

## METHODS OF GEOREFERENCING OLD MAPS ON THE EXAMPLE OF CZECH EARLY MAPS

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### BACKGROUND AND OBJECTIVES

Old maps are unique source of information about our historical landscape. For comparing maps from different eras there is a need of their spatial overlay using common coordinate system. Thus, the crucial problem is to transform old maps into any well-defined system. This article shows methods of georeferencing old maps on the example of early maps of Bohemia and Moravia.

Nowadays old maps are much more accessible than ever before. Digital archives are full of scanned images of old maps. Usually these images are only digital copies of their analog version. Map itself contains two main types of information: relationships of spatial objects (adjacency, neighborhood, distance) and position of these objects in the real world. If we want to capture the information about real position of map objects we have to georeference the map. For doing that properly it is necessary to be familiar with mathematical definition of transformation methods, cartographic projections and coordinate systems, and methods of adjustment. Most people working with old maps are not so well-educated in this background and are not able to choose correct method for georeferencing at all. I would like to explain typical characteristics of old maps and propose the methodology for georeferencing of specific categories of old maps.

There are many categories of old maps and any of them requires its own approach. First of all, we have to define these categories. The main characteristics of analyzed old maps are: number of map sheets, knowledge of used coordinate system, and knowledge of original dimensions of map sheets.

Number of map sheets is the key parameter. If the map is depicted on the only map sheet, the situation is much easier. All transformation and adjustment parameters are connected just to this only map sheet. Early maps, which are not based on the geodetic networks and measurements, are typical examples of this category. Early maps were created in small scale (usually 1 : 500 000 and smaller) very often and thus there was no need of many map sheets for the mapped area. Early maps in large scale were usually plans without any ambition of displaying large area (on adjacent map sheets, typically city plans). With development of geodesy and astronomy in 18th century first fundamental geodetic networks were created and adjusted. Based on these networks new map series in middle or large scale were created (such as Cassini map of France in 1 : 86 400; 1750-1793). These map series are precise enough to place adjoining map sheets together. For Central Europe 2nd Military Mapping Survey of Austria-Hungary (1 : 28 800; 1806-1869) could be good example. Previous 1st Military Mapping Survey of Austria-Hungary (1 : 28 800; 1763-1787) was not based on precise geodetic measurement.

Knowledge of used coordinate system is essential for georeferencing old maps. The oldest early maps didn't use any real cartographic projection. Position of some features (usually cities and towns) was measured astronomically; some lengths were measured on the ground. Usually the map was depicted with rectangular graticule leading to equidistant cylindrical projection (first used by Eratosthenes and Marinus of Tyre in ancient Greece). In 18th century transverse equidistant cylindrical projection was very popular. Newer maps usually used conformal projections (due to angle-preserving from geodetic measurement). We can find many other projections and coordinate systems used on old maps. In any case, the knowledge of used projection is very beneficial information for later georeferencing.

Original dimensions of map sheets can be used for reconstruction of image dimensions. Analog maps suffer from shrinkage of paper. Every map is somehow distorted and original dimensions can help us remove these distortions. Unfortunately, in many cases we don't know exactly the dimensions. Early maps have no standardized size and the only solution is to use numbers found in historical literature. Another solution could be measurement of the original print matrices, but it is very improbable to find them, especially for early maps.

### APPROACH AND METHODS

Previous text divided maps into categories based on the knowledge of number of map sheets, used projection and coordinate system, and original dimensions of map sheets. For any combination of these input parameters the proper method for georeferencing will be proposed.

For any transformation method within georeferencing, there is a need of collecting identical points (on the map and in reality). These points for transformation are usually called “ground control points” (GCPs). There are some important recommendations for GCPs collection: GCPs should be laid out through the whole map image (if possible); GCPs should be represented by stable well-identifiable objects; the more GCPs collected the better input data for georeferencing. The last remark led me to the method of full vector data model of the map, where the map is vectorized at first. Then any vector point from the model identifiable in reality can be used as GCP. Some points can be later omitted (e.g. evident errors made by author of the map).

