Advances and Trends in Geodesy, Cartography and Geoinformatics II

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Using strain analysis to test positional precision of cartometric scanning

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ABSTRACT: In the process of digitizing and publishing old maps, it should be kept in mind that maps created with geodetic or astronomical measurements have their own positioning accuracy. This accuracy is principally affected by an accuracy of measurement, applied cartographic projection, a map scale, used drawing method and so on. The map accuracy is important when we want to extract information about objects in maps and about their relationship. In most cases we want to know how precise the outputs are because it influences our next decisions.

Digitization of maps and map atlases should be performed on special scanning devices. A large flatbed scanner is recommended for digitizing old maps because image distortion is minimal due to the scanner's design principles. In the paper, ScannTech cartometric scanner of Proserv company with optical resolution of 800 dpi and also described experience with this large format scanner (A0+) is introduced. The necessary part of the article is devoted to testing its accuracy, which is characterized by the average position error (0.10 mm declared by the manufacturer). Mentioned are also reasons why old maps should not be digitized as documents or books are and why it is important to choose different approach. Factors that have impact on a quality and the accuracy of digitized map are also listed.

Major part of the article is given to methods for testing of an accuracy of scanners. It is proposed to use strain analysis to test the positional accuracy of cartometric scanning. The benefits of this new approach are discussed. Test sheets for doing tests are also presented. Results from long-term monitoring are also presented. These results describe behavior of scanners and show how a distortion of digital images (maps) is changing in a time.

1 INTRODUCTION

Digitized old maps are usually displayed on the internet as images, e.g. as Zoomify (zoomify.com). Another option is georeferencing the maps and provide them as Web Map Service (WMS) or Tile Map Service (TMS). Georeferenced form is usually more sought after for its practical advantages. Such maps can be used in GIS applications and are much easier to compare with other maps. To make such visual comparison feasible the positional accuracy of drawing localisation must be better than 0.4mm in exceptional cases 0.5 mm in map's scale.

Localization accuracy in tenths of millimetres in map scale can be achieved when georeferencing maps created by geodetic methods with the use of a cartographic projection. One example is georeferencing of Third Military Survey of Austrian Monarchy (1869-85) using elastic transformation with collocation. This georeferencing achieved standard error of position of 0.36mm in map scale (1:25 000) for the area of the Czech Republic (Talich et al. 2013).

To achieve such precision in georeference all cartographic properties of the map has to be taken into account. That means compensate for shrinkage of paper, take into account cartographic projection, transform coordinates and eliminate local deformations (errors of position) caused by imperfections of instruments, mapping procedures and geodetic bases. Quantity and configuration of control points have a large impact on the final accuracy. But the most basic condition is high fidelity of input data, i.e. scans of old maps.

Positional accuracy of drawing in old maps, especially large scale maps, is usually 0.1 mm. To avoid degrading map's cartographic properties it should be scanned with comparable accuracy, i.e. 0.1 mm or maximum deviation of 0.2 mm. Typically only specialized cartometric scanners satisfy this requirement. Even these scanners have to be regularly tested to ensure they still conform to the requirements.

First mentions of evaluation of scanners for their use in digitization of cartographic works come from (Carstensen & Campbell 1991). (Ho & Chang 1997) paper examines the accuracy of desktop scanners. Experimental results showed acceptable mean square error of 0.12 mm. The effort to use digitized old maps in practice led to creation of formal requirements and regulations for positional accuracy of scanners and methods of testing it. An example of such state regulations is (ČÚZK 2004).

Further research and practice showed positional accuracy is essential for the exploitation of digitized old maps. (Achilleos 2010) presented a method of estimating accuracy of digitized contours from analysis of their geometry. (Cintra & Nero 2015) devised a new way to assess accuracy from control points. At the same time research into improving the precision of cadastral maps had been underway. These efforts focused mostly on the choice of suitable transformation method usually recommending elastic transformation TPS (Felus, 2007). Other experiments tried to improve the positional accuracy by using linear elements (e.g. communication networks) for transformation (Siriba, Dalyot & Sester 2012). (Tuno, Mulahusic & Kogoj 2017) tried to improve the selection of control points to eliminate errors of position and so achieve homogeneous positional accuracy of cadastral maps.

