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The use of GIS tools in the automation of examining the cartometry of old maps

Abstract. Using the full potential of old maps requires interdisciplinary research, which allows for a comprehensive assessment of facts recorded on the map along with their features. The author of the article is interested in cartometric analysis. It is used to study one of these features – the location of an object in geographical space. The author describes and evaluates the usefulness of GIS tools in the automation of examining the cartometry of old maps and presents her own tool for determining the general scale of maps.

Keywords: old maps, map accuracy, map scale, cartometry, research automation

1. Introduction

Old maps are a valuable source of information in the study of changes taking place in the natural and anthropogenic environment as well as in demographic and cultural studies (A. Konias 2000). In order not to limit the subject of interest of cartography historians, B. Konopska (1994) suggested to adopt and disseminate B.J. Harley's and D. Woodward's (1987) definition of maps as "graphic representations that facilitate a spatial understanding of things, concepts, conditions, processes, or events in the human world". Using the full potential of these maps requires interdisciplinary research, which allows for a comprehensive assessment of a fact (object, phenomenon) registered on the map along with its features (expressed through visual variables). The author of the article is interested in one of these features – the location of an object in geographical space. The basis for assessing the accuracy of the location of individual objects on the map is the cartometric analysis.

Examining the cartometry of maps not only indicates the degree of their inaccuracy, but also provides information on the precision of measuring instruments used in the past, on the chronology of map formation, and borrowings from other cartographic sources (A. Konias 1984; A. Alexandrowicz, E. Jankowska 1989). A pioneer in the study of cartometry of maps covering Polish lands in the past was Henryk Merczyng, who in 1913 published his dissertation *Map of Lithuania from 1613. of Prince Radziwiłł Sierotka in terms of mathematics and cartography* (J. Łuczyński 2001, J. Ostrowski 2014). The literature on the subject shows that W. Hartnack (1939) was the first researcher to visualize the inaccuracies of the location of objects on the map of West Pomerania by Eilhard Lubinus from 1618 using a distortions grid. M. Jankowska, A. Konias, E. Krzywicka-Blum, S. Pietkiewicz, J. Szeliga, J. Łuczyński, K. Nieścioruk, K. Strzelecki also dealt with the cartometry of maps of old Polish lands. Tedious studies of the cartometry of maps, reluctantly undertaken by researchers, were in the 1960s and 1970s a popular subject of master's and doctoral dissertations (mainly at the University of Warsaw[1]). The change took place with the advent of advanced tools of the Geographic Information System (GIS), which began to be perceived as

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[1] A list of 30 master's theses containing assessments of the accuracy of old maps made under the supervision of Prof. S. Pietkiewicz in the years 1955–1971 is provided by J. Ostrowski, 2014, pp. 45–46.

the possibility of at least partially automating the research process.

Initially, the Geographic Information System allowed for the storage, compilation, and analysis of spatial data on personal computers, and with time many processes were automated. In 1989, S. Alexandrowicz and E. Jankowska put their hope in modern IT solutions that would enable a comprehensive assessment of the accuracy of old maps. Despite the fact that since then many solutions have appeared to facilitate the analysis of old maps and to help interpret the obtained results, there is still no comprehensive, fully automated method of testing their accuracy. The author of the article describes and evaluates the usefulness of GIS tools in the automation of examining the cartometry of old maps and presents her own tool for determining the overall scale of maps.

2. Methods of assessing the accuracy of old maps

The most frequently used by researchers classification of map accuracy testing methods is the classification proposed by A. Konias in 1984, who distinguished:
• the geo-historical method,
• the cartographic and mathematical method,
• the geodetic method.
The first is a description in which the researcher should include the circumstances and purpose of the map as well as the analysis of individual elements, e.g. symbols, labels, geodetic control network, reference system, legend, and the scale shown. This method should not be omitted because of the valuable information that may influence the final assessment of the map's accuracy. K. Nieścioruk (2006) wrote that this method allows to avoid mistakes at the very beginning. The intentions of the map's author are very important from the point of view of its accuracy, as he or she could deliberately present some elements in detail and ignore the rest, borrowing them from other cartographic studies.

