GEOREFERENCING OF HISTORICAL MAPS USING GIS, AS EXEMPLIFIED BY THE AUSTRIAN MILITARY SURVEYS OF GALICIA

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Abstract

Archival maps are an invaluable source of information about the state of the geographical environment. They represent the primary research material for analysis of changes in spatial characteristics of the environment. However, a prerequisite for any reliable analysis is an accurate match between archival maps and contemporary cartographic materials and the estimation of error inherent to every match. The most effective way of achieving this nowadays is to use GIS software.

The aim of this work is thus to present and discuss georeferencing methods of archival paper maps that make a precise comparison with contemporary reference layers possible. Two alternative georeferencing methods for maps based or not based on a geodetic network are described, and the georeferencing of archival maps is discussed further by reference to the First, Second and Third Military Surveys of Galicia conducted by the MGI (*Militärgeographisches Institut*), and completed in 1783, 1863 and 1879 respectively.

Introduction

Historical GIS (HGIS) represents a new approach to the study of the past based on Geographic Information Systems technologies (Knowles 2008). In the view of Knowles, it is not so much a study method as a scholarly practice increasingly recognized as an interdisciplinary research direction on the borderlines between historical geography, geoinformation and geoecology. Changes in land use and spatial management, plus the reconstruction of historical landscapes and administrative boundaries are among the principal research topics for HGIS.

In recent years there has been an increase in the number of studies and projects using HGIS in Poland. Among the more interesting initiatives are the GeoHistory Centre (*Centrum Geohistorii*; www.geohistoria.pl), presenting the spatial dimension of the history of the Masovia (*Mazowsze*) region, or else the projects arising under the auspices of the Historical Geoinformation Laboratory (*Pracownia Geoinformacji Historycznej*) of the Institute of History at the Catholic University of Lublin (*KUL*; www.hgis.kul.lublin.pl/lab). A further worthwhile

undertaking is the bringing into operation of a historical geoportal at www.hgis.cartoninjas. net which uses similar principles to the state-run geoportal of Poland's Head Office of Geodesy and Cartography (*Główny Urząd Geodezji i Kartografii – GUGiK*) in making available by way of a Web Feature Service (WMS) rectified pre-war Polish and German maps originating in online map archives (www.mapywig.org, www.mapy.amzp.pl).

Studies employing the HGIS approach need databases with a spatial dimension. Such bases are created using descriptive archival sources (like censuses and tax reports) and cartographic archival sources (cadastral and military maps, town plans). A key element to work – on which the utility of a database and strength of scientific inference will depend – is the process by which the old maps are transformed from paper form into digital form with a vector format. This process comprises the three stages: scanning, georeferencing and vectorisation (Gregory & Ell 2007).

While the Polish terminology regarding the processing of maps from paper to digital forms is not precise, in English widespread use is made of the terms 'georeferencing' and 'rectification'. The first of these terms, more general, means defining existence in physical space. In turn, when used in the GIS context, 'rectification' means converting images to a common map coordinate system. In this paper, the term 'georeferencing' will be used and narrowly defined as the process by which a scanned image of a raster map is processed into a digital raster map with geographical coordinates defined in a contemporary geographic reference system.

In line with GIS terminology, the data obtained from maps are secondary data (Gregory & Ell 2007). A map does not present the results of the direct measurement of reality, but is a model of reality based on the cartographer's interpretation and adjusted to a map's scale and application (Pasławski 2010). However, it is not possible to gather unprocessed data on the landscape a century or more ago – of the kind that we would now derive from satellite imagery or aerial photographs – since the technology necessary for that was obviously not yet known back then. The secondary nature of data therefore ensures automatically that the information value thereof cannot be greater than that of the source data. However, a professionally conducted process of transforming old paper maps into digital form does raise

utility (cartometric[1]) value, while minimising unavoidable losses of information value.

In comparison with the georeferencing of maps coming into existence today, the equivalent work with old maps is far more complicated. Contemporary paper maps most often have generally-known projection parameters, being based on geocentric (Earth-centered) geographic coordinate systems, with graticules[2] or measured grids[3] marked on each sheet. If the print of a source map and the scanning are done properly (with a calibrated large-format scanner, appropriate resolution and image file format), then it is enough to define coordinates of two selected corners of a map and register the image with the aid of the Helmert transformation (shift, rotation, change of scale). The only matter needing to be taken account of is to ensure that the map datum and projection of the data frame in the GIS application are like of the rectified map.

In the case of historical maps, procedure is dependent on whether or not a given map was done on the basis of a geodetic measurement network (Affek 2012), defined as a network of appropriately selected and stabilised points in the field whose mutual spatial interrelationships are established by means of geodetic measurements (Pasławski 2010).

The main objective of this study is therefore to introduce principles for the georeferencing of historical maps based or not based on a geodetic network, as exemplified by the First, Second and Third Military Topographical Surveys of Galicia (a former province of the Austrian Empire, today a part of southern Poland and western Ukraine).

Unless accounted for otherwise in the text, the work described made use of the ArcMap 10.1 software from the ESRI Company.

Georeferencing of maps not based on a geodetic network

Up to the end of the 18th century, maps were not created on the basis of detailed geodetic measurements (Pasławski 2010). Distances and angles were estimated rather than calculated.

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[1] Cartometric (map) – a map that may serve as source of quantitative characteristics of the presented objects (by making measurements on it) (Ratajski 1989).

[2] Graticule – a network of lines on the map representing meridians and parallels.

[3] Measured grid – a network of evenly spaced horizontal and vertical lines based on projected coordinates.

Nevertheless, the relative locations of objects were usually presented correctly (e.g. the mill is to the west of the road, while the forest extends between the inn and the church).

An example of a map not based on a geodetic network is the First Military Topographic Survey of Galicia (*Originalaufnahme des Königreiches Galizien und Lodomerien*) which was conducted in the years 1779-1783 on a scale of 1:28,800, as part of the First Topographic Survey of the Habsburg Monarchy known as the Josephine Survey *(Josephinische Landesaufnahme)* (Konias 2000). The First Survey of Galicia does not meet cartometric requirements, which means that when untransformed, it cannot serve as a source of quantitative features of the presented objects.

In Galicia, only few main points were measured trigonometrically. The elaboration of details proceeded with a compass, ruler and surveyor's table, while areas less important from the military point of view were mapped by eye only (*à la vue*). Field sketches were produced by riding back and forth across the terrain, distances being determined in relation to the average size of a horse's step (Konias 2000). No materials exist that would unambiguously define mathematical formulae for the projection method applied, but contemporary researchers point to similarity with the Cassini projection (Podobnikar 2009). It is now known that maximum errors as regards the positioning of objects exceed 1 km (Podobnikar 2009; Timár 2009). However, notwithstanding these obvious flaws, the Josephine Survey is regarded as the most detailed and best-quality cartographic work to have been done up to the end of the 18th century (Podobnikar 2009), and work is underway in Poland to publish a complete facsimile edition of the First Survey of Galicia (along with the accompanying descriptive part). The first volumes are out already (Bukowski et al. 2012).