From the above it overview it is clear that the importance of precise digitization of old maps will continue to grow in the future.

2 TESTING GEOMETRIC ACCURACY OF SCANNERS

Common desktop scanners are unsuitable for scanning maps because of the maps' usually large size. Such large maps can only be scanned on common desktop scanners part by part and the parts then have to be joined into a single image in some software. That is not only inconvenient but also introduces errors of position in individual blocks. Large format scanners, either pullout or flatbed, are a better solution. Pullout (cylinder) scanners run the map through them and scanner head remains static. On the other hand in flatbed scanner the map is static and the sensing instrument (camera) moves. Flatbed scanners are less invasive to the map and usually have better geometric accuracy.

Scanner's cameras scan the map from short distance (less than 20 cm) in rows which minimalizes imperfections of the optical system. Large format scanners typically employ several cameras with overlapping fields of vision to cover the whole width of scanned work. This yields several images (one for each camera) during the scanning process. These images are merged into a single one by the scanner's service software (firmware). This merging process, stitching, is a critical part of the procedure as it can be a source of image distortions.

Evaluation of scanner's geometric accuracy can be approached in two ways. First is assessing absolute accuracy. This is a measure of how accurately is the map reproduced, that is how big are errors of position of test points in resulting digitized map compared to paper original. The second approach is relative accuracy - measure of consistency of digitization over time and homogeneity of positional errors over the whole digitized area. In other words it is a measure of difference between repeated scans and also a measure of difference between errors in various parts of the scan.

2.1 *Testing absolute accuracy*

In principle absolute accuracy is evaluated by comparing digitized image of a known template with its real size and geometry. This way of testing is used for example in state regulation (ČÚZK 2004). The template is usually a regular grid of cross-shaped markers. Line widths of the markers should not be larger than 0.1 mm which corresponds to 3 pixel width in resulting image when scanning with 600 dpi resolution. The position of markers in the template has to be measured with precision in the order of hundredths of millimeters. A suitable instrument is for example laser interferometer. The template has to be made from a material resistant to thermal expansion it has to be flexible so it can be pressed against the scanning glass of a flatbed scanner or pulled through a pullout scanner. Such a template is scanned, the markers' positions (image coordinates) are measured and compared to coordinates of the markers on template. Differences in the two sets of coordinates characterize absolute geometric accuracy of the scanner.

Drawback of this method is the necessity to precisely measure the template which is a time consuming process in practice limiting the number of markers and therefore test points. Relatively low number of test points limits this method in catching potential local deformations of small areas. For example the distance between neighboring markers in the template used in aforementioned state regulation (ČÚZK 2004) is 50mm. Another disadvantage is the necessity for estimating marker centers for manual measurement of the template which can lead to errors.

2.2 *Testing relative accuracy*

Relative accuracy testing is a more recent method of scanner quality evaluation. It also uses a testing template of regular grid of cross-shaped markers but there is no need to measure the markers' coordinates on the template. Instead the template is scanned repeatedly and markers' image coordinates transformed into a common coordinate system are compared between multiple scans. Detection of marker position in the image can be automated with various image processing techniques. That allows much denser marker placement while avoiding laborious manual measurements. Detailed description of marker detection by image correlations, calculation of position changes and interpretation of measurements is for example in (Antoš, Böhm & Talich 2014).

A dense grid of markers is necessary to detect areas with distinctly higher deformations than the rest of the image. Such a template can be evaluated in the same way as in the case of absolute accuracy testing. This provides more detailed view of errors of position homogeneity caused by scanner and thus can be used to determine relative accuracy of individual parts of the scanning area. But this method requires precise measurement of the template to allow comparing image coordinate with reference coordinates. That can present a problem because the template can contain even several thousands of markers depending on its size and density of its marker grid. Errors in manual estimation of marker centers play a role in this method too.

3 USING STRAIN ANALYSIS FOR RELATIVE ACCURACY TESTING

Experience with practical absolute accuracy testing has shown that the results are often dependent on placement of template in the scanner. This led to a hypothesis about the existence of local deformations in areas smaller than is the gap between markers on template. When some markers lie in such an area, their positions show larger deviations. But when the template is shifted slightly so that no markers lie in these problematic areas, the marker positions are not affected by them and all deviations are small.