On the other hand, the cartographic and mathematical method consists of a series of analyses which A. Konias divided into two groups: cartometric and graphic analysis. In cartometric analysis, he included the analysis of scale, distance, directions, geographic coordinates, and areas. These are numerical ways of determining errors on a map, which means that the researcher uses numerical values and mathematical operations. In graphic analysis, errors estimated during the analysis of quantitative data are visualized. In this group, A. Konias included the methods of the distortions grid, circles, polar coordinates, scale variability isolines, and directions. The graphical presentation of errors can also consist of a simple overlay of old and reference maps or a presentation of area errors in the form of a choropleth map (K. Nieścioruk 2006). A similar approach to the above analyses was presented by J. Szeliga (1993), who grouped them into quantitative and graphical analyses.

The geodetic method concerns the preparation of cartographic materials for cartographic and mathematical analysis by assigning them georeference. According to A. Affek (2012), it is "the process of transforming a scanned raster image into a numerical raster map with specific geographic coordinates in a modern reference system", which is commonly called raster calibration. There are two methods of calibration, depending on whether the map has a geodetic control network. One of them is calibration using common points, which is useful when there is no information about the reference system and geographic coordinates on the map. It consists in finding points that have not changed their location or shape and matching them to points on the reference map, which should be the oldest possible cartometric map of the studied area, similar in scale and projection (A. Affek 2012, J. Cajthaml 2011). In this case, it is important to select the method of transforming the calibrated raster. The *adjust* transformation is the recommended type. It combines polynomial methods with the triangulation technique, which causes less distortion of the map, at the same time generating low RMSE (Root Mean Square Error) (M. Jaskulski et al. 2013). However, when analysing the accuracy of an old map, it is important to achieve the smallest possible deformation of the image and preserve angles. This is ensured by the Helmert transformation in which the calibrated map is scaled, rotated and shifted in such a way as to adjust it as precisely as possible to the reference map in accordance with the smallest squares method (B. Jenny et al. 2007, G. Bitelli et al. 2009). According to B. Jenny, this type of transformation differs from others mainly in that it allows for the subsequent calculation of the scale and

rotation of the studied material. This type of research also uses affine transformations using the 1st degree polynomial to move, rotate, and scale separately on the X and Y axes (B. Jenny et al. 2007; P. Noszczyński 2012; V. Baiocchi, K. Lelo 2005). In the literature on the subject, there is also a transformation of the 2nd degree polynomial, which corrects the geometry of the map, while only slightly deforming its content (M. Palczewski 2020; G. Bitelli, G. Gatta 2011).

The commonly used classification by A. Konias was supplemented by K. Strzelecki (2016) with a new computer-cartometric method, which appeared around 2005 thanks to the availability of the MapAnalyst application, used to assess the accuracy of maps in a fully automatic manner. It is worth considering whether a new method should be added to the generally accepted classification, which would include all analyses carried out with the use of a computer, including GIS tools (K. Strzelecki 2016 after D. Beineke 2001; B. Jenny 2006; B. Jenny, L. Hurni 2011).

From the above-described methods of examining the cartometric nature of old maps according to the order proposed by A. Konias, the author was most interested in the mapping and mathematical method due to the greatest potential in the field of process automation.

3. The automation of examining cartometry by means of using GIS tools

The last two decades have brought several solutions allowing to fully or partially automate examining the cartometry of old maps. Each of these methods is briefly described and tested by the author in the following subsections.

3.1. The MapAnalyst application

MapAnalyst (www.mapanalyst.org) is a non-commercial application developed by Bernhard Jenny in 2005 for analysing the accuracy of old maps and visualizing their results. It is an *open-source application*, which means that the user has the ability to add to the *Java* source code, thus contributing to the application's expansion. The use of the tool is not complicated as it only requires importing the old map and the reference map and marking clearly identified points on them.

As part of the expansion of the application, the author introduced the possibility of using the OpenStreetMap map as a base, which shortened the time of adding your own reference map to the view. Another useful function is the import of points previously marked by other GIS programs. However, the inability to import vector graphics data (files with the .shp extension) forces the user to load the data as comma--separated values (CSV) files. It is also important to remember about the appropriate projection of points that should be in the Google Mercator coordinate system (EPSG: 3857). When loading the coordinates of an old map, there is a risk of making an error because in MapAnalyst the origin of the coordinate system is located in the lower left-hand corner, unlike other GIS programs where it is located in the upper left--hand corner (B. Jenny 2006).

