ORTHORECTIFY HISTORICAL AERIAL PHOTOGRAPHS USING DLT

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ABSTRACT

A large amount of aerial photographs were taken early 1900s for reconnaissance and planning purposes. These aerial photographs provide valuable baseline data for a great variety of environmental studies. In order to be used for analysis within a GIS environment, these photographs need to be referenced to a ground coordinate system. The great topographical variation within photo ground coverage demands that such a photograph needs to be orthorectified for acceptable map accuracy. However, camera models for these historical photographs are usually unavailable due to various reasons. Additionally, land cover change makes it a challenge to collect ground control points. In this study, the direct linear transformation (DLT) method was investigated to orthorectify such historical aerial photographs. Ground control points were collected from existing map products. The accuracy of the orthophotos produced using the DLT was evaluated against the National Map Accuracy Standards.

KEYWORDS: direct linear transformation, orthorectification, historical aerial photograph, rational function

INTRODUCTION

Aerial photographs capture a snapshot of the earth surface and they are widely used in many geospatial applications. Historical aerial photographs acquired back in early 1900s captured valuable geographic information of the environment before modernization and provide priceless baseline data for many different studies including physical geography, environmental studies, biology conservation, and urban and regional planning. The great value of such photographs has been recognized as evidenced by the National Digital Information Infrastructure and Preservation Program formed by the Library of Congress (NGDA, 2011). Efforts have been taken to build portals for data collection and distribution such as the National Geospatial Digital Archive by libraries of UC Santa Barbara and Stanford University (NGDA, 2011).

Given the value of these historical photographs, however, they have been underused to understand and quantify land use changes and human activities and migrations. One important reason for the lack of use is the challenges of accurately geo-referencing the photos to a ground coordinate system to be compared with other geographic datasets in GIS. Geo-referencing an image is fundamentally a transformation where an image is transformed from a 2D image space into another 2D ground coordinate system. In areas with flat terrain, a geo-reference method will be able to transform a photograph into a ground coordinate system with satisfactory accuracy. However, in areas with great terrain variation, a geo-reference method will introduce large errors due to the fact such a does not account for relief displacement caused by terrain variation. For example, southern California in general has a rough terrain and aerial photographs in this region cannot be accurately geo-referenced to a ground coordinate system. In this case, these photos have to be orthorectified using photogrammetric methods to remove relief displacements.

Orthorectification is the most accurate method of transforming aerial photographs to a ground coordinate system and it requires a well-established imaging geometry, with which a ground point in a 3D space with known position (X, Y, Z) can be transformed to its corresponding image position (x, y). Generally, there are two imaging geometry models often used in orthorectification, namely rigorous camera models and rational function models (RFMs) (Di, Ma, and Li, 2003a; Robertson, 2003; Tao and Hu, 2001; Toutin, 2004; Yang, 2000). As a special case of RFM, direct linear transformation (DLT) is often discussed independently from RFM in the literature.

In order to use the rigorous camera model in representing the imaging geometry, the camera used to collect the photographs should be carefully calibrated to obtain the interior orientation parameters that include accurately measured focal length, lens distortion parameters, and fiducial mark positions. The interior orientation parameters are used to accurately establish the geometry between a photograph and the camera. It is also used to establish the transformation from a measurement system, such as a computer screen or a tablet digitizer, to the image coordinate system represented by the fiducial marks. However, these interior orientation parameters usually are not available for historical aerial photographs. Either they are very difficult to find out or they were not available in the first place. Although interior orientation parameters can be calculated from accurately measured ground control points, the process is not practical for working with historical photos due to its demand of a large group of well-configured high accuracy ground control points. A period of more than 70 years sees great changes of the land cover, which makes it very difficult to establish high quality control points.

Without the interior orientation parameters, RFM can be used to approximate the exact imaging geometry of an aerial photograph. A rational function is a ratio of two polynomial functions (NIST/SEMATECH, 2011). A RFM uses such a function to represent the imaging geometry of an aerial photograph and modern satellite images.

