology (would involve ellipsoidal coordinate points in ETRF);

– utilization of terrestrial surveying techniques (theodolites, distance meters, level instruments);

– utilization of existing sets of maps.

Quasi-geoid determined via the astronomical method in the Research Institute of Geodesy, Topography, and Cartography (VÚGTK) has been applied for transformation of altitudes above the sea level to ellipsoidal ones (1994).

This performance is considered to be the zero stage in constructing the geocentric system in the Czech Republic.

Pilot versions of all S-JTSK/95 and transformation relationships among ETRF89 and S-JTSK, pertinently S-42/83 belong among working versions.

Further information on performance of subsequent stages of the S-JTSK/95 system, on European elevation system and the Czech State Level Network

(ČSNS) and further projects (GEODYN, CZEPOS, GNSS-EUPOS) are listed in [4].

Transformations between coordinate systems

In general, a transformation is perceived as a method of changes in the trigonometric coordinates or other planimetric points – individually or collectively for the area in question, in fact without changing the point position on the physical earth's surface.

The major reasons to carry out transformations are as follows according to [5]:

1. Choice of another reference ellipsoid when geographic coordinates of a point are changed – different coordinate differences correspond to an identical length of a trigonometric side ($\Delta\varphi,\Delta\lambda$).

2. Scale shift, rotation or adjustment of a whole network of fixed points when scale specification occurred, orientation changed or a network was approximated to surrounding networks.

3. Change in the method of ellipsoid projection into a plane. Geographic coordinates of a point (φ,λ) remain unchanged but may be transformed into a plane, e.g. of a conical or cylindrical projection. It is the case of a direct transformation $(x,y)\Rightarrow(X,Y)$ without a mediated transition via geographic coordinates, where x,y are coordinates of the original (former) coordinate system and X,Y are of the new one.

4. New survey of a network section. This also includes new triangulation (formerly), new measuring of distances using GNSS technology (Global Navigation Satellite System).

5. Change to new coordinate systems (geodetic datum). This comprises new measurements, new processing.

In the first three stated cases these are transformations of homogeneous coordinates. In the course of such transformations the angle values remain constant and precise mathematical relations apply between the original (primary) and the new (secondary) system. In cases 4 and 5 these are transformations of heterogenous coordinates, when angle and distance values change randomly and there is no exact mathematical relation to convert coordinates from one system to another.

It is possible to transform coordinates of not only real, i.e. monumented points, but also of lost or notional points (e.g. corners of map sheets). The first step in a transformation is set-up of a key of transformation, whose form depends on the applied transformation method and the selection of identical points. Identical points are such points of which we know coordinates in both the original and new systems. If a necessary number of identical points are available, the calculation of other point coordinates is executed directly by means of a simple key of transformation.

The choice of identical points is crucial [6]. To maintain homogeneity and for possible shifts in certain point stabilization, it is convenient to relate densification points (non-identical) to the given (identical) points in a way they lay inside a polygon circumscribed by marginal identical points of the densified (transformed) area. Worse homogeneity may occur, for example, when relating the determined points only to two or one identical point. To assess the quality of insertion of new networks into the original ones, or vice versa, in particular, scale conversions, angular rotations and position deviations of identical points may be useful.

The number of identical points is usually higher than necessary, so to calculate adjusted coefficients of a key of transformation, a least squares adjustment method is used. Such transformed point coordinates of a new system are burdened by residual deviations arising from differences between the given and transformed point coordinates. These deviations have the same values as coordinate corrections, but with an opposite sign. In order to avoid the lack of homogeneity (deformation) of a whole minor control towards identical points, it is vital to introduce corrections also in case of other detailed survey points. Among a number of methods permitting a classification of coordinate corrections there are:

- graphic method (plotting a chart of corrections);
- method of a general arithmetic mean of an identical point shift – Jung's transformation;
- Spline interpolation [7].

Planimetric transformation between S-SK (St. Stephen Datum, Gusterberg Datum) and S-JTSK

Derivation of a factual relation between the systems of S-SK (stable cadastre coordinate system) and S-JTSK encounters certain below mentioned drawbacks.