These small deformation areas are important for objective evaluation of scanner's relative accuracy. The only way to detect them is to use a denser template (with smaller distance between markers). That makes absolute accuracy evaluation unfeasible due to difficulties with manual reading of all marker coordinates. Relative accuracy evaluation is better method in such a case because it can be in large part automated.

A suitable mathematical tool to assess changes in relative relation between markers is strain analysis. This theory is based on continuum mechanics but in geometric sense it can be considered theory of small deformations. It describes changes in shape and size of observed objects through interpretation of repeated measurements. In this case the observed objects are markers on the template and repeated measurements are image coordinates of markers on repeated scans. Displacement vectors are a function of coordinates:

$$\mathbf{x}_i^{\circ} - \mathbf{x}_i^{t} = \mathbf{d}_i = (u_1, u_2, u_3)_i^T = \mathbf{u}(\mathbf{x}) = (u_1(\mathbf{x}), u_2(\mathbf{x}), u_3(\mathbf{x}))^T, \ \mathbf{x} = (x, y, z)^T$$

Where $\mathbf{x}_i^{\circ}$ (resp. $\mathbf{x}_i^{t}$) is the vector of P_i point coordinates of fundamental (resp. actual in t-time) epoch.

The strain tensor $\mathbf{E}_i$ in the P_i point is defined as a gradient of the function in this point:

$$\mathbf{E}_i = \operatorname{grad}(\mathbf{d}_i).$$

The most illustrative indicator of the scale of geometric deformation at point P_i is total dilatation:

$$\Delta = \frac{\partial u_1}{\partial x} + \frac{\partial u_2}{\partial y}.$$

Positive values indicate extension at P_i, negative value signify compression. This allows identifying areas with largest local deformation and also the extent of these deformations. Conveniently total dilatation is invariant with relation to translation and rotation and therefore unrelated to choice of coordinate system used to measure marker coordinates. Thus there is no need to transform marker coordinates into a common coordinate system. Apart from numerical values of dilatations for discreet points, the results can also be displayed as hypsometry for the whole template.

Theoretical solution and derivation of these formulas in question may be found in a number of publications - e.g., (Szostak-Chrzanovski 2006), (Talich 2008) and (Kostelecký, Talich, Vyskočil 1994).

4 RESULT OF RELATION ACCURACY TEST OF SCANNTECH 800I SCANNER

Practical use of strain analysis for relative accuracy evaluation is demonstrated on ScannTech 800i scanner. The test included a total 193 of scans of a template in varied time intervals. The template was made from shrink-proof material astralon and contained 1886 markers (46 rows x 41 columns). The distance between markers in row/column was 20 mm. Time intervals between scans were 30 minutes, 5 minutes and no interval at all (save for the time it took to save the scan). The reason for varied intervals was an effort to assess effect of time between scans on geometric accuracy of scans. Scans were taken in 800 dpi resolution and 24 bit color depth.

Marker positions were detected to a sub-pixel precision using image correlation. Pixel size in this case was 0.03175 mm. Differences in image coordinates of corresponding markers on multiple scans were used to calculate total dilatations and other deformation parameters. Total dilatations were represented in hypsometry form for each scan.

Analysis of the results showed differences in reproduction of the template. Largest deformations were in places of stitching - where individual cameras' images overlap and are stitched together by scanner's software. For ScannTech 800i there are three such areas. Figure 1 shows