The described tool automatically generates a distortions grid, displacement vectors, isolines of scale and rotation variability, and creates statistical indicators summarizing the accuracy of the old map, additionally showing its scale and rotation angle. The application uses Helmert and affine transformations to perform the analyses. To facilitate the selection of a transformation, a report is generated that compares the results of each transformation, which includes the parameters of the scale factor, rotation values, standard deviation, and average position errors. A useful function is also the export of graphical analysis results to various types of files: ESRI Shape, SVG, WMF, Ungenerate, DXF, JPEG, and PNG (B. Jenny, L. Hurni 2011; C. Porter et al. 2019).

Although the application is already quite advanced, the author predicts more opportunities in the future that the expansion of MapAnalyst may bring to users, as there is still no tool that could define the projection of an the old map (B. Jenny 2006).

3.2. The ModelBuilder application

ModelBuilder is an application available in the commercial ArcMap program, used to construct data flow models between geoprocessing tools. This solution allows the user to create their own geoprocessing tools without knowing any programming languages (https://desktop.arcgis.com/en/arcmap/10.3/analyze/modelbuilder/what-is-modelbuilder.htm).

In this application, the input and output layers and the workspace are marked with parameters

that allow the user interface to be displayed after starting the model. This helpful feature makes it easy to reuse the model and share it with a larger audience.

This method was used by M. Palczewski (2020) when building a model of distance analysis and thus automating the process of creating lines between the stable points of the old map and the reference material (Construct Sight Lines tool), calculating their lengths (Add Geometry Attributes tool), combining the attribute table of two sets of stable points (Join Field tool), creating a new field of the attribute table and calculating the absolute distance error (Add Field and Calculate Field tools), and finally determining the sum of distance errors for individual points (Dissolve tool) (fig. 1).

The author additionally combined the table of attributes of the output layer of the model with the table of attributes of the input layer representing the stable points of the old map in order to visualize the results of the circle method analysis.

The non-commercial QGIS program has a similar solution, which provides a graphical modeling tool that works in a similar way to ModelBuilder.

3.3. The Surfer application

Surfer is a commercial suite of Golden Software, Inc. developed with the purpose of imaging the terrain surface using isolines. Depending on the data set, the user can use one of 12 interpolation methods (*Surfer. User's guide* 2002). K. Nieścioruk (2006) made isolines of scale variability and the correlation coefficient with the help of this program, choosing natural neighbor interpolation (fig. 2). In his opinion, this is the best method when the data is not regularly distributed and when the expected result should not exceed the input data set.

3.4. Python script

QGIS is a non-commercial *open-source* program created by GIS enthusiasts for viewing, editing, and analyzing spatial data. Its advantage is the ability to create your own tools and plug-ins using the Python programming language. This gives users the ability to manage data and automate processes. Taking advantage of this possibility, the author attempted to develop
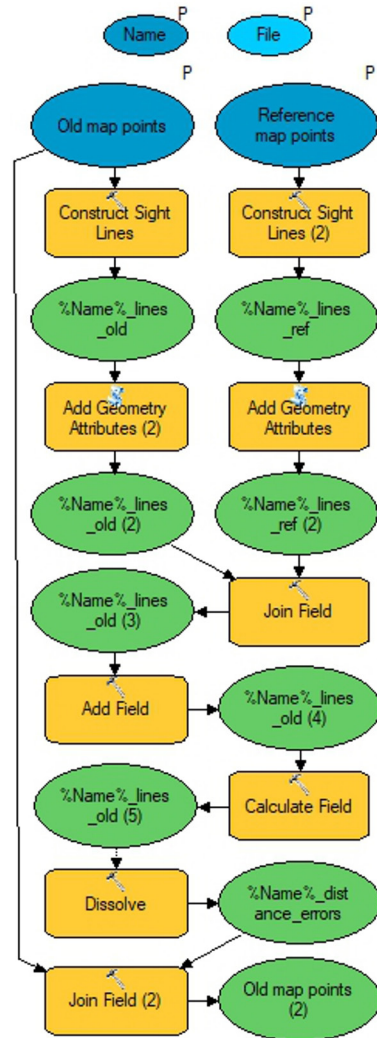

Fig. 1. Model of data flow between geoprocessing tools presenting the procedure of old map distance analysis (source: M. Palczewski 2020)

a simple tool that determines the general scale of the studied map, aiming at automating the process of assessing the accuracy of old maps using scripts written in Python.