1. An error occurred in the determination of the Gusterberg datum direction as an axis X does not identify with the meridian of point Gusterberg, but it forms a small angle (4´22.3´´) westwards. The original cadastral maps of Bohemia are thus oriented according to a different meridian [8].

2. In [9] it is stated that there is no established transition method from an ellipsoid to a reference surface or a reduction of bearings into a plane. Reduction of bearings into a plane is described in e.g. [10], but it is not documented whether this reduction was introduced. Horizontal angles in

triangles were corrected only of a spherical excess (only in order I) and the calculation was done in planimetric nets.

3. The net was constructed according to the needs of detailed measuring, therefore the procedure from large to small was not observed.

4. The conversion coefficient value to convert from fathom to metric system is not identical in different literature sources. The coefficient value was identified in UAZK archive materials (Central Archives of Surveying, Mapping and Cadastre) and one value was always found out – 1°=1.896483843 m. This value corresponds to e.g. data in [11] and [12].

5. It is possible to come across different values of coordinate systems origins, either in Gusterberg Datum or St. Stephen Datum.

6. The variability of both projections $Q = M_{jtsk}:M_{sk}$ results in a fact that the direct point series of one system are transformed into another system as a curve. It is most manifested in straight lines parallel to isometric lines q = const. In perpendicular sides straight line retention applies, but there is a maximum failure of a dividing ratio.

Spatial transformations between S-SK or S-JTSK and ETRS89 systems:

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix}_{Bess/Zach} = \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}_{Bess/Zach} + \\ + \begin{pmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{pmatrix} \cdot \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix}_{ETRS89} .$$

Coordinates obtained from measuring using GNSS technology in ETRS89 system may be transformed into S-JTSK or S-SK (system of Stable Cadastre) in the following manners [13], [3].

1. Through transformations of rectangular coordinates of X,Y,Z in ETRS89 system to rectangular coordinates of Bessel (S-JTSK) or Zach (S-SK) ellipsoid by means of:

a. spatial identity transformation;

b. spatial similarity transformation;

c. $L_{Bess} - L_{ETRS890} = \Delta L = \sum_{i=0}^{k} \sum_{j=0}^{i} b_{i-j,j} \cdot U^{i-j} \cdot V^{j}$

$$B_{Bess} - B_{ETRS890} = \Delta B = \sum_{i=0}^{k} \sum_{j=0}^{i} a_{i-j,j} \cdot U^{i-j} \cdot V^{j} .$$

d. general polymetric transformation of a k-degree and a follow-up conversion of the transformed rectangular coordinates to geographic coordinates with a further conversion into an plane system.

2. Converting rectangular coordinates of X,Y,Z in ETRS89 system to geographic coordinates of ellipsoid, followed by a cartographic conversion into the plane and through a planimetric similarity transformation of Y,X coordinates in Křovák's univers conform conic projection with additional height transformationm or Cassini – Soldner projection.

3. $U = p(B - B_0), V = p(L - L_0), p = c\pi / 180$.

Converting plane coordinates of Y,X and height *h* of identical points from S-JTSK or S-SK system to ellipsoid, followed by identity transformation to centric ellipsoid, adjusting GNSS vectors on this ellipsoid with identical points as fixed and inverse identity transformation of all the points back to ellipsoid, finally classically converting into planar system.

4. Reducing the measured vectors by GNSS technology to ellipsoid, converting into planar system and classical adjustment as during terrestrial measuring.

5. Through an interpolation method without the knowledge of map projection, or relevant reference ellipsoid dimensions. The grounds of the solution are identification of projection relation between identical point coordinates.

Identity transformation

Identity transformation is used if a network shape has been changed in a new position and the transformed points should better comply with the given identical points. The objective of an identity transformation is adjustment of a shape and dimensions of a pattern formed by points in one system to the shape and dimensions of a point pattern in another system.

The transformation key comprises the following parameters:

- ΔX, ΔY, ΔZ are coordinate differences which express a Bessel or Zach ellipsoid shift to a GRS80 ellipsoid;
- α, β,γ are angles expressing transformed system rotation with respect to coordinate axes.