The georeferencing of a map not based on a geodetic network requires a reference layer, i.e. another map already aligned with satisfactory accuracy. However, before aligning the old map to the reference layer, it is necessary to restore the original geometrical shape to the scanned sheets. In the case of maps from the First Survey of Galicia, the frames of the sheets have a rectangular shape with sides of horizontal and vertical lengths equal to 24 and 16 Vienna inches[4] (63.2 and 42.1

cm) respectively (Konias 2000). Raster images are aligned to a grid of rectangular cells of dimensions corresponding with those of the map frames, making use of an 'adjust' transformation that warps the map sheet to the given dimensions (ESRI 2011). Where the area of interest extends beyond a single sheet, mosaicking of raster images takes place, this entailing clipping the scans to the extent of map frame, followed by merging adjacent raster images into one entity. Prior to the move to the next stage, the aligned raster image should be rectified[5] by computing a coordinate transformation for each pixel in the image using one of the pixel resampling[6] techniques. The recommended resampling technique for scanned maps is cubic convolution, this giving the best results, albeit requiring more processing time than the popular nearest neighbor technique (ESRI 2011).

The next stage of georeferencing is the matching of the obtained image to the reference layer. The best reference for a map not based on a geodetic network is a previously georeferenced oldest cartometric map of a given region at the largest possible scale and in a projection as close as possible to the probable projection of the currently georeferenced map. The shorter the time interval between the creation of the two maps, the more the details of the land cover will find their equivalents. In the georeferencing of the series of maps under discussion, the previously georeferenced sheets of the Second Military Topographical Survey of Galicia and Bukovina dated 1863 were used as a reference layer.

Maps not based on geodetic networks are georeferenced using Ground Control Points (GCPs) assigned to characteristic objects presented on the two maps. The best such objects for this purpose are churches, bridges, crossroads, more significant non-forested peaks and the courses of streams and brooks (Podobnikar 2009). The more points indicated, the more precise the alignment. In the case of major imprecisions on a map, it is worth locating points even in less clear-cut places, to the extent that the difference between the locations of the given object on two maps is greater than the potential imprecision with which the

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[4] 1 Vienna inch = 2.63401 cm (Konias 2000).

[5] Rectification (in the narrow sense) – creation of a new transformed raster.

[6] Resampling – the process of interpolating the pixel values for the new pixel configuration.

location of the given object (e.g. a domelike summit) is denoted.

In the case of maps not fulfilling the cartometric requirements, use is made of a transformation of the rubber-sheeting type, this entailing the distortion of the source raster image in such a manner that the source control points match exactly the target control points of the reference layer (Podobnikar 2009). In these circumstances the matching error of control points is zero. On the basis of the GCPs, an algorithm creates a Triangular Irregular Network – TIN – based on the Delone (Delaunay) triangulation, transforming the area of each triangle by means of a separate formula. The ESRI software provides rubbersheeting-type 'spline' transformation which is based on a spline function – a piecewise polynomial that maintains continuity and smoothness between adjacent polynomials (ESRI 2011). Spline requires a minimum of 10 control points.

Georeferencing of maps based on a geodetic network

The Second Military Survey

The first maps based on detailed trigonometric measurements emerged at the beginning of the 19th century and were characterised by markedly higher accuracy than had been achieved hitherto. An example of such mapping is that arising from the Second Military Topographical Survey of the Austro-Hungarian Empire (*Zweite (Franziszeische) Landesaufnahme*). Coming into being between 1806 and 1869, via eight independent coordinate grids, this cartographic masterwork comprises 2628 sheets on the scale 1:28,800 (Timár 2009). However, the only original hand-drawn sheets of this series prepared to meet the Emperor's needs as regards strategic planning are preserved in the Military Archive (*Kriegsarchiv*) in Vienna (the same being true of the Josephine Survey).

For correct georeferencing of a map based on a geodetic network it is essential to be familiar with the mathematical and geodetic bases underpinning it, first and foremost as regards the map datum or geographic coordinate system, as well as the projection used. The Second Survey of Austro-Hungarian Empire was conducted on the basis of Vienna Datum with the point of origin at St. Stephan's Tower (*St. Stephan Turm*) (Mugnier 2004).

Two coordinate grids of the Second Survey cover the present-day Polish territory: Lviv Grid for the Province of Galicia together with Bukovina, and the Vienna Grid, applied *inter alia* to the Province of Silesia and Moravia (Murzewski 1936). The georeferencing will be discussed on the example of the Military Survey of Galicia and Bukovina (*Militär Aufnahme von Galizien und der Bukovina*).

The Lviv Grid was centered at the Lviv Castle Hill. Coordinates for the mapping were based on the simplified Cassini-Soldner equidistant transverse cylindrical projection, which was applied previously by Cassini in the mapping of Bavaria (Słomczyński 1933).

The map datums of maps arising in the 19th century are not introduced into GIS software by default, though these applications provide for the option of entering custom parameters. A full

Table 1. Parameters of the local reference system (map datum) of the Second Military Survey of the Austro-Hungarian Empire.

Parameter			Value	Source
Angular unit	Degree		1° = 0.0174533 rad	–
Prime meridian	Austrian Ferro		17°39'37.5''W from Bradley's* Greenwich	(MGI 1845: 194)
Ellipsoid	Bohnenberger (1810)	Semimajor axis (a)	6,376,033 m (3,362,328 fathoms)	(Słomczyński 1933)
		Semiminor axis (b)	6,356,354 m	
		Inverse flattening (1/f)	324	

* Greenwich prime meridian defined by Bradley in the middle of the eighteenth century runs about 5.61 arcsec west of the Greenwich prime meridian used today in WGS-84.

Table 2. Projection parameters of the Second Military Survey of Galicia and Bukovina.

Parameter	Value
False Easting (FE)	0
False Northing (FN)	0
Scale factor	1
Latitude of origin	49°50'57''N
Longitude of origin	41°42'32,19''E from Austrian Ferro
Linear Unit (*Vienna fathom*)	1.896315 m

Source: Słomczyński (1933).

description of the applied geographic coordinate system (GCS) requires entering 2 of 3 parameters of an ellipsoid (semi-major axis, semi-minor axis, inverse flattening), plus the prime meridian and angular unit (Tab. 1).

A full description of the Cassini-Soldner projection requires entering geographical coordinates (consistent with the applied GCS) for the standard parallel and central meridian of the projection, as well as setting the scale factor and a unit of distance. It is also possible to add a constant shift for flat coordinates to make the numbers convenient (false easting, false northing) (Tab. 2).

