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Transformation of initial cartographic materials for the "Main State Topographic Map" to coordinate system UCS-2000

Abstract. Initial cartographic materials were determined to create the topographic database of the "Main State Topographic Map". They require preparation for creating (updating) digital topographic maps at the scale of 1:50,000. One of the stages of preparation of input cartographic materials is their transformation to the coordinate reference system UCS-2000. The goal of the article is to research the problem of transformation of points coordinates by the rigorous mathematical method for referencing cartographic materials from the coordinate systems CS-42/CS-63 to the State Geodetic Coordinate Reference System UCS-2000 (after this – UCS-2000) by geographic information systems (GIS) for creation (updating) digital topographic maps at the scale of 1:50,000 to create the seamless topographic database of the "Main State Topographic Map" on the territory of Ukraine. Authors propose a method of transformation orthophoto at the scale of 1:10,000 to UCS-2000 in Cartesian coordinates of Gauss-Krüger projection in the corresponding 6-degree zone in the adopted state interchart of topographic maps at the scale of 1:50,000. This method consists of cartographic materials transformation using a transformation field in the form of a GRID model based on the triangulation TIN model using the finite element method. The choice of the finite element method and the peculiarities of affine transformation are mathematically substantiated. Also, the authors determined the requirements for the method of coordinates transformation.

Keywords: topographic mapping, finite element method, transformation coordinates, UCS-2000, GIS

1. Introduction

The necessary condition for developing the National spatial data infrastructure is the geoinformation approach to topographic mapping (Karpinskyi & Lazorenko-Hevel, 2020).

Furthermore, the traditional requirements for measuring and imaging properties, such as relevance, reliability, accuracy and clarity are inherited from the classic topographic map. Instead, digital and electronic topographic maps make additional requirements. First, it is necessary to highlight the requirements for internal design – the aligned points, their accuracy characteristics and spatial location and distribution. If the number and density of aligned points are insignificant in the geographic area to be transformed, then the requirements for the accuracy of transformation methods increase. The choice of transformation methods depends on the properties of the obtained results that must ensure the achievement of the purpose for the transformation of coordinates (Karpinskyi & Lazorenko-Hevel, 2020).

The authors of the article research the problem of transformation of points coordinates by rigorous mathematical method for referencing cartographic materials to UCS-2000 by geographic information systems (GIS) for the creation (updating) digital topographic maps at the scale of 1:50,000 to create the seamless topographic database of the “Main State Topographic Map” on the territory of Ukraine (after this – project).

2. Formulation of the problem

Input cartographic data and project materials are:

– the existing digital topographic maps at the scale of 1:50,000,

– the PlanetScope orthophoto,

– the raster models of topographic maps production print at the scale of 1:50,000,

– the raster models of topographic maps production print at the scale of 1:10,000,

– the orthophoto at the scale of 1:10,000.

The last update of the existing digital topographic maps on Ukraine’s territory was performed in 2002–2004 based on available cartographic materials and remote sensing data of the Earth of the IRS satellite imaging system (image resolution is 5.9 m).

The PlanetScope orthophotos are provided in GeoTIFF format in UCS-2000, Cartesian coordinates of Gauss-Krüger projection in the corresponding 6-degree zone in the state interchart of maps at the scale of 1:50,000 with the resolution of 2.6 – 3.1 m. The area’s status is 2017.

The orthophotos at the scale 1:10,000 were created in the coordinate system CS-63 based on aerial photographs of the territory of Ukraine in the period from 2006 to 2012 within the World Bank project “Issuing the state acts of land ownership in rural areas and development of cadaster system”. Orthophotos are provided (junction blocks of 16 orthophotos) in GeoTIFF format in UCS-2000 in Cartesian coordinates of Gauss-Krüger projection in the corresponding 6-degree zone in the state interchart of maps at the scale of 1:50,000 with the resolution of 1.0 m.

The existing digital topographic maps at the scale of 1:50,000 and the raster models of topographic maps production print at the scale of 1:10,000 and 1:50,000 were created in the CS-42 coordinate system, the Gauss-Krüger projection.

As the existing cartographic materials were created on other datums in coordinate systems whose implementation in Ukraine has distortions of up to 6 m, they can only be transformed to the UCS-2000 using a transformation field.

