RASTER IMAGE WARPING FOR GEOMETRIC CORRECTION OF CARTOGRAPHIC BASES

Larry Moore, William Harris, Tim Kochis
U.S. Geological Survey, Mid-Continent Mapping Center
Rolla, Missouri
573-308-3661

Matthew Reed
Science Applications International Corporation

ABSTRACT: The U.S. Geological Survey (USGS) 7½-minute mapping program began in the mid-1940's. Maps from the early days of the program were made with technologies that were obsolete by 1960. These technologies included field triangulation and longbar aerotriangulation. Recent work has raised the possibility that many of these early maps are not as accurate as previously believed. Many old maps do not match more recent USGS products, particularly digital orthophoto quadrangles (DOQ), to within acceptable tolerances.

A goal of the USGS map revision program is to ensure that revised graphics meet the accuracy specifications for the appropriate map series. The USGS map revision program is not funded for remapping with new field control, but there are other ways to improve the horizontal accuracy of old bases. DOQ's are more accurate than older map bases and can therefore be used to improve the accuracy of the map.

Image warping methods can be used to adjust an old map base to newer, more accurate control. This technique is fast and inexpensive compared to obtaining new field control and doing new compilation. A prototype system based on commercial geographic information system image rubber sheeting has greatly improved the accuracy of some maps and improved the consistency of clusters of maps. In the best case tested so far, the root mean square error of 50 test points was reduced from 93 feet to 33 feet, relative to the DOQ.

INTRODUCTION

The 1:24,000-scale, 7½-minute topographic quadrangle is the primary product of the National Mapping Program. This map series includes some 57,000 sheets and is the only uniform map series that covers the entire area of the United States in considerable detail (National Research Council, 1990, p. 8). The 7½-minute mapping program lasted for about 50 years, from the mid-1940's to the early 1990's. This program consisted of new mapping. New photography was flown, field control was obtained, and field-based photointerpretation was done for every project. Feature names were verified by personal contacts with local residents and local government agencies. These methods produced consistent, high-quality maps, but they were very expensive.

Several significant technical advances in mapping occurred during the life of this program. Mapping in the 1940's and early 1950's used methods that were out of date by 1960. The absolute positional accuracy of some of the early maps is not as good as it was believed to be at the time. The National Mapping Division (NMD) of the U.S. Geological Survey (USGS) is now revising and updating these maps and finding that some do not actually meet the National Map Accuracy Standard (NMAS).

The errors discussed in this paper have the following characteristics:

- The errors are in absolute position, not in local relative position.
- They tend to be in the range of 0.02 to 0.10 map inch (40 to 200 ground feet).

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

- They are associated with specific mapping technologies, particular dates, or both.

Isolated blunders may cause errors that are larger or more noticeable, but these occur infrequently and are outside the scope of this paper.

EVALUATING ACCURACY PROBLEMS

In 1941, the U.S. Bureau of the Budget issued the "United States National Map Accuracy Standards," which applied to all Federal agencies that produce maps. A revision issued in 1947 is still used today. In 1958, the USGS began systematically testing the accuracy of its maps by collecting independent field control for a sample of new 7½-minute quadrangles (USGS, 1997).

This testing program was not generally applied to maps completed before 1958. One exception was a cooperative study with the State of Kentucky in 1986. This study tested 83 Kentucky quadrangles made between 1948 and 1958, using rigorous sampling methods and new field control. The primary conclusion was that "…33 [quadrangles] pass, 21 are borderline, and 29 fail." The Kentucky study was not extended to other States, primarily because of the testing expense. The study cost approximately $1,500 per quadrangle (unpublished data).

Over the years, USGS personnel have derived empirical rules for predicting whether or not a map is likely to be horizontally inaccurate. The horizontal accuracy of a map is suspect if both of the following conditions apply:

- Field control was by transit traverse or triangulation
- Aerotriangulation (AT) method was bridging by longbar

In other words, maps made with particular old technologies tend to be less accurate.[1] Experience suggests that most inaccurate maps were made with these methods, but the converse is not true: not all maps made with these methods are inaccurate.