Differences between projected coordinates calculated using full or simplified Cassini-Soldner formulae are dependent on distance from the center of projection (Castle Hill), and rise to a maximum of 60 m within the Galicia. Słomczyński (1933) provides the full and simplified formulae, as well as the method used to convert between flat coordinates, which is worth applying in the georeferencing of sheets presenting an area far from Lviv.

A data frame in ArcMap set in this way allows for the process of designating control points to get underway. It is assumed that the original sheets of the map series under discussion met cartometric requirements, even though the raster images are distorted (e.g. by contraction of the paper and imperfections in the scanning process).

The transformation recommended for this type of map is the affine transformation, preserving straight lines, while rectangles are changed into parallelograms (ESRI 2011). It can be performed with at least three links (control points of known coordinates). The frame of the sheet, graticules or marked trigonometric points may serve as sources of control points with known coordinates. In the case of the Second Survey of Galicia and Bukovina the frame of the sheet is square in shape with sides 20 Vienna inches (52.7 cm) long, equivalent to 8000 Vienna fathoms[7] (15.17 km) in the terrain. The starting point (Castle Hill) is located at the point where 4 sheets meet (Konias 2000). Each sheet has a column and row ascribed to it, this making calculation of the flat coordinates of sheet corners a simple matter. The map has no grid overlain on it, and the corners of the frame (other than the top right-hand one) coincide with folds in the paper and so cannot by precisely determined (Timár 2004). However, marks for trigonometric points for first-, second- and third-order cadastral triangulation are plotted on the map, whose coordinates can be read off from the 1932 Catalogue of trigonometric points (Michałowski & Sikorski 1932). On average there are 9 such points per sheet. The author obtained a mean RMSE (root mean square error) from the matching of four selected sheets to the data frame equal to 8.27 m on the terrain, or 0.29 mm as appeared in the maps (!), this therefore attesting to the high level of precision to the plotting of trigonometric points, as well as to a limited distortion of the raster image of the maps that is capable of being corrected using the affine transformation.

A further step in the georeferencing of a map based on a geodetic network entails the transformation of the historical local reference system to the contemporary global one, such as WGS-84 or in practice equivalent to it ETRS89, which serves as a reference system for projected coordinate systems currently used in Poland (Poland CS92, Poland CS2000 and UTM).

Beyond the transformation of geodetic coordinates due to different shapes of ellipsoids it is

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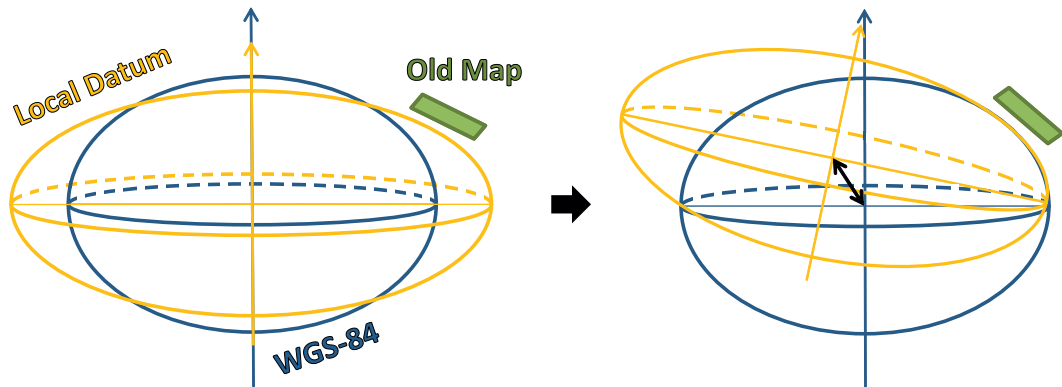[7] 1 Vienna fathom = 1.896315 m (Słomczyński 1933).

Figure 1. 3-D datum transformation, a necessary step following the transformation of geodetic coordinates (between ellipsoids).

necessary to take account of mutual shift of the ellipsoids in space (datum shift), as determined by rotation, shift and change of scale of the coordinate system (Fig. 1). Many researchers neglect this issue, but the effect of this stage of the transformation being omitted may be a shift of several hundred meters between historical and contemporary map (which is very often blamed on inaccuracy of old maps). This happens because global map datums use the Earth's center of mass as the point of origin, as designated on the basis of satellite measurement. Meanwhile, the historical local map datums computed only to map a sector of the globe had a point of origin on the Earth's surface. That is why the coordinate system origin of a local datum (center of the ellipsoid) is offset from the Earth's center.

The Second Survey of Galicia arose from generalised cadastral maps, which were based on the Bohnenberger ellipsoid with the point of origin at St. Stephan's Tower in Vienna (Słomczyński 1933; Mugnier 2004). To fully take into account the shift between local and global datum it is essential to perform a mathematical *similarity* transformation (a so-called Helmert transformation) with seven parameters (dx, dy, dz – shift of the coordinate system origin; dα, dβ, dγ – rotation of axis, s – scale factor). In meeting the needs of the georeferencing of topographical maps of a small area it is enough to apply the simplified transformation (geocentric translation) with the three parameters dx, dy and dz, making use of Molodensky formulae (NIMA 2000; ESRI 2011).

However, these parameters are not available for the territory of Galicia and so it is necessary to calculate them using inverse Molodensky

formulae (e.g. by using the 'Inverse Molodensky' add-on to the free ILWIS GIS software: http://www.itc.nl/ilwis/downloads/tools/geodeticTools.asp#ilw_inv_molodensky). In carrying out the calculations, it is essential that there be knowledge of the parameters to the historical ellipsoid and geographical coordinates of at least one (better several) control point in the historical and contemporary systems, as well as of its ellipsoidal height[8]. The historical coordinates for trigonometric points are read off from the Catalogue thereof (remembering to convert flat coordinates into geographical ones – using the formula given by Słomczyński (1933), or else from the sheets already aligned to the historical coordinate system (less precise). For a historical local datum it is possible to accept zero distance between the geoid and the ellipsoid (Timár 2004, 2009), i.e. the ellipsoidal height equal to the mapped elevation. The mean distance of the geoid from the WGS-84 ellipsoid equals 34 m (range 27-44 m) in the case of Poland, and this value is added to the height of the point above sea level. For more precise calculations it is possible to make use of the TRANSPOL software, to which GUGiK introduced a quasigeoid model accurate to just a couple of centimeters (Kadaj 2001). A good alternative in the case of the georeferencing of maps beyond Poland's borders is the Internet-based *WGS 84 Geoid Calculator* service, which is run by the National Geospatial-Intelligence Agency, and thus offers a basis for the calculation of the distance separating the geoid from the WGS-84 ellipsoid across almost the entire