3. The purpose of the research

The purpose of the article is to research the problem of transforming the points coordinates by rigorous mathematical method for referencing cartographic materials from the coordinate systems CS-42/CS-63 to the State Geodetic Coordinate Reference System UCS-2000 by geographic information systems (GIS) for the creation (updating) digital topographic maps at the scale of 1:50,000 to create the seamless topographic database of the “Main State Topographic Map” on the territory of Ukraine.

4. Methods and theory

4.1. Transformation from CS-42/CS-63 to UCS-2000

Topographic, geodetic and cartographic work in Ukraine is carried out by using UCS-2000 according to some resolutions (Nakaz, 2012; Postanova, 2016; Zakon Ukrainy, 2020) starting from January 1, 2007. The structure of UCS-2000 includes (Bondar et al., 2001; Kucher et al., 2003):

– the XYZ spatial Cartesian coordinate system,

– the BLH geodetic (ellipsoidal) coordinate system,

– Gauss-Krüger Cartesian coordinate system in 6- and 3-degree zones,

– 27 local coordinate systems.

The structure of UCS-2000 is presented in Figure 1. The *XYZ* spatial coordinate system and the *BLH* geodetic (ellipsoidal) coordinate system extend to the entire territory of Ukraine. The Cartesian coordinate systems in 6- and 3-degree zones in the Gauss-Krüger projection with the corresponding standard central meridians cover territory as the whole of Ukraine. The local coordinate systems are used to provide large-scale topographic and cadastral surveying. The State Enterprise “Research Institute of Geodesy and Cartography” (hereinafter – SE “RIGC”) created a description of the coordinate systems UCS-2000 in the terms of ArcGIS for the territory of Ukraine in the **.prj* format.

The input cartographic data and project materials must be transformed into the current coordinate system UCS-2000. The authors recommended rigorous mathematical methods (Kin & Karpinskyi, 2020) of coordinate transformation to solve this problem.

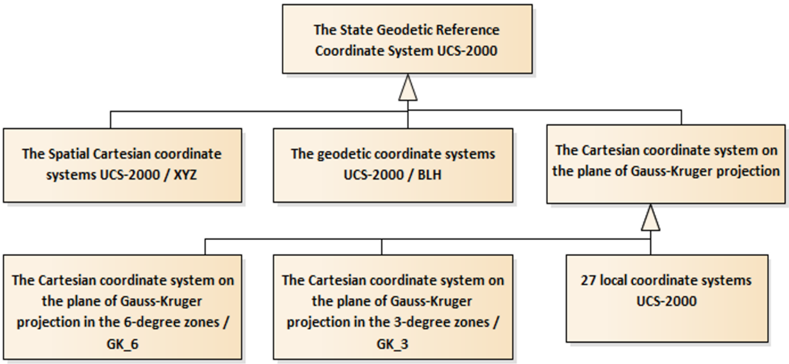

Figure 1. UML – diagram of the structure of the State Geodetic Reference Coordinate System UCS-2000

4.2. Requirements for coordinate transformation

About the accuracy of determining point coordinates in different coordinate systems, the authors set the following requirements:

– *Inhomogeneity of transformation*. It consists of selecting such transformation parameters in which the coefficients of a scale change on each coordinate axis are different, which determines the heterogeneity of the coordinate systems. Thus, as a result of the transformation, the listed coordinates of the input system aligned points precisely determine the coordinates values of the output system points.

– *Continuity of transformation*. It is in fact that a point lying on the boundary of one geographic area of the coordinate system is transformed into a point that will also lie on the boundary of the same geographic area, and its location will be the same when using the transformation parameters of one or another geographic area.

– *Independence of local transformation* provides a consistent local refinement of the transformation parameters in geographic areas where the density of the aligned points increases.

4.3. Mathematical formulation of the problem

The article by Karpinskyi (2002) describes transformation methods and analyses the compliance with the requirements for the coordinates transformation and determines that the affine transformation by the finite element method fully satisfies these requirements.

4.4. Affine transformation by finite elements

The problem of coordinate transformation can be effectively solved by affine transformation with finite elements (Grachov, 2005; Karpinskyi & Grachov, 2001; Karpinskyi, 2002). Consider the task of transforming coordinates in a two-dimensional field. The affine transformation of any point from one coordinate system to another can be represented as:

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} m_x \cos\theta_x & m_y \sin\theta_y \\ m_x \sin\theta_x & m_y \cos\theta_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \end{pmatrix} \qquad (1)$$

To determine the six transformation coefficients: $x_0, y_0, \theta_x, \theta_y, m_x, m_y$ it is necessary and sufficient to have the coordinates of three aligned points that do not lie on one line. These three points form a triangle. If the number of aligned points is more than three, then the whole geographic area given by the aligned points should be divided into finite elements – triangles, the vertices of which are the aligned points that form the TIN-model (Triangulated Irregular Network). The division of a geographic area into triangles by the Delaunay method is often used (Karpinskyi, 2002). Delaunay triangulation is well-balanced: its triangles go to equilateral ones, and the system of triangles always has a convex boundary (Karpinskyi, 2002).