3.5. The author's proposal of a tool determining the general scale of the map

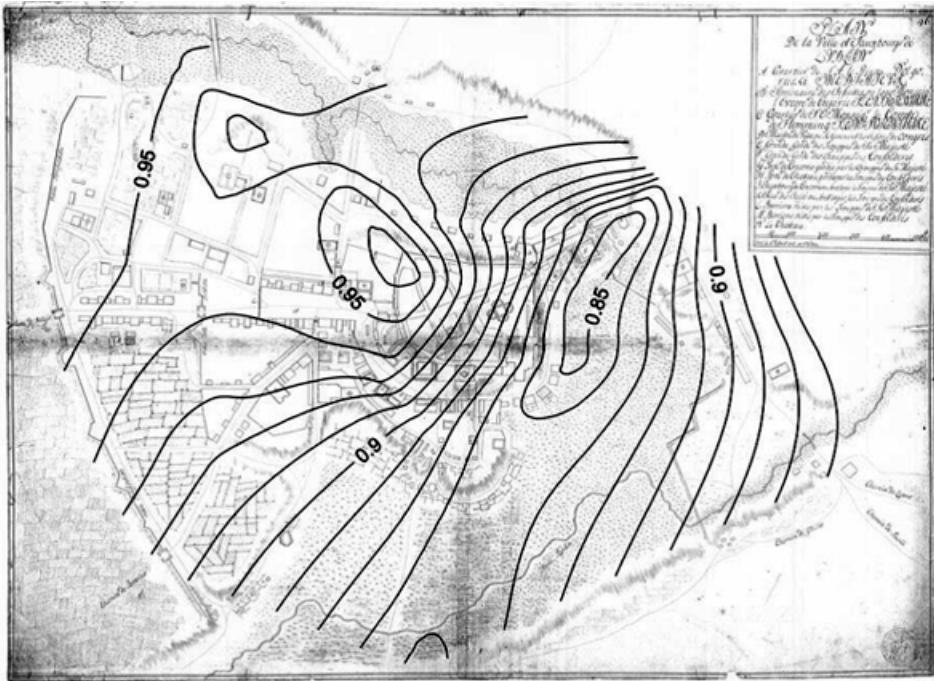The tool takes two input layers – the reference map stable points and old map stable points,

Fig. 2. Isolines of the correlation coefficient (source: K. Nieścioruk 2007)

and then creates two sets of distances between the points of both input layers without repetitions. Based on the obtained results, it calculates the local scale coefficient and the local scale for each stable point according to the following formula (J. Łuczyński 2001):
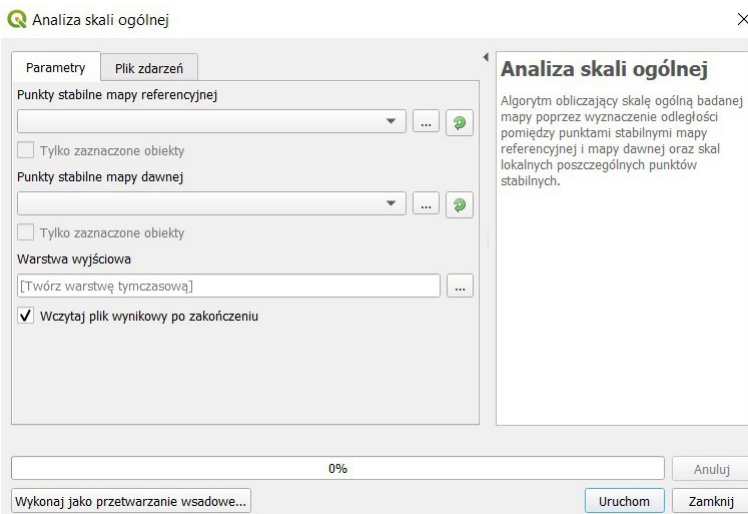
$$S = \frac{R}{D}$$

Fig. 3. Interface of the tool calculating the general scale of the studied old map (prepared by M. Kuźma)

Where:

S – local scale coefficient

R – distance on the reference map

D – distance on the old map

This operation is followed by the calculation of the general scale by determining the arithmetic mean of all local scales and presenting it in numerical form (fig. 3). The proposed table of attributes contains the first two columns that indicate the ID of two sets of input data, the distance between the stable points of the reference material and the old map, the local scale, and finally the general scale of the studied map (fig. 4).