Transformation methods used within georeferencing need brief explanation. There are two main groups of transformations: global, and local. Global transformation methods use two mathematical equations (for two coordinates) for the whole image; local transformation methods use other approach where either the image is cut into areas (e.g. triangles of GCPs) with own equations (“rubber-sheeting” method) or any point is transformed with own equations (usually based on interpolation methods such “Thin plate spline” or “Inverse distance weighted”). Local transformations are non-residual where GCPs after transformation fit precisely, but the image can be distorted very ugly. Global transformations use only two equations and are non-residual only for minimal number of GCPs for equation solving. If having more than minimal number of GCPs global transformations are residual. Transformation parameters are then adjusted, usually by Least squares method (LSM).

My approach of georeferencing old maps is based on global transformation methods. If georeferencing the map, I am not interested only in overlay the map with other ones, but I am interested in map parameters (precision, mean scale, rotation against graticule,...). These parameters can be computed within the adjustment of enough GCPs using global transformation methods. Local transformation methods deform the original image and are not suitable for such research. Of course, there could be plenty of global transformation methods. For map georeferencing there are suitable only several methods (linear, or low degree polynomials).

***a) Only map sheet, unknown projection, unknown dimensions***

This combination is typical for the oldest maps. If we don't know used projection it is proposed to georeference the map in “Lat/Long” projection (in geographic coordinates). In fact, “Lat/Long” projection matches equidistant cylindrical projection with undistorted equator (so called Plate Carree). This projection is usually used in GIS software for displaying “Lat/Long” data (e.g. in ArcGIS). GCPs are collected in “Lat/Long” (in reality), respectively in pixel coordinates for the image. As the shrinkage of the paper is unknown the used transformation should reduce the distortion. After affine transformation the image can be scaled in both axes and skewed. After second or third order polynomial transformation the image can be bended locally (especially near margins); texts on the map can be damaged. For the whole map sheet transformation I prefer affine transformation. If the aim of transformation is only local area within the map sheet, low order polynomial can be used for better fit of GCPs. Transformations are adjusted by LSM.

***b) Only map sheet, unknown projection, known dimensions***

If we know original dimensions of the map (by measurement of print matrices or by other source) the procedure should be little different. Before GCPc collection the image of the map should be reconstructed to its original size. The easiest way is to fit original dimensions to corner points of the map image. As we have four corner points and want to fit these points precisely projective (collinear) transformation is the best solution. It transforms any quadrangle into other quadrangle as non-residual. After having the map image with real size GCPc can be collected. The shrinkage of the map is removed by reconstructing original size. For the whole map sheet transformation here I prefer similarity transformation. Compared to affine transformation, it preserves angles. It consists only of uniform scale, rotation and shift. Different scaling or skew is no longer needed for reconstructed images.

***c) Only map sheet, known projection, unknown dimensions***

If we know used projection of the original map georeferencing should be done within this projection. Known projection means known geodetic datum (used ellipsoid or sphere parameters) and cartographic projection with parameters (prime meridian, undistorted parallels,...). GCPs should be collected in this projection either directly in GIS software that can on-the-fly transform the data or it is necessary to transfer coordinates from projection where data were collected into original projection (e.g. using software package PROJ.4). Then affine transformation can be used for adjustment by LSM.

***d) Only map sheet, known projection, known dimensions***

Special case of the previous category can occur, when within known projection the corner points of map sheet have defined coordinates. Then the map should be transformed within original projection, but only with four corner points using non-residual projective transformation. This case is usually combined with known dimensions of the map sheet (original dimensions and corner coordinates within known cartographic projection are in fact dependent).

***e) Several map sheets, unknown projection, unknown dimensions***

If we have map series with unknown projection and dimensions, it is the most complicated case. This combination is typical for early map series which were not based on the geodetic basis. At first it is necessary to collect GCPs for every map sheet in “Lat/Long” projection (in geographic coordinates). Then the adjacency of neighboring sheets should be solved. Proposed method is based on the overall adjustment of particular transformations of map sheets (affine or low order polynomial) using LSM with constraints. These constraints are defined as conditions that joint edges of adjacent map sheets will be after transformation identical. After overall adjustment all map sheets are transformed with adjusted parameters and adjacent edges fit precisely.

***f) Several map sheets, unknown projection, known dimensions***

This case is very similar to previous one. Before GCPs collection all map sheets are transformed to its original dimensions. Then GCPs can be collected in “Lat/Long” projection (in geographic coordinates). The adjacency of neighboring sheets is solved as described in previous case. Overall adjustment of particular transformations (now similarity instead of affine) is realized using LSM with constraints (joint edge identity after transformation).