It should be noted that in this study, 24 426 points of the State Geodetic Network, which were created in the past by triangulation, are used to create triangles for the TIN model (see Figure 2). And the conditions for the creation of Delaunay triangles and the triangulation network are similar by almost 80%.

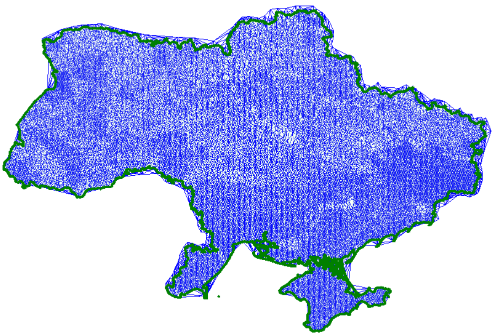

Figure 2. The transformation field by TIN-model

The best solution would be a conscious division into triangles based on an in-depth analysis of the geodetic network. The linear system of six equations with six unknowns is formed and solved after dividing the area into the finite elements – triangles, for each triangle based on the equation (1): $x_0, y_0, \theta_x, \theta_y, m_x, m_y$.

Transformation (1) can be obtained through the linear basis functions of a triangular finite element (Karpinskyi, 2002). The found transformation parameters are used only for those points that belong to this finite element – a triangle.

Affine transformation by the finite element method is characterized by the following properties:

– determination of transformation parameters for each triangle depends only on the coordinates of the vertices of the triangle;

– when transforming coordinates, each point (vertex of a triangle) in one coordinate system exactly "passes" to an identical point (vertex of a triangle) in another coordinate system;

– the transformation is continuous because the points lying on the edges of the triangles in one coordinate system are transformed into the points lying on the edges of the transformed triangles in another coordinate system, regardless of which parameters were used to transform adjacent triangles;

– increasing the number and density of aligned points in some geographic areas causes only a local refinement of the transformation parameters, and the transformation parameters in other areas remain unchanged.

The specified characteristic properties of affine transformation fully satisfy all the requirements for the transformation coordinates by the finite element method.

5. Results

For the TIN model, the input data were 24 426 geodetic points of the State Geodetic Network, which were also determined in UCS-2000 (800 points by GNSS methods, which formed the framework), then in CS42/CS63 by linear-angle measurements and rigorous compatible network alignment. The RMS value of the geodetic points as a result of the alignment of the entire network to the whole territory of Ukraine does not more than 10–15 cm. For CS42/CS63, the coordinates of previous years were used, and the distortion in this network reaches 6 metres.

The transformation coordinates were calculated using the transformation field, which was created on the basis of 48 514 triangles. This transformation field was also aligned with the edges of the triangulation networks of the State Geodetic Network (see Figure 3). In this figure, the blue lines and blue triangles form the second- and third-class triangulation network, and the red lines and red triangles are the first-class triangulation network.

The procedure for creating the transformation field is as follows:

– creating of the TIN model,

– determining the size of the GRID model for the territory of the object,

– creating a regular GRID model,

– determining the values of corrections to the coordinates in the grid nodes using the interpolation method,

– checking the accuracy of the GRID model.

Nowadays, many countries resort to the practice of transforming from one coordinate system to another using a grid-based method – the method of National Transformation version 2 (hereinafter – NTv2, Ahrens & Böhmer, 2010; Berk & Komadina, 2013; Carosio & Plazibat, 1995; Fazilova, 2022; Garnero, 2014; González-Matesanz et al., 2003; Markič et al.,