This requires converting the coordinates to a Mercator projection (EPSG: 3857) and creating a CSV file or other file that separates values with commas. Another way is to import the old and reference maps or use the ready-made OpenStreetMap (OSM) base and determine the stable points in the application (B. Jenny 2007). The author decided to identify common points on the OSM base and the old map loaded into the application. In this way, 25 pairs of points were created, which were later used to compare the results of the general scale analysis performed in MapAnalyst and with the Python script in QGIS.

	Zestaw punktów nr 1	Zestaw punktów nr 2	Dystans (mapa referencyjna) [m]	Dystans (mapa dawna) [m]	Skala lokalna	Skala ogólna
0	0	1	32121	31379	1:1023670	1:999908
1	0	2	38928	39319	1:990055	1:999908
2	0	3	11937	12212	1:977507	1:999908
3	0	4	23133	23469	1:985694	1:999908
4	0	5	7978	7919	1:1007522	1:999908
5	0	6	15691	16216	1:967601	1:999908
6	0	7	19838	20207	1:981746	1:999908
7	0	8	19479	20358	1:956834	1:999908
8	0	9	29931	29513	1:1014179	1:999908
9	0	10	22200	21792	1:1018760	1:999908
10	0	11	23891	24573	1:972254	1:999908
11	0	12	8534	9141	1:933630	1:999908
12	0	13	19484	19956	1:976346	1:999908
13	0	14	42337	43079	1:982785	1:999908
14	0	15	22281	22848	1:975190	1:999908
15	0	16	52362	52006	1:1006855	1:999908
16	0	17	45463	45194	1:1005937	1:999908

Fig. 4. An example of the result layer attribute table of the algorithm calculating the general scale of the old map (prepared by M. Kuźma)

4. Comparison and evaluation of the presented methods

In order to compare the methods for examining the cartometry of old maps, a map of the Duchy of Cieszyn at the scale of 1:200,000 was chosen as an example (fig. 5). It was analysed using the methods presented above.

Before starting the analyses, two sets of stable points should be determined – one set for the reference map and the other for the old map. When starting the analysis in MapAnalyst, the user has a choice of two methods of entering points into the application. If the user already has such sets, he can load them as a text file.

The first analysis compared isolines of scale variability. The default interval of 5000 was selected as the input parameter. The process is invisible to the user. The application generates two raster grids, calculates the scale and rotation value in each grid cell, and then creates isolines using the contouring algorithm (B. Jenny 2007). The application does not show the labels, which makes it much more difficult to interpret the result (fig. 6). You can check the value of the isolines by hovering the cursor over them. It is much more time consuming to create isolines in Surfer. It is necessary to determine a mesh of triangles whose vertices are stable points, then calculate for each side of the local

Fig. 5. General map of the Duchy of Cieszyn, 1:200,000, Cieszyn 1918 (source: Archive of New Files, group 260, reference number 84)

scale, generate triangle centroids and assign them the arithmetic mean of the three nearest values (K. Nieścioruk 2006). The data was compiled by the author in ArcMap. Difficulties that may be encountered by the user when trying to construct an isoline of scale variability in this program have been described by M. Palczewski (2020). The data prepared in this way can be used to create isolines by means of several interpolations. For the purposes of this comparison, the author used the natural neighbor method. Surfer, like MapAnalyst, provides a layer properties window, thanks to which the user can quickly change the isoline interval, as well as their transparency and size. The result of the analysis carried out in this program is clearer than in the case of MapAnalyst. The automatically created labels are a great help in interpreting the result (fig. 6).

To assess the usefulness of the author's tool for assessing the overall scale of the map, the previously created sets of stable points were exported to the Esri Shape (.shp) format. The points loaded into the QGIS program were placed in the 1992 coordinate system (EPSG: 2180) and the algorithm was launched. The result was compiled with a report comparing MapAnalyst transformations (fig. 7).