Estimating the number of inaccurate bases without new and independent control is therefore difficult. The Kentucky study supplies almost all the available quantitative evidence. Nearly all Kentucky bases fit the criteria for suspect accuracy, but the 1986 study found that 40 percent of Kentucky quadrangles did meet the NMAS and another 25 percent were borderline. If these results apply to the entire map series, it is possible that between 3,000 and 6,000 quadrangles do not meet the NMAS. There are about 57,000 7½-minute quadrangles.

If relative positions are correct, errors in absolute accuracy of less than 0.10 map inch (200 ground feet) are difficult to detect on a paper map. But in recent years, horizontal inaccuracy has become visible owing to the USGS digital orthophoto quadrangle (DOQ) program. DOQ accuracy is relatively independent of topographic base map accuracy, and DOQ's are generally more accurate than 7½-minute maps. Geographic information systems (GIS) allow different map products to be displayed at the same time and at high magnification, which makes positional differences between products obvious (figure 1).

THE 7.5-MINUTE MAP REVISION PROGRAM

With the completion of the 7½-minute mapping program in 1992, the USGS began formulating a graphic revision plan to keep primary series maps current. A variety of processes are used to revise maps (USGS, 1998). Some revisions use traditional analog processes, some use digital processes. Some work is done by USGS employees, some by contractors. Much of the revision work depends on cooperative funding from other State or Federal agencies, and these organizations therefore have influence over the type and content of the revision.

Revising maps without fieldwork

There are two categories of map revision: basic and complete. In basic revision, many features are revised by interpreting DOQ's and aerial photographs. No fieldwork is done for either control or photointerpretation. A goal of basic revision is to maintain the positional accuracy of the previously published map, a fact that is especially relevant

---

[1] Although many old maps have been revised one or more times, these revisions were of feature content only. Most revisions did not include new field control, new AT solutions, or any positional control other than the existing map base.