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[8] Ellipsoidal height – elevation of a point above a reference ellipsoid, as measured along a normal to the ellipsoid.
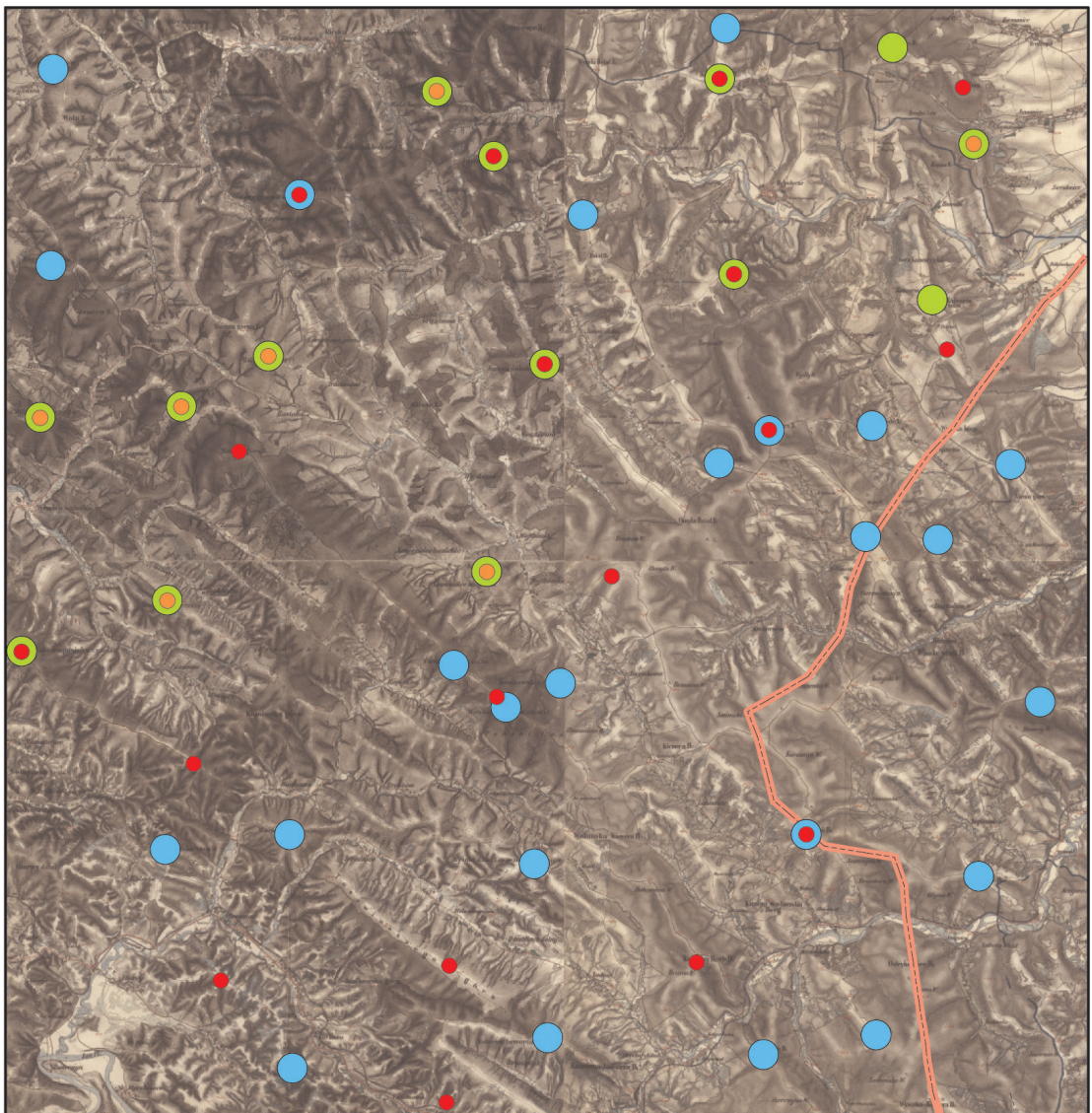
Datum: Austrian (1810)   Projection: Cassini

0   1.5   3   6 km
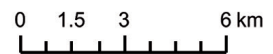
Legend

- ● Contemporary points of the geodetic horizontal first class network
- ● Chosen contemporary points of the geodetic horizontal second class network

Points of I, II and III order cadastral triangulation of the years 1819-1851:

- ● used to transform datums
- ● not used to transform datums
- ▭ Contemporary Polish-Ukrainian border

Figure 2. Mosaic of sheets of the Second Military Survey of Galicia in the original geographic coordinate system with marked historical and contemporary trigonometric points.

Source: based on scanned maps from the *Kriegsarchiv* in Vienna (signature AT-OeStA/KA KPS KS), the geodetic network's central bank's WMS layer from www.geoportal.gov.pl and the Catalogue of trigonometric points (Michałowski & Sikorski 1932).

Table 3. Descriptive statistics of the geographic translation parameters from the local reference system of the Second Military Survey of Galicia to WGS-84.

Parameter	points	Mean	Min	Max	SD
dx		2168.5 m	2165 m	2171 m	2.0 m
dy	14	345.6 m	342 m	350 m	2.9 m
dz		-299.4 m	-303 m	-296 m	2.5 m

world (http://Earth-info.nga.mil/GandG/wgs84/gravitymod/wgs84_180/intptW.html). Contemporary coordinates of trigonometric points of the first and second class geodetic network (generalized with 1 m precision) may be obtained using the Web Map Service *(WMS)* of the central bank of geodetic networks (CBO) from the www.geoportal.gov.pl service (http://sdi.geoportal.gov.pl/wms_osnowy/request.aspx).

On the basis of 14 control points, the author obtained mean values of geocentric translation parameters from the Vienna Datum to WGS-84 as follows:

$$dx = 2168.5\,m \qquad dy = 345.6\,m \qquad dz = -299.4\,m,$$

these then being usable in the georeferencing of sheets of the Second Military Survey of Galicia, as well as Austrian cadastral maps for Galicia (Tab. 3, Fig. 2).

Shift parameters for several hundred local map datums used in the 20th century compared with the WGS-84 – as calculated using the Molodensky method – may be found in a report of the US agency NIMA (2000).

The Third Military Survey

Along with the development of knowledge and civilisational progress in general, the second half of the 19th century brought certain new geodetic and cartographic solutions that bore fruit in more precise and accurate representation of reality on maps (Molnár & Timár 2009). A further great achievement of Austrian cartography given the epoch in which it was done is the geodetic network-based Third Military Topographical Survey of Galicia (*Dritte (Franzisco-Josephinische) Landesaufnahme*). Survey elaborated in topographic sections of scale 1:25,000 were done in the years 1873-1879 (Konias 2000; Cechurova & Veverka 2009). Unfortunately, everything points to the fact that the original detailed sections at 1:25,000

handed over to Poland's Military Institute of Geography (WIG) in 1923 by its Austrian counterpart the Militärgeographisches Institut *(MGI)* – by virtue of the Treaty of St. Germain (Słomczyński 1934) – did not survive the subsequent perturbations of World War II (Konias 2000).