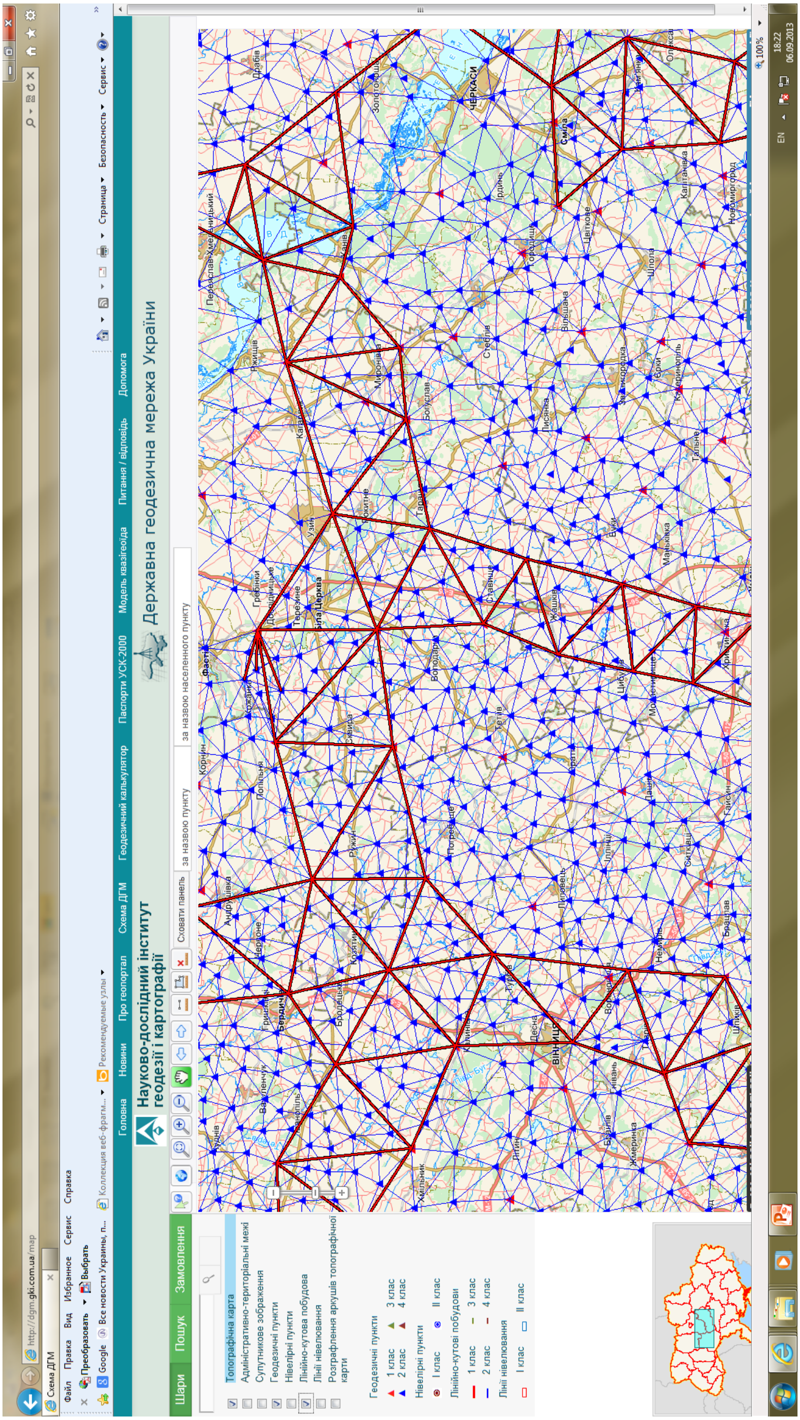

Figure 3. The alignment of the transformation field with the edges of triangulation networks of the State Geodetic Network

2018; Ono, 2009; Van der Marel, 2014; Weber et al., 2022). A set of binaries contains the differences between two coordinate systems. To calculate the exact values for each point, the method of bilinear interpolation is used (Grachov, 2005). NTv2 – is a file describing a binary grid with an extension *.*gsb*. This format describes two-dimensional (2D) transformation, which does not use the third coordinate – height. Therefore, considering the world practice, it is advisable to create a transformation field in the form of a GRID model.

In this case, according to the finite element method, the transformation field is divided into quadrangular finite elements. The task of constructing a transformation field in the form of a GRID-model is solved by constructing a regular array of values Δx, Δy of nodal points on an irregular array (x, y) – coordinates, and then determining the interpolation coefficients to transform the coordinates for each finite element. The general algorithm for transforming the coordinates of coordinate points from CS-42 to UCS-2000 consists of the following stages:

– creation of an interpolation model of the transformation field for a given territory,

– transformation of coordinates according to the interpolation model of the transformation field.