In order to carry out an analysis of the general scale from start to finish in the QGIS program, two sets of stable points should be determined – one set for the reference map and the other for the old map. The author used the point layer of the State Register of Geographical Names (PRNG) as reference material, symbolizing settlements located in the territory of contemporary Poland (http://www.gugik.gov.pl/pzgik/dane-bez-oplat/dane-z-panstwowego-rejestru-nazw-geograficznych-prng). Settlements located in Slovakia and the Czech Republic were obtained from geoportals of these countries (https://www.geoportal.sk, https://geoportal.cuzk.cz). In order to be able to read the information from the original, uncalibrated map sheet, the author determined the local system using the scale placed on the map and calculating the approximate dimensions of the sheet, which served as coordinates (P. Noszczyński 2012). The next stage involved the creation of two sets of regularly spaced points clearly identified on the old map and reference material. The result of the analysis shown in figure 8 shows the general

Fig. 6. Scale variation isolines with an interval of 2000 generated in Surfer (left) and isolines of scale variation with an interval of 5000 constructed in MapAnalyst (right) (prepared by M. Kuźma)

scale equal to 1:192,562. The error in the calculations may result from the inaccuracy of matching the stable points of the old map with

the reference material, consisting of points representing the areas of individual towns. Additionally, the creation of a local coordinate system was an experiment conducted to test the algorithm and had a large impact on the inaccuracy of the result.

The comparison presented above proves that deriving the scale of the old map from the affine or Euclidean transformation is more accurate than the classic method based on measuring the distance between stable points (B. Jenny 2011). However, the goal of the author of this article is to show the potential user what automation capabilities GIS tools have. Perhaps this direction of the expansion of the QGIS program will bring new solutions in the future for the assessment of the cartometry of old maps.

5. Conclusions

The above-mentioned tools for automating the process of assessing the accuracy of old maps differ in terms of application, difficulty of use, and time consumption, but each of them is useful and has possibilities for further expansion. The ModelBuilder application is often used by GIS users to streamline even the simplest but recurring operations. However, it is not suitable for the visualization of the obtained results. It is an application that runs in the commercial ArcMap program, which means it cannot be used universally, like Surfer. It seems promising to expand Python scripts towards a multitasking

```
Helmert (4 Parameters)
Scale:              1:202 200
Rotation:           0° [cw]
Std. Deviation:     ±927m
Mean Pos. Err.:     ±1 311m


Affine (5 Parameters)
Scale Hor.:         1:196 000
Scale Vert.:        1:210 700
Rotation:           0° [cw]
Std. Deviation:     ±754m
Mean Pos. Err.:     ±1 067m


Affine (6 Parameters)
Scale Hor.:         1:196 000
Scale Vert.:        1:211 000
Rotation X:         0° [ccw]
Rotation Y:         1° [cw]
Std. Deviation:     ±746m
Mean Pos. Err.:     ±1 055m
```

Fig. 7. The result layer attribute table of the algorithm and a report generated by MapAnalyst showing the generall scale of the old map depending on the applied transformation method (prepared by M. Kuźma)

Fig. 8. The result layer attribute table of the algorithm, presenting the general scale for the input data obtained in the program (prepared by M. Kuźma)

tool that limits the role of the user to only selecting input parameters. The program will perform further analysis without the user's involvement. The ease of expanding this method was checked and confirmed by the author of the article.

The analysis of the available GIS tools supporting the process of analyzing the accuracy of old maps showed that the most useful, as a comprehensive, non-commercial and fast solution, is the MapAnalyst application, which efficiently carries out as many as 6 basic analyses. Operations on numbers are also visualized in this application. The graphical form of the research results in the analysis of old maps is a great advantage.

The tests of the cartometry of old maps performed by the author led to drawing a general conclusion about the automation of the process. Automation speeds up work and often allows to avoid errors that we are not able to notice without IT tools. However, an uncritical approach

to process automation tools may result in false test results. This is because errors may occur in the operation of the algorithms. Therefore, users should be vigilant and approach such solutions with limited confidence, preferably by testing the results with several methods. Sometimes the most professional way is the use of time-consuming and traditional procedures.

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