The Third Military Survey was brought out in print as the series of maps known as the *Spezialkarte der Österreichisch-Ungarischen Monarchie* on a scale of 1:75,000 (i.e. with one *Spezialkarte* sheet coinciding with 4 topographical sections). The *Spezialkarte* 1:75,000 series came out between 1873 and 1918. The later editions of *Spezialkarte* (following reambulation carried out in the years 1892-1897) with improved land cover and relief were of higher cartometric quality than the first edition (Słomczyński 1934).

The sheet dimensions were 15' of latitude and 30' of longitude. Each sheet in the *Spezialkarte* series was drawn up in a separate local oblique stereographic projection (Timár et al. 2011). The geometric center of the sheet designated the central point of the projection (Molnár & Timár 2009). The frame of the sheet had the shape of a trapezium, this not therefore allowing for the creation of a continuous mosaic without distortion of the maps (Fig. 3). Such projection of multi-sheet maps is known as polyhedric projection (Mugnier 2004).

The basis for the map datum of the Third Survey of the Habsburg Monarchy was a Bessel ellipsoid with the point of origin at Hermannskogel near Vienna (Fig. 4). Molnár and Timár (2009) suggest that the Third Survey and *Spezialkarte* series at a scale of 1:75,000 were drawn up on the basis of quite coarse non-standardised geodetic data that go rather a long way to impairing the accuracy of the series as a whole. They compared the coordinates for 650 trigonometric points from the 1892 catalogue and demonstrated that the geodetic network divides into several smaller trigonometric networks set around points measured
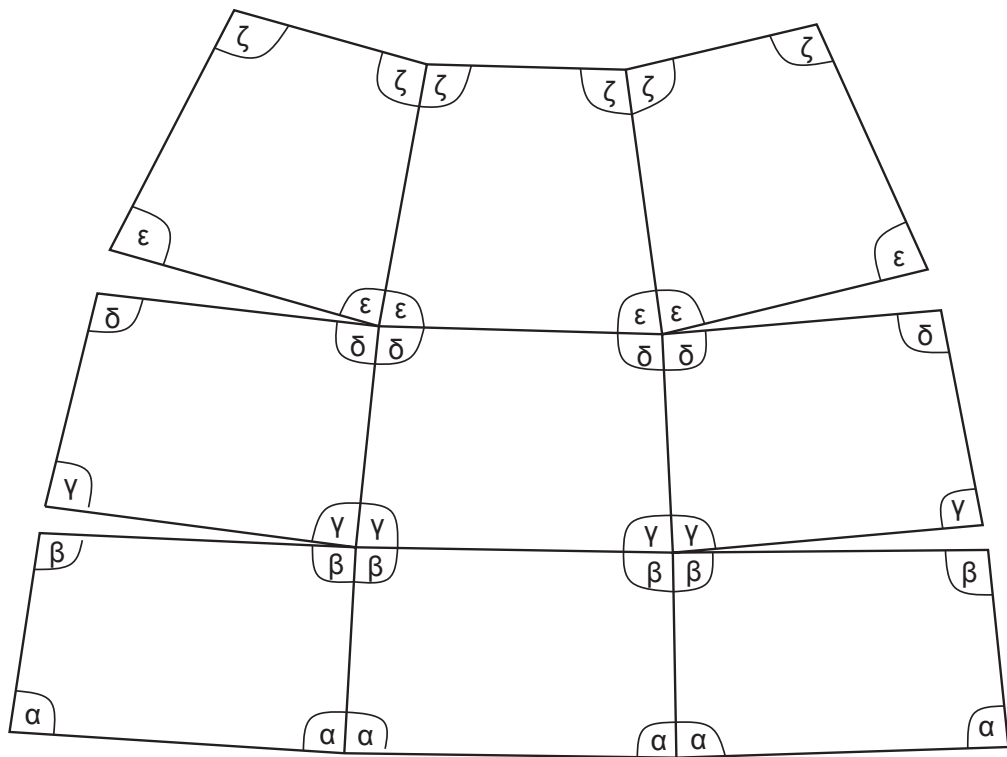
Figure 3. The original structure to the sheets of the *Spezialkarte* series – polyhedric projection.

Source: Sárói Szabó (1901).

astronomically and independently of one other (Molnár & Timár 2009). The inaccuracies within these networks are relatively small (of 35-40 m, i.e. around 0.5 mm on the map), but the discrepancies between networks may be of as much as 250 m (Molnár & Timár 2009, 2011). In the case of Galicia, the astronomically measured points are to be found at the observatories in Cracow and Lviv (Molnár & Timár 2009), while the baseline was lain down at Partyń near Tarnów (Mugnier 2004).

Neither the map datum for the Third Survey of Galicia nor the parameters for the transformation of this system to WGS-84 are available in the EPSG Geodetic Parameter Database, or in the official ESRI registers. However, what is available is Hermannskogel map datum elaborated in 1892 by the MGI (known from one country to another as MGI, MGI_1901 or S-JTSK), along with several proposals for sets of transformation parameters.

While it is true that the Hermannskogel map datum was devised after the *Spezialkarte* series had already been published (Molnár & Timár 2009), its basic specification (Bessel ellipsoid with a Hermannskogel point of origin, as well as a network of trigonometric points) largely coincides with the map datum employed earlier in the elaboration of the Third Military Survey within the Habsburg Monarchy.

A fundamental difference concerns the prime meridians. The map datum of the Third Survey adopted the Ferro Meridian as the prime meridian, while that of Hermannskogel adopted the Greenwich Meridian after Airy as longitude zero. When it comes to the georeferencing of the Austrian historical maps, a basic problem is to obtain the real shift of the Ferro Meridian versus the Greenwich prime meridian as measured today using satellites. In GIS software, the Greenwich prime meridian calculated by satellite methods is treated as the reference meridian. All conversion factors applied in the instructions to those drawing up maps in the 19th and most of the 20th centuries (pre satellite measurements) adopted the prime meridian at Greenwich calculated by Bradley and later

Figure 4. The Habsburgwarte tower on top of the Hermannskogel Hill near Vienna – the starting point for map datums used in the Habsburg Monarchy in the 19th century.

Source: photography by Michael Kranewitter (*Wikipedia*, CC-BY-SA).

Airy (the difference between them amounting to approximately 6 m). The difference between satellite Greenwich and Airy Greenwich is in turn of 5.31 seconds of arc, this translating to more than 110 m at the 49th parallel.

For example, in the Catalogue of Trigonometric Points (*Katalog punktów trygonometrycznych*) from Poland's Military Institute of Geography (WIG), the transfer from the Austrian Ferro Meridian to the Greenwich Meridian (Airy) uses a numerical conversion factor equal to 17°39'49'' – as given in *Mitteilungen der Landes – Triangulation* for 1929/30, No. 3 (Michałowski & Sikorski 1932).