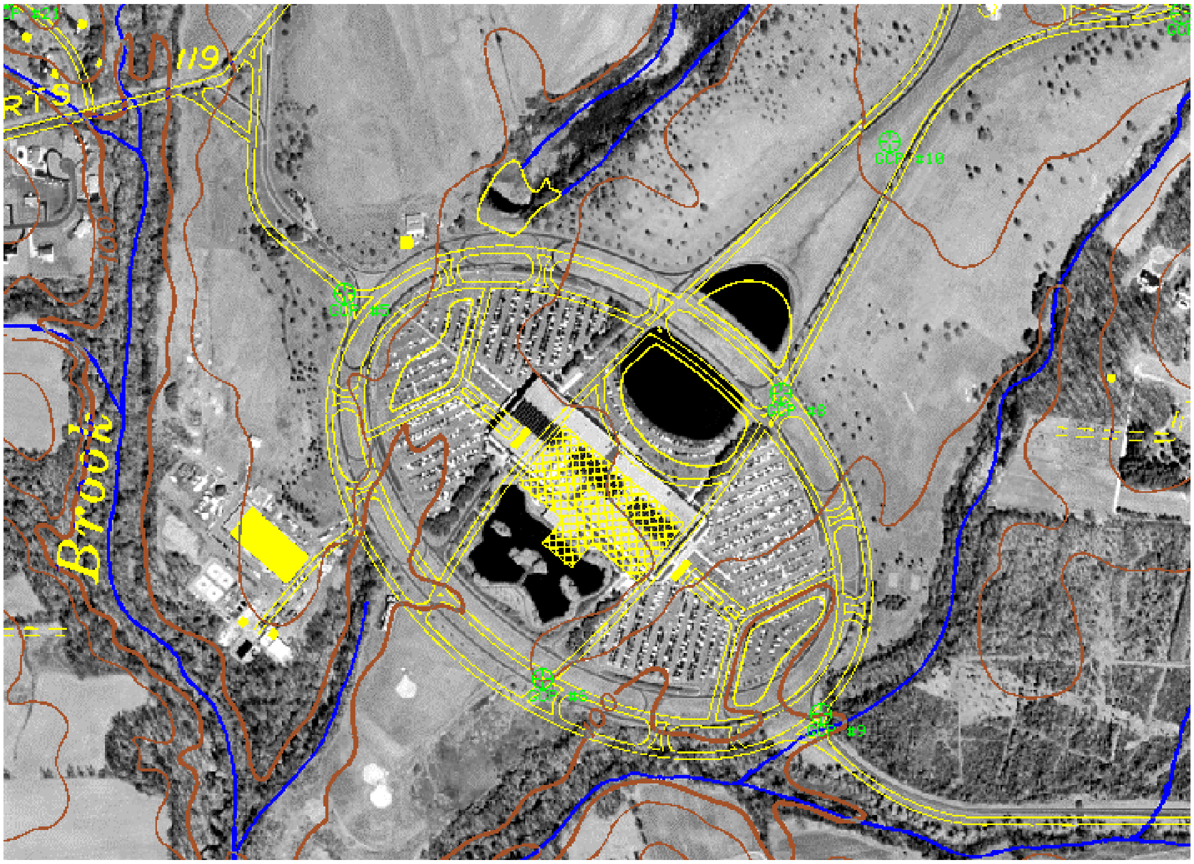


Figure 1. Example of discrepancy between map base and DOQ. The image shows a shopping mall. The major axis of the outer road ellipse is 2,950 feet, the minor axis 2,052 feet. The map base is about 112 feet south-southwest of the DOQ image, or about 0.056 inch at map scale. The RGC process improved this fit so that the map base and the DOQ for this particular area matched to within 30 feet.

to this discussion.

Complete revision is essentially new mapping. The old map is used as a reference, but field crews establish new control and interpret photographs. Because this method is much more expensive, it is not often used.

So in most cases, the USGS map revision program assumes that existing map bases are accurate. The revision program was not designed to do replacement mapping; Congress has not authorized a repeat of the 7½-minute mapping program or allocated money for new field control or field-based feature interpretation. Most map revision is done from remote and secondary data sources, including the following:

1. Geometry is controlled and some feature content interpreted from DOQ's.
2. Most feature content is interpreted by using stereophotographs from the National Aerial Photography Program (NAPP).
3. Boundary and name information is collected from other maps and from State and local agencies.
4. Some content may be checked by Volunteers for Science – private citizens who donate time to do field verification work.

Error propagation and ground-truth estimation

Because DOQ's are used for horizontal control, the revised map has errors from two sources: the DOQ and the revision process.

DOQ's are held to more exacting accuracy standards than are 7½-minute maps. No saleable USGS DOQ's are produced using published maps as control. DOQ's are made with new aerotriangulation solutions that include a mixture of pre-existing and new ground control. The evidence from independent field testing is that the average DOQ is significantly more accurate than required by the NMAS.

Nevertheless, any accuracy statement about a revised map depends in part on assumptions about the accuracy of the DOQ. These assumptions cannot normally be verified by direct measurement because of the expense of the required fieldwork.

IMPROVING OLD BASES THROUGH IMAGE WARPING

One goal of the revision program is to ensure that the revised map matches the corresponding DOQ (figure 1). This is not the same as making the map with ground control, and it does not absolutely guarantee that the map will be improved or will meet the NMAS. The goal of matching the DOQ is justified in two ways:

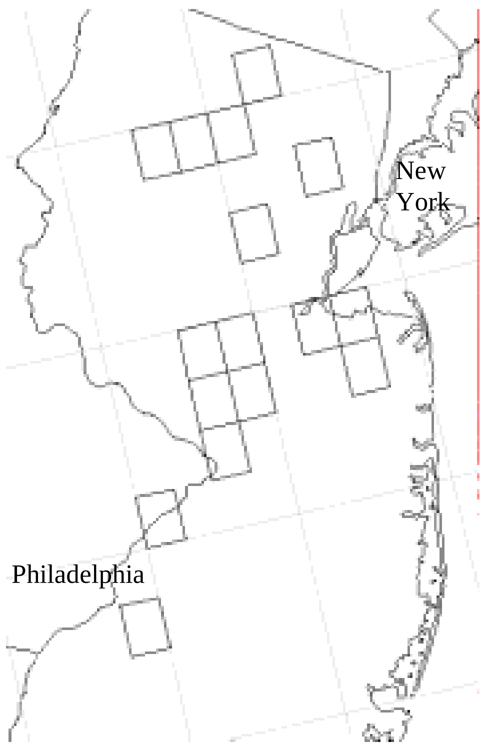


Figure 2. Quadrangles in pilot study

1. Available evidence shows that the average DOQ is more accurate than the average 7½-minute map.
2. Product consistency and relative position are at least as important to most users as absolute accuracy.