The transformation key does not include a coordinate scale change.

General Polymetric transformation

This transformation method may be used for the transformation of point position as well as for transformations of heights. Its principle is an interlay of polynomial spatial function of a k-degree with identical points [14].

The transformation relation of geographic coordinates of B,L:

where parameters are:

- B,L, geographic coordinates;
- a,b, searched ransformation parameters;
- U,V, reduced geographic coordinates in ETRS89;
- B_o,L_o selected reduction values;
- c selected constant (reduced coordinates should be in the interval <-1,1>);

and indexes:

- k general transformation degree
- i,j integers with a condition $i - j \cap j \leq 9$, limits individual member powers integers with a condition $i - j \cap j \leq 9$, limits individual member powers. Increasing the number of polynomial function degrees a planar polynomial more approaches all the identical points and this way it is possible to obtain lower values of transformation key accuracy characteristics. Using a sufficient Increasing the number of polynomial function degrees a planar polynomial more approaches all the identical points and this way it is possible to obtain lower values of transformation key accuracy characteristics. Usin a sufficient number of quality identical points and their balanced distribution it is possible to give a true picture of a local network deformation via a polynomial function. This transformation was applied for the whole Czech Republic between ETRS89 and S-42/83.

Other methods of converting local planimetric systems into geocentric ones

Conforming transformation of higher orders

This transformation respects angles to avoid a new network shape disruption. Its application is exceptional, e.g. when inserting a more accurate network into an older, less accurate basis. The transformation is grounded in a condition which stipulates that elementary patterns in both the coordinate systems are similar. Straight lines in one coordinate system are represented in another one as generally bended with a disrupted dividing ratio, but the angles between their images are preserved. This method's disadvantage is ambiguous results on the borders of transformed areas and therefore, this method is not much suitable to convert points from a larger area [15]. This transformation of the third order was applied to create the 1952 Coordinate System (S-52).

Transformation of system coordinates through a multiple regression analysis

Helmert transformation, according to [16], has a linear character. By means of its parameters it is not possible to put a local nonuniformity of a reference triangulation network well. Nonuniformity of local triangulation networks may be reduced by means of multiple regression relations used for transformations.

$$\Delta B = A_{0,0} + A_{1,0}U + A_{0,1}V + A_{2,0}U^2 + A_{0,2}V^2 + + A_{1,1}UV + ... = \sum_{p,q} A_{p,q}U^pV^q.$$

The transformation can be described by means of the following multiple regression relations:

$$\Delta H = C_{0,0} + C_{1,0}U + C_{0,1}V + C_{2,0}U^2 + C_{0,2}V^2 + + C_{1,1}UV + ... = \sum_{p,q} C_{p,q}U^pV^q$$

$$\Delta L = B_{0,0} + B_{1,0}U + B_{0,1}V + B_{2,0}U^2 + B_{0,2}V^2 + + B_{1,1}UV + ... = \sum_{p,q} B_{p,q}U^pV^q,$$

where p,q = 0,1,2, …, U=k(B-B_0) is normalized geodetic latitude. V=k(L-L_0) is normalized geodetic longitude, k is a scale factor and B_0, L_0 are coordinates of a transformed area centre.

The author states [16] that multiple regression transformation is more than four times more effective than Helmert transformation into EUREF89 and as much as six times more effective in case of transformation of S-42/83 to EUREF89.

Transformation of system coordinates by means of non-linearized rotation matrixes and conforming projection

In [17] there is a processed transformation method from WGS-84 geodetic datum coordinates into local coordinate system by means of non-linearized rotation matrixes in a way millimetre transformation accuracy was ensured and thus there was a high accuracy of point position determination using NAVSTAR GPS technology. The method has several advantages. Through the transformation a high relative accuracy of point position determination using GNSS technology is preserved and next, the local system is implemented in a way no difficult relations to reduce the measured parameters were necessary. Comparing it with a similarity transformation, instead of surveying in three identical points, one is sufficient.