A year later, Słomczyński (1933) made use of his own calculations to propose a corrected conversion factor of 17°39'56.72''.

Today, to simplify calculations a conversion factor of 17°40' is used to transform from the Austrian Ferro to the Greenwich Meridian obtained by satellite methods. Possible further discrepancies are then corrected with transformation parameters, first and foremost an Earth axis rotation parameter (dz).

ArcGIS 10.1 makes available several formulae for transformations between the Hermannskogel system and WGS-84, including also a full 7-parameter Helmert transformation according to the Bursa-Wolf formula (position vector in ArcGIS), in line with the European convention for axis rotation (OGP 2013).

The formulae in question derive first and foremost from the EPSG database, though also from ESRI's own registers. Each formula is devoted to a particular area under the old Habsburg Monarchy (including, for example, for Croatia, Slovenia and Austria), since the Hermannskogel map datum was not uniform for the whole area of the old Empire. Neither the databases nor any other sources were able to offer formulae for conversion between the above systems that might be applied to the area of the former Galicia. The nearest region for which a Hermannskogel–WGS-84 transformation formula has been calculated is Slovakia. S-JTSK Map Datum (*System Jednotne Trigonometricke Site Katastralni* – The System of the Unified Czech/Slovak Trigonometric Cadastral Net) is one of the local versions of Hermannskogel map datum. It was adopted on the territory of the Czech and Slovak republics (former Czechoslovakia) in 1927 (Cechurova & Veverka 2009).

The author's transformation (Hermannskogel-WGS-84) of geographical coordinates for 30 first-order trigonometric points in the Galicia – using the Slovakian transformation parameters – is nevertheless found to give better results than any of the other sets of parameters available in ArcGIS. These transformation parameters are included in Table 4.

The results of the transformation were related to contemporary coordinates of first-class points from the geodetic network based on the European Terrestrial Reference System '89 (ETRS89), which is in practice equivalent to the WGS-84. Following elimination of points for which location errors departed markedly from average values (due to

Table 4. Parameters of 3D similarity (Helmert) transformation based on the Bursa-Wolf formula (position vector) from the Hermannskogel map datum (S-JSTK Ferro*) to WGS-84.

Transformation	Parameter	Value	Unit
X axis translation	dx	485	
Y axis translation	dy	169.5	Meter
Z axis translation	dz	483	
X axis rotation	rx	7.786	
Y axis rotation	ry	4.398	Arcsecond
Z axis rotation	rz	-4.103	
Scale factor	s	0.0	Part per million (ppm)

*S-JSTK Ferro – S-JSTK map datum with Ferro prime meridian, Ferro – Greenwich shift equal to 17°40′00″.
Source: EPSG.

physical change in the location of geodetic marks), it was possible to arrive at a mean error for the location of points amounting to around 13 m. Naturally, this result is not satisfactory for geodetic purposes, but is entirely adequate for the georeferencing of maps on scales of 1:10,000 or less. Unfortunately, the georeferencing accuracy of the *Spezialkarte* sheets based on the geographical coordinates marked on the sheet frames is far from the expected 13 m. This happens because the real spatial coordinates of objects represented on the sheets (including trigonometric points) fail to coincide with those marked on the frames of the sheet. In 1935, Babiński used the following description in relation to the processing of *Spezialkarte* series of maps: "All of these cuts, pastes and matching to section corners, rather than trigonometric points, caused many fundamental deformations of map content. [...] Whole belts of the depiction along the frames have to be shifted if a reasonable faithfulness is to be obtained. Furthermore, it is sometimes the case that the poor projection of trigonometric points leaves one with no basis for any completely certain shifts" (Babiński 1935: 127-128).

The analysis carried out indicates that the content of the *Spezialkarte* maps is shifted by around 100 m to the north-east in comparison with the graticule tick marks.

The georeferenced mosaic of all the sheets of the *Spezialkarte* map series covering the whole of the former Habsburg Monarchy is available as the work of the Arcanum Database Ltd., Hungary (Biszak et al. 2007). Molnár and Timár (2009) described in detail the method of georeferencing and mosaic making, along with the estimation of the error of match (up to 250 meters).

Discussion

Georeferencing of maps not based on a geodetic network

With the proposed procedure for georeferencing maps not based on a geodetic network there arises the problem of goodness of fit obtained. This cannot be expressed in terms of RMSE, because the control points on the source (georeferenced) map and target (reference) map coincide precisely. However, this does not imply that the whole sheet is matched ideally. Jenny and Hurni (2011) propose a visual method for assessing geometric distortions on historical maps, on the basis of the observation of vectors for displacements of control points and a distortion grid, allowing for analysis of the spatial diversity of displacements (Fig. 5). A manifestation of the accuracy of alignment as a result of rubbersheeting-type transformation may be the density of control points per cm^2 of map.