***g) Several map sheets, known projection, unknown dimensions***

If we know used projection of the original map series georeferencing should be done within this projection (if it is the same for all map sheets). GCPs should be collected in this projection either directly in GIS software that can on-the-fly transform the data or it is necessary to transfer coordinates from projection where data were collected into original projection (e.g. using software package PROJ.4). Then affine transformation can be used for adjustment by LSM with constraints (joint edge identity after transformation).

***h) Several map sheets, known projection, known dimensions***

Special case of the previous category can occur, when within known projection the corner points of map sheets have defined coordinates. Then map series should be transformed within original projection, but only with four corner points using non-residual projective transformation for every map sheet. This case is usually combined with known dimensions of the map sheets (original dimensions and corner coordinates within known cartographic projection are in fact dependent). Now all map sheets are transformed separately but fit precisely on the edges.

**RESULTS**

From previous text it is clear that 8 categories of old maps were defined and methods of their georeferencing proposed. Some of presented categories are very rare and it is very difficult to find good example for testing. Nevertheless, other categories were tested on the early maps of Bohemia and Moravia. One sheet maps are represented by Klaudyán’s map of Bohemia (1518) and Criginger’s map of Bohemia (1568), both without knowledge about projection or original dimensions. Klaudyán’s map (1518) is the oldest known map of Czech lands. Its size is approximately 45 by 55 cm. The whole map was vectorized; 273 point features were used as possible GCPs. Lines (rivers and routes) were not used for georeferencing. From the set of 273 GCPs one point was removed after initial testing of transformation key (evident error made by author). The map was georeferenced using affine transformation into “Lat/Long” projection with RMSE 13.9 km in reality (see Figure 1). The scale of the map and rotation against south-north direction were computed from the adjusted values.



Figure 1. Klaudyan's map of Bohemia (1518) georeferenced and superimposed with Czech republic borders

Criginger's map (1568) is the second known map of Czech lands. Its size is approximately 51 by 34 cm. The map was vectorized as well; 319 point features were used as GCPs. After removing 5 points (errors by author) the map was georeferenced using affine transformation into "Lat/Long" projection with RMSE 14.0 km in reality. Other parameters such as mean scale or rotation of the map were computed as well.

Both maps after georeferencing show similar errors. After deeper study I found out many similarities between both maps. It can be assumed that Criginger's map was based on the older Klaudyan's map.

Map series are represented by Müller's map of Moravia (1712, 4 map sheets with unknown projection), Müller's map of Bohemia (1720, 25 map sheets with unknown projection, but known dimensions of map sheets), selection of sheets of 1st Military Mapping Survey of Austria-Hungary (1763-1787, with unknown projection and size of map sheets) and selection of sheets of 2nd Military Mapping Survey of Austria-Hungary (1806-1869, with known projection and size of map sheets).

Müller's map of Moravia and maps of 1st Military Mapping Survey were georeferenced using the same method – adjusted affine transformation for each sheet with constraints of edge adjacency. After collecting GCPs for all map sheets the matrix for overall adjustment was filled. For affine transformation the definition of constraints was very simple. Coordinates of corner points from neighboring sheets must have after transformation the same position. These conditions were added to augmented matrix for LSM adjustment with constraints. Results of the adjustment are transformation parameters (6 parameters for every map sheet). After transforming all map sheets they fit precisely. RMSE for Müller's map of Moravia is about 2.1 km in reality, for selected 4 sheets of 1st Military Mapping Survey it is 550 m in reality.

Müller's map of Bohemia was firstly transformed to original dimensions of the map sheets. The size of map sheets was determined by measurement of original copperplate print matrices. These are archived in National Technical Museum in Prague. After having right dimensions map sheets were georeferenced using adjusted similarity transformation for each sheet with constraints of edge adjacency. Constraints were defined as in previous case. After transforming all 25 map sheets fit precisely (see Figure 2 and 3). RMSE for Müller's map of Bohemia is about 2.0 km in reality.