The mathematical formulation of coordinate transformation from the geocentric system into a local geocentric system by means of rotation matrixes and conforming projection [18] making use of P surface, osculating sphere and its consequent transformations into a local system retains a high accuracy of coordinate determination by means of GNSS technology. It does not distort angles or produce scale errors. In addition, it minimizes network point relative heights from the basic plane as a result of which distance reductions from relative height above sea level is mostly negligible. This also ensures sufficient conformity of the local planimetric system with S-JTSK by means of one identical point.

Non-linear 3-D transformations

It is apparent from the results in [19] that the lowest positional deviation is reached by a general quadratic transformation and it is stated that the most suitable transformations between the geocentric coordinate system and S-JTSK are non-linear transformations. According to [20] the model of local 3-D transformation masters the problem of correlation between estimated parameters, which occurs during global non-linear transformations and it is suitable for small areas.

Direct transformation between S-SK and ETRS89 systems

The direct transformation between the systems of S-SK (St.Stephen) and ETRS89 has been implemented in Brno and its environs. A set condition was to start from points of an observation grid and thus for the St.Stephen Datum, cadastral triangulation points (1822-1829) of order I –III within Brno region were used, in case of which it was possible to document their origin and accuracy. The original point coordinates of Stable cadastre system, St.Stephen in Brno, were obtained from archive materials of UAZK, namely in the protocols of triangulation calculations (1822-1827). After carried out terrain reconnaissance and identity analysis [1] 8 points were selected which were suitable for surveying using GNSS technology.

The reference station for point surveying using GNSS technology was decided to be the south-west pillar on the roof of the Faculty of Building at VUT in Brno. This pillar was labelled under a working title of TUBO_JZ. Three two-frequency apparati were used for measuring and the mean time of measuring in the individual points was about one hour. The following parameters were selected for calculations:

- Cut of angle:10°
- Ephemeris:Broadcast
- Tropospheric model:Saastamoinen
- Ionospheric model: Standard
- Maximum baseline length : 20 km
- Processing mode:all baseline

The information on the course of calculations or a computational record including the final coordinates, variance-covariance matrix and further accuracy characteristics are available in (Staňková 2006).

The transformation was implemented using software of Leica SKI-pro company, where an ellipsoid used for the St.Stephen Datum was defined and the commencement of the coordinate system (St.Stephen) in geographic coordinates was decided.

The applied software offers several types of transformations:

- *Classical 3D* , which is a classical spatial transformation according to Bursa-Wolf method, or Molodensky-Badekas method.
- *Interpolation*, is a method that inserts the measured coordinates among the coordinates of a given system, i.e. their position and height independent of one another. Errors in heights are not projected into positions and neither ellipsoid nor map projection must be known. There is no necessity to identify points for positional or height adjustments. The method is suitable for transformations within small areas (10-15km^2).
- *OneStep* transforms positions and heights separately. Positions are transformed individually through a classical 2D transformation.
- *TwoStep* is a method of split transformations of position and height. Position is determined by 3D transformation; heights are calculated separately.

For direct transformations between the systems of SK and ETRS89, *Interpolation Transformation* and *OneStep Transformation* were selected, due to independent transformations of position and height. Next, transformation keys and dX and dY residual values were calculated for *Interpolation Transformation* – See Tab.1 and *OneStep Transformation* – See Tab.2.

Tab. 1

Table of residual values of *Interpolation Transformation*

Interpolate Transformation		
dX [m]	dY [m]	Position [m]
-0,190	0,048	0,196
-0,044	0,042	0,061
-0,088	-0,082	0,120
0,058	-0,012	0,059
-0,093	-0,005	0,093
0,129	0,004	0,129
-0,150	0,085	0,172
0,377	-0,079	0,386

Tab. 2

Table of residual values of *OneStep Transformation*

OneStep Transformation		
dX[m]	dY[m]	Position m]
-0,308	0,251	-0,398
0,044	-0,014	-0,046
-0,152	-0,121	-0,194
0,262	0,004	-0,262
-0,214	-0,131	-0,250
0,146	-0,049	-0,154
-0,226	0,089	-0,243
0,448	-0,029	-0,449