On the other hand, it is possible to imagine a situation in which so many points are introduced that we in fact obtain a map identical with the target map, which is not the desired effect, since most often one of the objectives of georeferencing a source map is to compare it with the target layer and uncover differences. For this reason too, the process of georeferencing maps not based on a geodetic network (with a view to cartometric value being increased) may not be pursued automatically, first and foremost requiring a good level of familiarity with the area encompassed by the map, and the history thereof (Jenny & Hurni 2011). When assessing the cartometric value of a historical map it is necessary to keep in mind
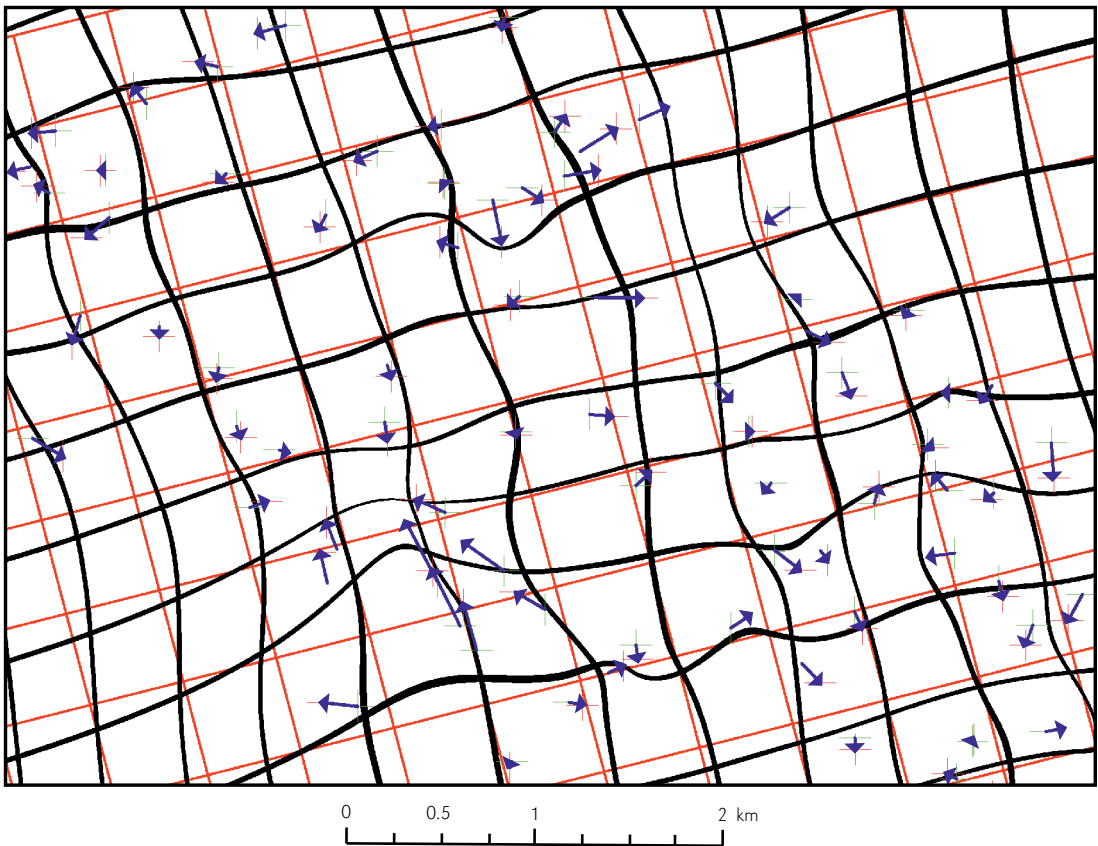
Figure 5. Distortion grid of a piece of a map from the First Military Survey of Galicia after spline transformation, as set against the background of the same grid before the transformation supplemented with displacement vectors of control points.

the general regularity that the projection of open areas and built-up areas is considerably more accurate than that of forest or high-mountain areas (Konias 2000).

The traditional method of studying historical maps entailed the overlaying of a copy of a map with a distorted graticule drawn in relation to the shifts of significant objects as compared with their locations on contemporary maps (Fig. 6a). The method of georeferencing maps using a rubbersheeting transformation distorts a map and adjusts it to the true shape of the graticule, this then allowing for overlaying and direct comparison of changes over time (Fig. 6b).

However, the use of rubbersheeting-type transformations in the georeferencing of historical maps has its limits. If a georeferenced sheet does not meet basic topological conditions for the locations of objects in space (e.g. village X in reality

west of village Y is projected on the map to the east of Y), then georeferencing by rubbersheeting will not bring the desired effects. The image obtained following warping will be entirely illegible. An example of a map that ceases to be a utilisable source of information following transformation by rubbersheeting is the map of Lublin Voivodship by Karol de Perthees dating from 1786 and on a scale of around 1:225,000 (Szady 2008). Under such circumstances, if the rectification of such a sheet is imperative, a better solution will be to apply the affine transformation.

Georeferencing of maps based on a geodetic network

The proposed method of georeferencing maps based on a geodetic network also has its limits. Above all, its application requires that
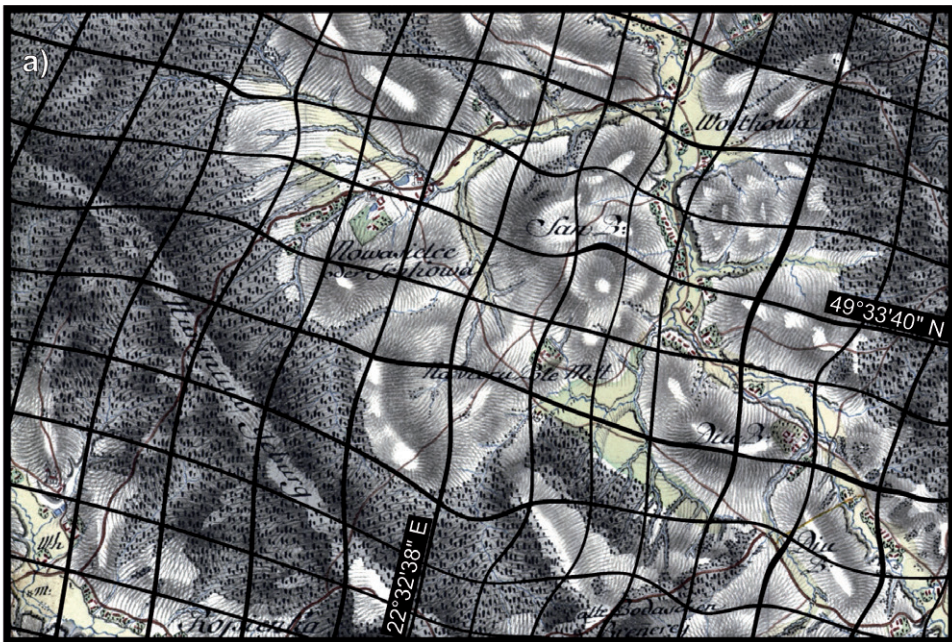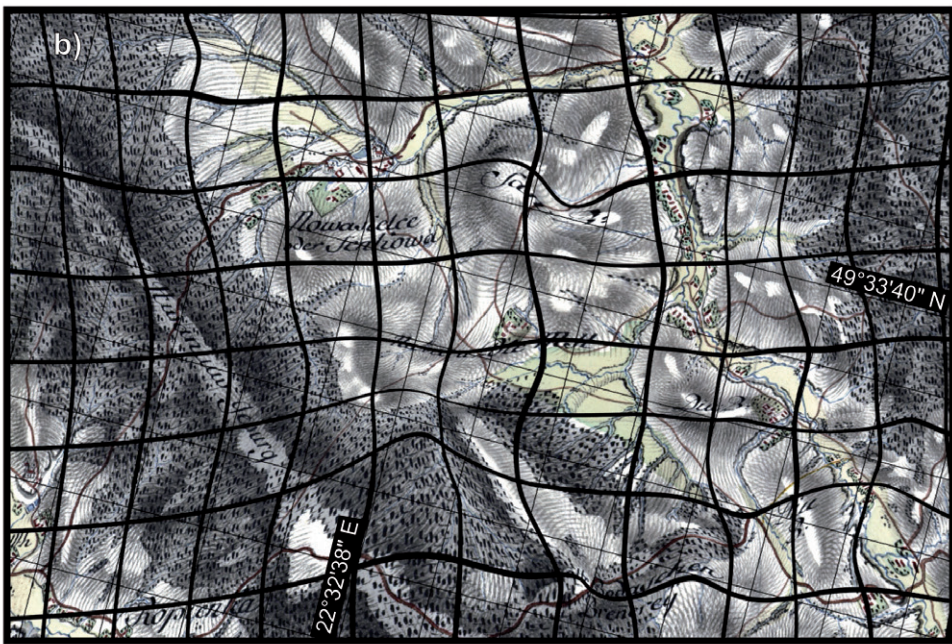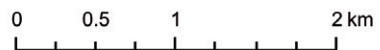
Figure 6. Part of a map from the First Military Survey of Galicia:

a) before transformation covered by a distorted geographic network (traditional method),

b) after spline rubbersheeting-type transformation covered by the graticule (thin lines) and distortion grid (thick lines).