"Image warping" is used here to refer to a class of rubber-sheet transformations. Imagine a map on a flexible rubber sheet which can be deformed algorithmically, forcing registration of control points distributed over the map with their counterparts on the fixed, stable base map (White and Griffin, 1985). These transformations are generally more advanced than more traditional transformations based on polynomials (Lembo and Hopkins, 1998). There are a variety of published methods for warping maps, and most commercial GIS's implement some type of map warping.

In late 1998, USGS personnel built a prototype system to fit raster map overlays to a DOQ. This system is based on the nonlinear rubber-sheeting functions of a commercial GIS. The prototype was named the raster geometric correction (RGC) system.

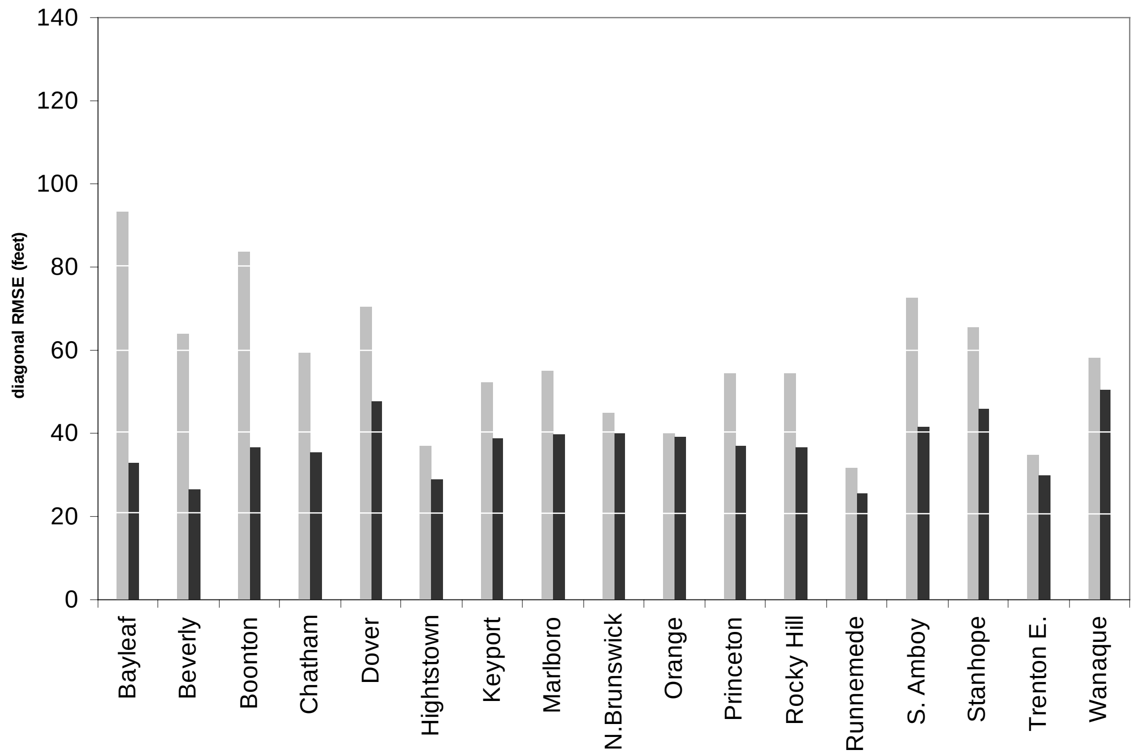
The archive materials for a quadrangle may consist of up to 30 feature separates. The RGC process begins with registering raster scans of these separates to each other and to the DOQ. Selected layers of the map – usually roads and other transportation – are displayed over the DOQ. Control points are collected interactively by associating map points with DOQ points. Collecting control points and applying the rubber-sheet transformation is often repeated several times. Selecting the control points is an art, and it is difficult to know when to stop trying for more improvement. In some instances, as few as 20 control points have resulted in a good fit. In other instances, up to 400 points were needed. Wide variations in direction and magnitude of error account for the variation in the number of points needed.