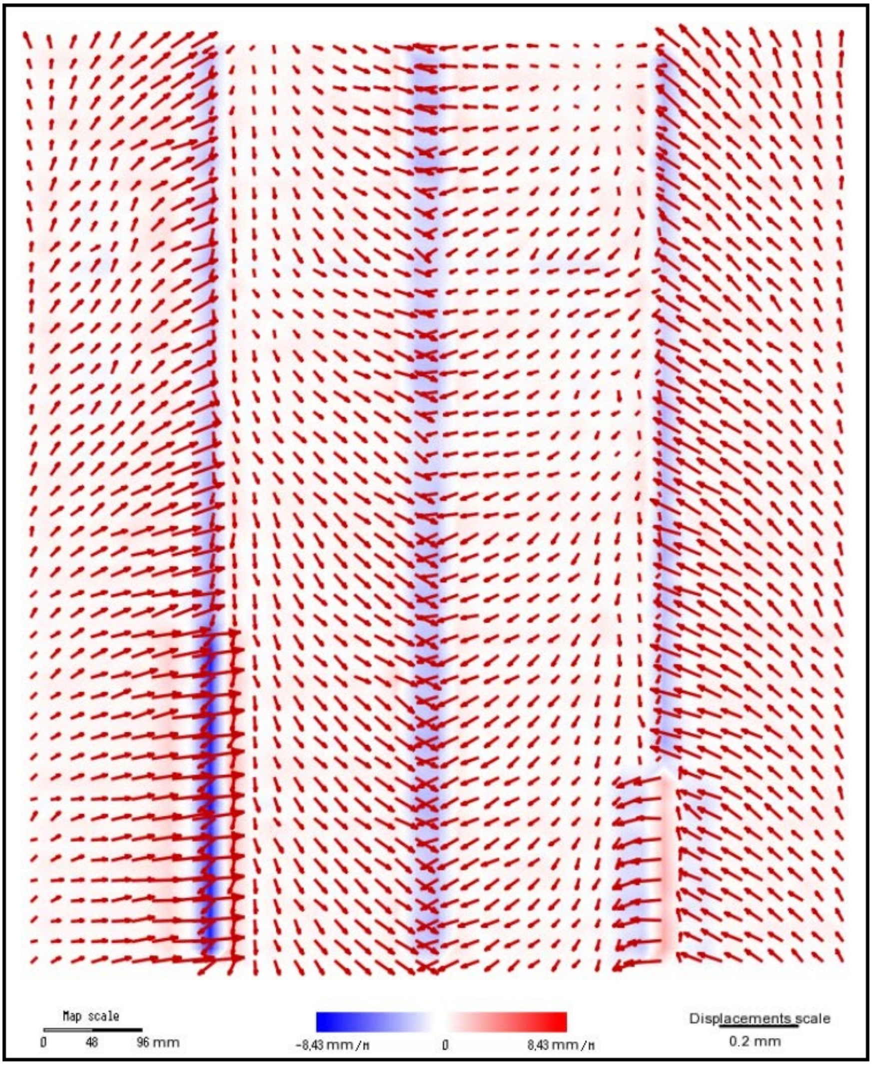

Figure 1. Image coordinate differences.

image coordinate differences between first and third scan, separated by 60 minutes time interval. The template was not moved between scans and only scanner head moved during scanning. Thus both sets of image coordinates were in the same coordinate system. Results show that the four strips taken by individual cameras are shifted relative to each other by 0.01 mm to 0.06 mm while being relatively homogeneous on their own. But the coordinate differences are up to 0.12 mm in the areas of stitching causing small areas of high local deformations. This is apparent on Figure 2 displaying total dilatations as hypsometry. Varied values of total dilatations in the same stitching areas point to imperfections in firmware joining the images from individual cameras together. Identical stitching areas show both extensions and compression on repeated scans, in some cases (in some scans) the coordinate differences were up to 0.25 mm. These small areas would likely not be detected at all using template with markers spaced 50 mm or more.

Deformations outside the stitching areas are an order of magnitude smaller. Figure 3, 4 and 5 show total dilatations for three consecutive scans with time interval of 5 minutes. There are visible distinct changes in total dilatations values between scans. Changes outside stitching areas