The GRID model was built in three stages:

– creating a transformation field as a TIN model (dividing the territory into separate triangles with the vertices of the combined geodetic points),

– creating a regular grid in increments of 15 × 15 seconds,

– determination of corrections (interpolation) to the coordinates of grid nodes.

Using the finite element method, a transformation field was created, namely in the form of a GRID model in NTv2 format. During the creation and updating of digital topographic maps at the scale of 1:50,000, ArcGIS for Desktop software was used, where the transformation field was implemented as a GRID model in NTv2 format.

It is proposed to transform coordinates from low-precision to high-precision coordinate systems in the following sequence (see Figure 4):

1. Conversion from the cartesian CS-42 6-degree zone of the Gauss-Krüger projection *(x, y)* to the geodetic coordinate system CS-42 *(B, L)*.

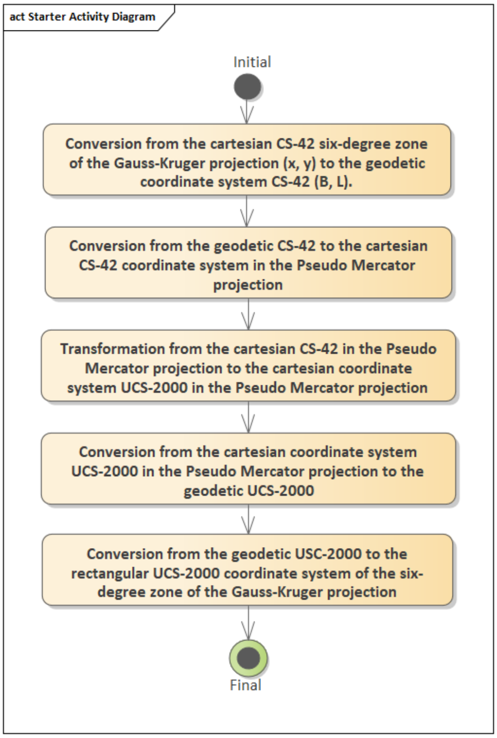

Figure 4. The block schema of the transformation method

2. Conversion from the geodetic CS-42 to the cartesian CS-42 coordinate system in the Pseudo-Mercator projection.

3. Transformation from the cartesian CS-42 in the Pseudo-Mercator projection to the cartesian coordinate system UCS-2000 in the Pseudo-Mercator projection.

4. Conversion from the cartesian coordinate system UCS-2000 in the Pseudo-Mercator projection to the geodetic UCS-2000.

5. Conversion from the geodetic UCS-2000 to the rectangular UCS-2000 coordinate system of the 6-degree zone of the Gauss-Krüger projection.

The need to use the Pseudo-Mercator coordinate system is because the rectangular Gauss-Krüger projection coordinate systems are divided into four 6-degree zones, so Pseudo Mercator was chosen to fully cover the entire territory of Ukraine.

Also, the Delaunay method is applicable for flat rectangular coordinates, and the points of the State geodetic network were also levelled in plan coordinates, but by the finite element method – in geodetic (ellipsoidal) coordinates.

Orthophotos at the scale of 1:10,000 were stored in the coordinate system CS-63, which does not operate in Ukraine now. So, the authors of the article propose the method of transformation orthophoto of the scale 1:10,000 to UCS-2000 in Cartesian coordinates in Gauss-Krüger projection corresponding 6-degree zone in the adopted state interchart of topographic maps at the scale of 1:50,000.

Transformation of coordinates was performed by using a transformation field (developed by SE "RIGC") to transform from CS-42 to UCS-2000 on the territory of Ukraine in NTv2 format, which implements the regular GRID model *NDIGK_NTv_2_Ukraine_v1.gsb*. Access to the data produced in this study is restricted due to the ongoing military conflict in Ukraine.

This transformation field in NTv2 format is defined as a GRID model with a regular grid size of 15 × 15 seconds and is based on the triangulation model (TIN) developed in SE "RIGC" using the finite element method (Grachov, 2005). TIN model is built on reference points – points of the State Geodetic Network-wide Ukraine, the coordinates B, L of which are defined in the coordinate systems CS-42 and UCS-2000 (*CS42 / (B, L) – UCS-2000 / (B, L) * SE "RIGC" ver.2.0*).

The NTv2 transformation field file consists of two parts:

– general information about the transformation field,

– the transformation field within the territory of Ukraine in the form of individual values of corrections from geodetic coordinates B, L in the coordinate system CS-42 to geodetic coordinates B, L in the State Geodetic Coordinate Reference System UCS-2000 in the nodes of the regular grid.