The rubber sheet used in this test divides the image into contiguous triangular regions based on Delaunay triangles, similar to the way the triangles of a triangulated irregular network (TIN) are created. The three vertices of each triangular region are control points chosen by the user, and a vertex generally is shared by more than one triangle. A separate polynomial transformation is computed and applied for each triangle. Nonlinear rubber sheeting is a higher order transformation that uses the three vertices of the triangle for which it is being computed as well as other control points outside this triangle. Applying the same transformation to all layers is important to maintain cartographic feature registration.

The outputs of this process are raster map separates that have been rubber sheeted to fit the DOQ control. Feature distortion caused by the rubber sheeting is never great enough to be seen without careful measurement. A base error of 200 feet is very severe, but it is only 0.1 inch on the map. Nevertheless, the outputs of RGC are not publishable map separates because the process warps the graticule and plane grids along with the map features. The warped images are useful only as inputs to map revision processes or for special-purpose GIS applications.

RESULTS OF PILOT STUDY

The RGC system was tested on a group of 17 quadrangles, 16 of which are in New Jersey (figure 2); the other one (Bayleaf) is in North Carolina and was included because of a pressing need to revise a base that was obviously inaccurate. These quadrangles were not selected by statistical sampling. The New Jersey maps made up a single project that was planned for revision through normal channels. All 17 maps were old enough to be treated as suspect



Before RGC	93	64	84	59	70	37	52	55	45	40	54	54	32	72	65	35	58
After RGC	33	26	37	35	48	29	39	40	40	39	37	37	26	41	46	30	51

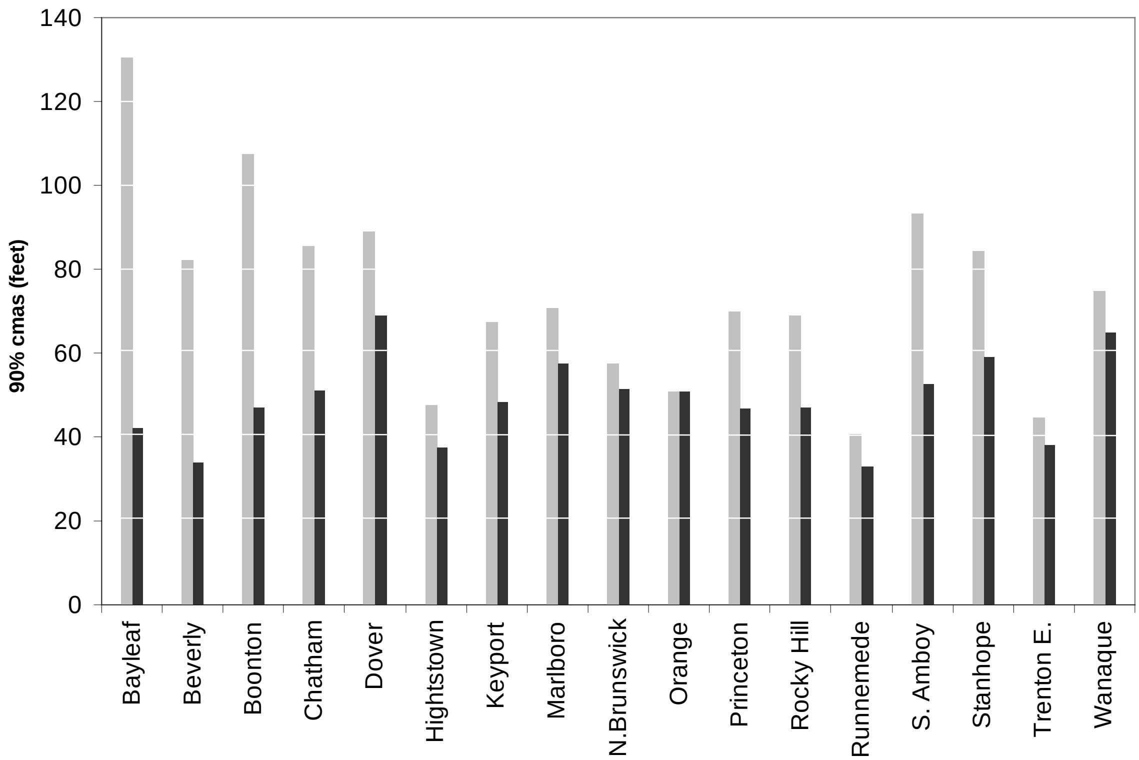
Figure 3. Effect of RGC on RMSE, measured against the DOQ. Gray bars are pre-warp, black bars are post-warp. All values are in feet, rounded to the nearest foot. RMSE calculations according to Greenwalt and Shultz (1962). Quadrangle order is alphabetical.

bases.