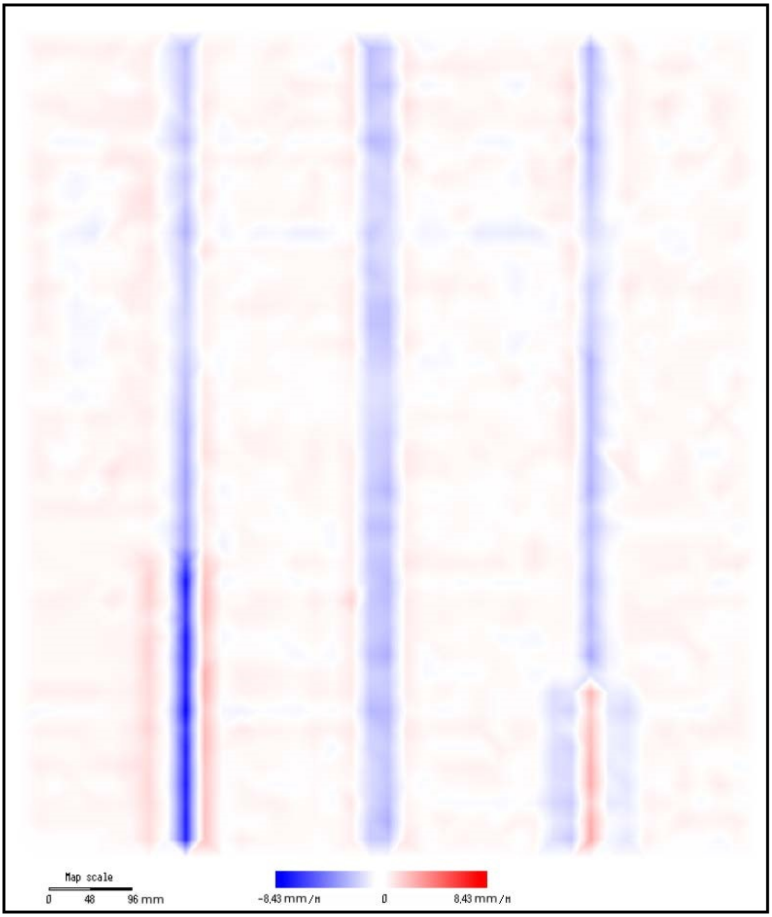

Figure 2. Hypsometry of total dilatations.

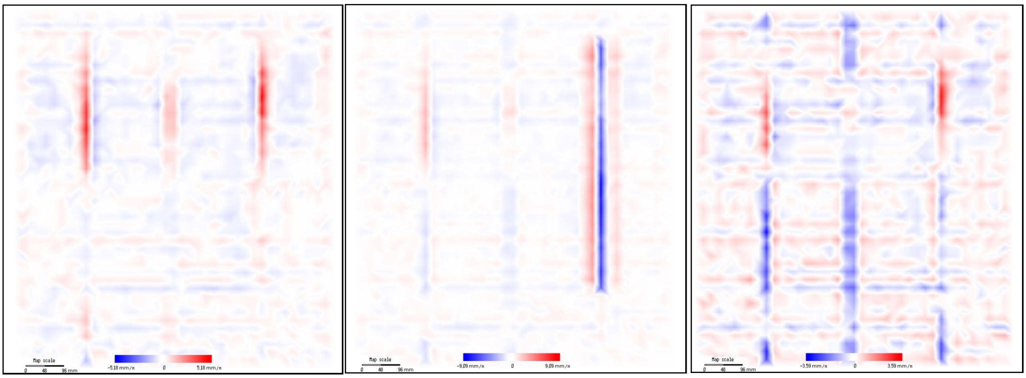

Figure 3, 4 and 5. Hypsometry of total dilatations for three consecutive scans.

are likely caused by variations in the speed of scanner's head. This is supported by alternation of extensions and compressions in rows in Figure 5.

Results showed that time interval between scans doesn't significantly affect variations in scans of identical model. Calculations of dilatations were carried out in own special software (Talich & Havrlant 2008).

5 CONCLUSION

The paper introduces a new method of testing relative accuracy of cartometric scanners. This method uses a reference template containing a regular grid of cross-shaped markers. Template marker positions are detected with use of image correlation obviating the need for manual measurement and increasing detection precision to sub-pixel values corresponding up to hundredths of mm depending on optical resolution. Strain analysis is used to process coordinate differences between repeated scans. With strain analysis being independent on coordinate system, detected coordinates don't have to be transformed into a common system, thus eliminating errors introduced by such a transformation and improving result accuracy. In addition it can effectively process and evaluate even dense marker grids (up to thousands of markers). Thanks to that it can detect even local deformations restricted to small parts of scans. These local deformations can then be clearly represented e.g. by the hypsometry of total dilatation in the form of strain maps.

Practical tests show comparatively largest deformations occur in stitching areas (overlaps of scanner's individual cameras). Uneven speed of scanner head movement causes much smaller deformations outside the stitching areas.

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