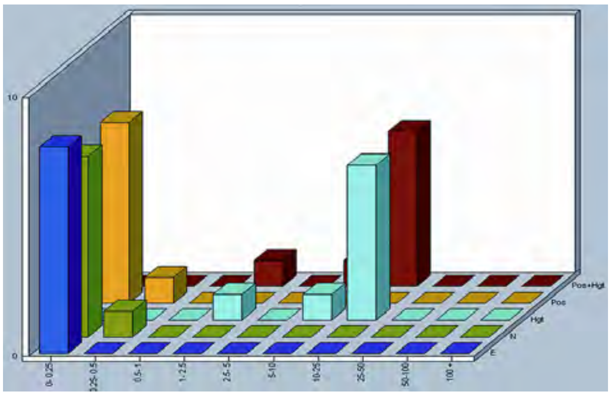

Chart 1. Residual values of Interpolation transformation

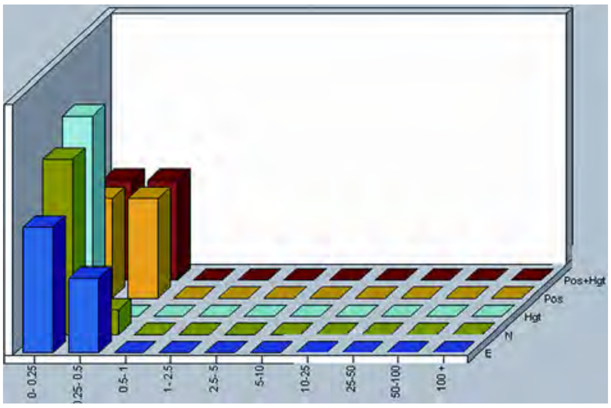

Chart 2. Residual values of Onestep transformation

Conclusion

The objective of the experiment implementation was to prepare a key of transformation for direct transformations between SK and ETRS89 systems. To make a transformation key two methods were used. A set of S-SK points (St.Stephen Datum) of order I –III from the original adjustment was selected for transformations. Identical point coordinates in ETRS89 system were surveyed using GNSS technology after reconnaissance of all 36 preliminary determined points. Measuring provided a set of 8 trigonometric points in SK and ETRS89 systems.

Two transformation methods were used for direct transformations between the systems of SK and ETRS-89:

- OneStep transformation and
- Interpolation transformation.

Both the transformations are executed through a key of transformation as separate tasks for positions and heights. Transformations were solved by means of computer software Leica SKI-pro, where an ellipsoid for SK system had been defined and St.Stephen Datum's origin coordinates had been inserted in geographic coordinates. In order to produce a transformation key, 8 identical points were used. For both the transformations, transformation keys and residual values of dY and dX were calculated. As expected, lower residual values were shown in case of an Interpolation Transformation.

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Результати міжсистемного трансформування в Чеській республіці

Г. Станкова

У дослідженні використано результати супутникових спостережень для цілей земельного кадастру. З опрацювання результатів супутникових спостережень отримано координати пунктів у глобальній системі координат $ETRS89$. Їх інтерполяційне перетворення в кадастрову систему координат $S-SK$, яка використовується в Чеській республіці, виконано двома методами: за допомогою трансформаційних степеневих поліномів та за допомогою тривимірного перетворення координат Бурші–Вольфа. Одержані результати показали, що вищу точність перетворення дають трансформаційні поліноми.

Результаты межсистемного трансформирования в Чешской республике

Г. Станкова

В исследовании использованы результаты спутниковых наблюдений, проведенных для земельного кадастра. В результате обработки спутниковых наблюдений получены координаты пунктов в глобальной системе координат ETRS89. Их интерполяционное преобразование в кадастровую систему координат S-SK, которая применяется в Чешской республике, проведено двумя методами: с помощью степенных полиномов и с использованием трёхмерного преобразования Бурша–Вольфа. Полученные результаты показали, что высшую точность преобразования дают трансформационные полиномы.