Source: based on the scanned map from the *Kriegsarchiv* in Vienna (signature AT-OeStA/KA KPS KS).

information be possessed as regards the geodetic and cartographic bases upon which the map was created, mainly the information about the local map datum, and parameters for the transformation thereof into a contemporary system, such as WGS-84. An ever-greater number of sets of transformation parameters from historical geographic reference systems are now available in online databases (GeoRepository, EPSG, ESRI), and many of these were devised by reliable national or international institutions. A lack of data on transformation parameters complicates the process by which georeferencing based on a geodetic network takes place, but it does not preclude it altogether. If it is possible to obtain a set of points on the Earth's surface with known coordinates in both contemporary and historical systems, then the transformation parameters can be calculated independently.

The georeferencing of historical maps based on the coordinates of sheet corners is particularly recommended when it comes to rectifying whole series of multi-sheet maps. Avoided in this way are difficulties with matching the edges of a sheet and subsequent mosaicing. A considerable amount of time can also be saved. With several sheets the time devoted to preparation of the data frame and subsequent matching of corners in the appropriate coordinates is many times shorter as compared with the georeferencing relying on ground control points (GCPs) and a target reference layer.

This method is also unequalled when it comes to the georeferencing of a single sheet of high cartometric value, especially where the priority is to obtain a high level of precision. However, if it is a single sheet of a map of imperfect quality (e.g. of the *Spezialkarte* series) that is to be georeferenced, then it is probable that better results will be obtained by way of georeferencing that applies a reference layer and GCPs on characteristic elements of the terrain. The author obtained an RMS Error for georeferencing of a selected Spezialkarte sheet (DOBROMIL – Zone 7 Kollone XXVII, published in 1903) equal to 29 m with 55 ground control points (affine transformation). This result is better than can be obtained with transformation of map datums. However, it needs to be recalled that the results of such georeferencing will only be reliable within the area confined by the GCPs, particularly where transformation of a map image with polynomials

higher than the first order is applied. At the same time, the distortions at the edges of the sheet may be much greater than would result from the RMS Error obtained. No such fears apply in a situation where georeferencing based on graticule tick marks located at sheet borders takes place. Georeferencing with GCPs can also be used after datum transformation of low-quality maps in order that local distortions might be eliminated (Podobnikar 2010).

Not losing much in accuracy terms, the georeferencing procedure based on the reference layer (in this same projection as a source map) may also be applied to map sheets of very good cartometric properties, but – for example – of unknown geodetic bases, or without graticule tick marks. Differences arising out of the use of different frames of reference (e.g. different ellipsoids) are often smaller than the inaccuracies of the maps themselves. A good justification for such an approach is offered by Słomczyński: "[...] two flat depictions of the same network of triangles, referred to two different ellipsoids, within limits of up to 600 km from the center thereof, remain unchanged (to a decimeter level of accuracy), if we use the same projection formulae" (Słomczyński 1933: 347).

Proceeding on the assumption that use may be made of the reference layer in a uniform projection, we approximate procedure to the method of georeferencing maps not based on a geodetic network.

Conclusions

Optimising the georeferencing process is fundamental to the development of the new research method of Historical GIS. The two main methods of georeferencing presented in this article – selected appropriately in line with the input material – make maximised use of information contained on historical maps possible. The method of georeferencing based on the transformation of map datums retains the high accuracy of representation of the land surface characteristic of maps based on a geodetic network, while the method based on rubbersheeting-type transformations increases the cartometric value of less-precise maps not based on geodetic network. Following vectorisation, maps georeferenced in this way become useful to researchers using precise numerical data on distances, as well as areas and shapes of objects, presented on them. They *inter alia*
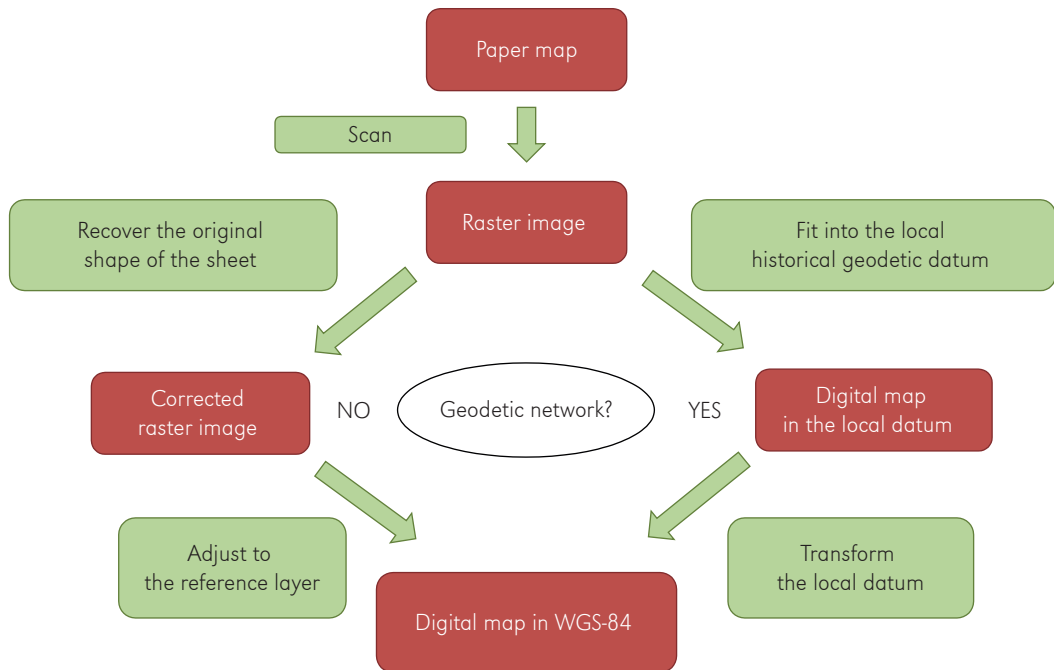
Figure 7. Scheme for the processing of historical paper maps into digital form.

allow for the determination of landscape metrics and the quantifiable recognition of changes over time (e.g. in land cover, ownership and administrative borders).

The proposed scheme for the processing of historical maps from paper into digital form with a contemporary frame of reference is presented in Figure 7.

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Editors' note:
Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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