Horizontal accuracy tests were run on each of the 17 quadrangles before and after RGC. Different people did the accuracy testing and image warping. Test points and other data were not shared during the study. About 50 accuracy test points were used on each quadrangle. These were well-defined points, mostly right-angle road intersections. The number of points selected to control the image warping varied widely between quadrangles. The warp was often repeated several times in response to the operator’s subjective evaluation of the improvement.

Figures 3 and 4 show the effect of RGC on two accuracy statistics. The 90 percent circular map accuracy statistic (CMAS) (figure 4) is particularly meaningful. Ninety percent of the well-defined points of a quadrangle can be said to be within this distance of their control position.

All accuracy tests were relative to a DOQ, which is not the same thing as ground control. A DOQ contains errors of



Before RGC	130	82	107	85	89	48	67	71	58	51	70	69	41	93	84	45	75
After RGC	42	34	47	51	69	37	48	58	51	51	47	47	33	53	59	38	65

Figure 4. Effect of RGC on 90 percent circular map accuracy statistic (CMAS). Gray bars are pre-warp, black bars are post-warp. All values are in feet, rounded to the nearest foot. CMAS calculations according to Greenwalt and Shultz (1962). Quadrangle order is alphabetical.

its own. Although these errors are generally much smaller than the errors of old map bases, they cannot be ignored completely. A discussion of the relationship of the distances in figures 3 and 4 to ground distances is beyond the scope of this paper.

Results for other error statistics were approximately the same as for the two statistics shown in figures 3 and 4.

DISCUSSION

Figures 3 and 4 illustrate several encouraging things about image warping as a method of correcting inaccurate bases:

- In no case did RGC make a map less accurate.
- Improvements in accuracy ranged from modest to dramatic. The largest improvements occurred in maps that were the worst to start with. On the Bayleaf quadrangle, for example, the RMSE was reduced from 93 feet to 33 feet, and the 90 percent CMAS was reduced from 133 feet to 42 feet.
- The outputs of RGC were more consistent than the inputs. That is, the variation in the accuracy of the bases was reduced.

One of the attractions of RGC is that image warping is relatively cheap. Given the availability of a DOQ, RGC does not require additional fieldwork. The total time required for testing and warping a map base ranged from 8 to 24 hours. The overall cost of a quadrangle revision is in the range of 300 hours. Experienced USGS map compilers believe that mismatches between the map base and the DOQ are a major source of added expense in map revision; time spent correcting this problem at the beginning pays for itself several times over during the revision.

The pilot study indicates that image warping alone is not powerful enough to improve inaccurate bases to meet the NMAS. However, collecting new features and other map revision processes also tends to improve the old base. It is possible that all these factors together may achieve NMAS compliance, at least in some cases.

REFERENCES

Greenwalt, Clyde R. and Shultz, Melvin E, 1962. Principles of Error Theory and Cartographic Applications: Aeronautical Chart and Information Center, United States Air Force.

Lembo, Arthur J. Jr. and Hopkins, Paul F., 1998, The Use of Adjustment Computations in Geographic Information Systems for Improving the Positional Accuracy of Vector Data: Surveying and Land Information Systems, v. 58, no. 4, p.195.

National Research Council, 1990. Spatial Data Needs: The Future of the National Mapping Program. National Academy Press, Washington, D.C.

U.S. Geological Survey, 1997, Map Accuracy Standards, Fact Sheet 078-96.

U.S. Geological Survey, 1998, Revision of Primary Series Maps, Fact Sheet 016-98.

White, Marvin S. and Griffin, Patricia, 1985, Piecewise Linear Rubber-Sheet Map Transformation: The American Cartographer, v.12, no. 2, p.123.