The Method of transformation orthophoto of the scale of 1:10,000 to UCS-2000 in Cartesian coordinates in Gauss-Krüger projection corresponding 6-degree zone in the adopted state interchart of topographic maps at the scale of 1:50,000:

1. Orthophotos at the scale of 1:10,000 are transmitted into raster data format in rectangular coordinates x, y in Gauss-Krüger projection in the coordinate system CS-63 in standard 3-degree zones. Each orthophoto is reduced to a rectangle described around the corresponding trapezoid – a topographic map nomenclature sheet at a scale of 1:10,000 (see Figure 5). Due to this, the orthophotos are represented by a raster model, an array of pixels that correspond to the trapezoidal frame of the topographic map nomenclature sheet at a scale of 1:10,000.

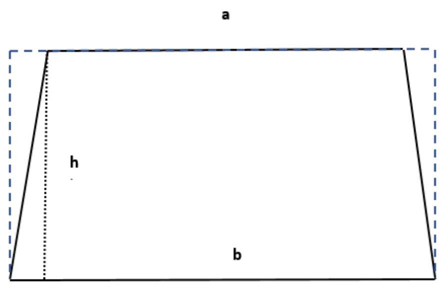

Figure 5. The corresponding trapezoid – a topographic map nomenclature sheet at a scale of 1:10,000

2. The transformation of orthophotos at the scale of 1:10,000 to UCS-2000 in Cartesian coordinates in Gauss-Krüger projection in the corresponding 6-degree zone in the adopted state interchart of topographic maps at the scale of 1:50,000 is carried out in the geographic information system ArcGIS 10.5.

3. The orthophotos at the scale of 1:10,000 to UCS-2000 are carried out in seven stages by the method (see Figure 6).

4. The orthophoto is formed as a result of the reduction of orthophotos at the scale of 1:10,000 in Cartesian coordinates x, y in Gauss-Krüger projection in a standard 6-degree zone in the form of the rectangle described around the corresponding trapezoid – the topographic map nomenclature sheet at the scale of 1:50,000 with the removal of the extra image outside the trapezoid.

The method of orthophotos transformation at the scale of 1:10,000 to UCS-2000 in Cartesian coordinates of Gauss-Krüger projection in the corresponding 6-degree zone in the adopted state interchart of topographic maps at the scale of 1:50,000 was performed by using the GDAL library to work with geospatial data: *gdalinfo, gdal_trnalsate, gdalwrap, gdaladdo, nearblack*, which allowed to perform quickly the preparation of 29,319 orthophotos of scale 1:10,000 directly on the server. The

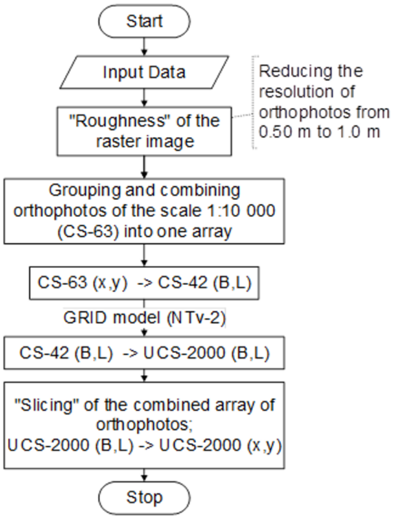

Figure 6. The block schema of the transformation method in ArcGIS

orthophoto is formed as a result of the reduction of orthophotos at the scale of 1:10,000 in Cartesian coordinates x, y in Gauss-Krüger projection in a standard 6-degree zone in the form of the rectangle described around the corresponding trapezoid – the topographic map nomenclature sheet at the scale of 1:50,000 with the removal of the extra image outside the trapezoid.

6. Conclusions

The method proposed by the authors was implemented due to the GDAL library, which provided the quick and accurate solution to the problem of points coordinates transformation for referencing cartographic materials to the State Geodetic Coordinate Reference System UCS-2000 into geographic information systems for creation (updating) digital topographic maps at the scale of 1:50,000.

The authors use affine transformation by the finite element method, which effectively solves the problem of transformation coordinates from one coordinate system to another. It should be noted that the proposed method is effectively implemented in software packages (Karpinskyi & Kin, 2020; Meaden et al., 2013). Also, the use of this method allowed to transfer by the TIN model and the GRID model, forming the transformation parameters for the nomenclature of maps of any scale.

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