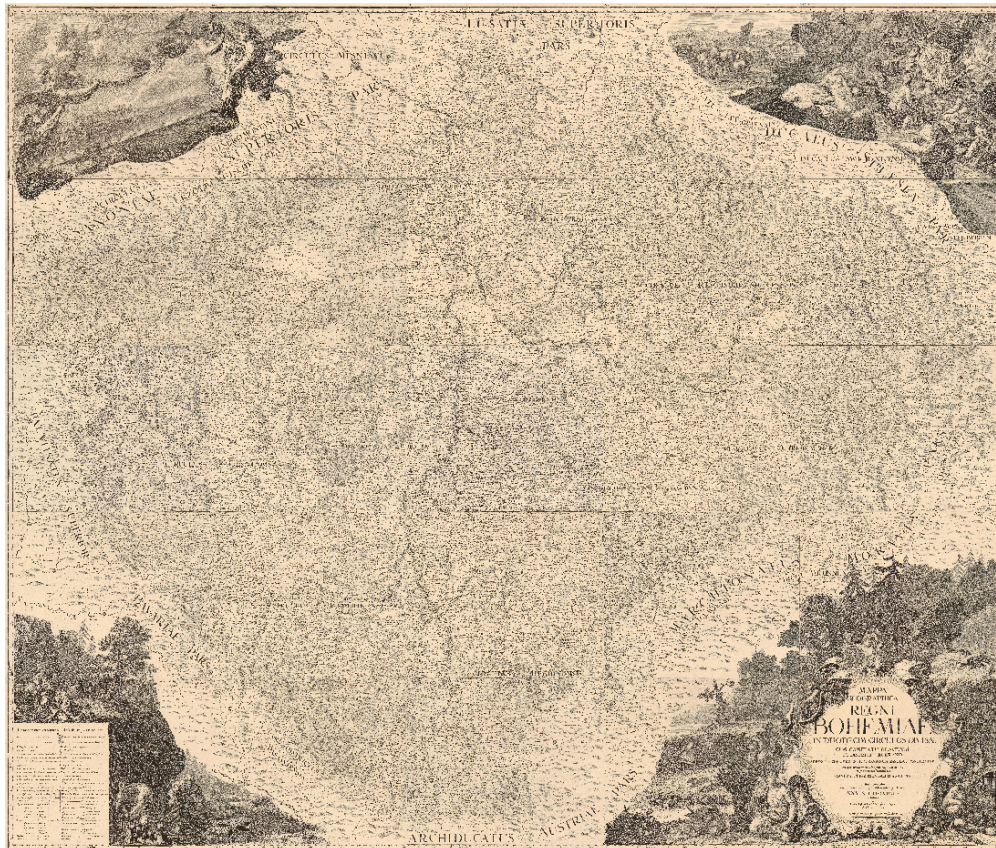


Figure 2. Müller's map of Bohemia (all 25 georeferenced map sheets)



Figure 3. Müller's map of Bohemia (detail of georeferenced map sheets)

Maps of 2nd Military Mapping Survey of Austria-Hungary are based on the cadastral mapping and have defined cartographic projection and size of map sheets. It is possible to compute coordinates of corner points in Gusterberg coordinate system (for Bohemia) or St. Stephen coordinate system (for Moravia). Cartographic projection is Cassini-Soldner (transverse cylindrical projection equidistant in cartographic meridians with fundamental points Gusterberg for Bohemia and St. Stephen for Moravia). Thus all corner points of map sheets were computed. After that every map sheet was georeferenced separately using projective transformation with 4 corner points. Precision of these maps was tested by independent control points. RMSE for maps of 2nd Military Mapping Survey of Austria-Hungary was only about 20 m in reality.

## CONCLUSION AND FUTURE PLANS

In this article georeferencing methods for old maps were presented and new method for map series (adjustment with constraints of edge adjacency) was introduced. Used georeferencing methods are based on global transformation methods. It is not the only solution. Local transformation methods can be used for local areas. For better GCPs fitting low order polynomials can be used, but maps are then deformed. Nevertheless, even for polynomial transformations can be defined constraints of edge matching.

Another approach to map series could be based on the image processing and automated edge matching during creating joint raster data. I left out these methods because of high hardware demands. For example joint raster of Müller's map of Bohemia (composed of 25 map sheets) exceeded 1GB of data. Such raster is very difficult to work with. Proposed method works only with one map sheet, but guarantee edge fitting.

My future plans are focused on 1st Military Mapping Survey. All map sheets will be adjusted together and overall seamless map from the area of Bohemia and Moravia will be created.

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