A RFM is often used by satellite image providers to approximate the rigorous imaging geometry, which maps a 3D ground space to a 2D image space. The choice of using a RFM, instead of a rigorous camera model, is the result of several reasons. First, camera models and ephemeris data are usually proprietary data and imaging companies do not want to reveal them to users. Second, imaging geometry of high-resolution satellite images is very complicated because the current cameras used are pushbroom scanners. Each image line from such a scanner has its own imaging geometry and the imaging geometry parameters of nearby lines are usually correlated to each other. Using RFMs can greatly simplify the mathematical representation of such imaging geometries, and potentially standardize image geometric processing. When a user purchases an imagery data, the data provider will calculate the RFM using its rigorous camera model and satellite ephemeris data.

Extensive studies have been conducted to investigate the accuracy of RFM in geometrically processing satellite imagery (Eisenbeiss et al., 2004; Li et al., 2007; Li, Di, and Ma, 2003; Li et al., 2009; Tao, Hu, and Jiang, 2004; Zhou and Li, 2000). Studies have shown that a RFM can closely approximate the rigorous camera model, and its accuracy is at the same level as the original camera model (Dial and Grodecki 2002; Grodecki and Dial, 2003; Hu, Tao, and Croitoru, 2004; Tao and Hu 2001). A user can use ground control points to refine the vendor provided RFM using various methods including the Kalman filter and polynomial transformations; and RFMs of a block of images can also be refined together (Di, Ma, and Li, 2003b; Dial and Grodecki 2002; Grodecki and Dial, 2003; Hu, Tao, and Croitoru, 2004). To calculate the parameters of a RFM, data providers usually use hundreds of virtual control points that were generated systematically from their rigorous camera models and satellite ephemeris data (Dial and Grodecki 2002; Grodecki and Dial, 2003; Tao and Hu, 2001).

Despite extensive studies on RFMs in the literature, there has been very limited research on using RFMs in aerial photographs. Historical aerial photographs were acquired using frame cameras instead of scanners as used in modern satellite image acquisition. The commonly used collineraity condition in rigorous camera models is essentially a special expression of linear RFM, which is referred as DLT in the literature. DLT was developed independently in early 1970s to solve the collinearity condition (Abdel-Aziz and Karara, 1971). It can be used in place of rigorous camera model in representing the imaging geometry for image geometric process (Molnar, 2010; Remondino, 2002).

Given the interior orientation parameters are not available and the difficulties in measuring high accuracy of ground control points from historical aerial photographs for calculating these parameters, the DLT method was evaluated in this study to orthorectify historical aerial photographs.

DIRECT LINEAR TRANSFORMATION

Essentially DLT is a different expression of the rigorous camera model represented using the collinearity condition; and its parameters are combinations of a camera’s exterior orientation parameters. Compared with a rigorous camera model, DLT uses more parameters than the rigorous camera model in representing the imaging geometry. Because of that, the DLT parameters are correlated to each other due to the fact that they are combinations of the six exterior orientation parameters. This section discusses the relations among the DLT, RFM, and the rigorous camera model.

Rigorous Camera Model

A rigorous camera model is commonly represented using the collinearity condition, which states a ground point, its image point, and the camera lens center lie on a straight line. An example of such a rigorous frame camera model is represented in equation 1:

$$\begin{cases} x - x_0 = -f\frac{m_{11}(X-X_0)+m_{12}(Y-Y_0)+m_{13}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)} \\ y - y_0 = -f\frac{m_{21}(X-X_0)+m_{22}(Y-Y_0)+m_{23}(Z-Z_0)}{m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)} \end{cases} \quad (1)$$

where, f is the focal length of the camera; (X, Y, Z) is the position of a ground point in the ground coordinate system; (x, y) is the position of the same ground point in the image space which is represented using the calibrated fiducial marks; (x_0, y_0) is the position of the calibrated principal point; (X_0, Y_0, Z_0) is the position of the camera in the ground coordinate system when the photograph was captured; and m_{ij} are the data entries of the rotation matrix from the ground coordinate system to the image coordinate system. The rotation matrix is derived from the three rotation angles around the x, y, and z axes respectively. The afore-mentioned exterior orientation parameters are the three rotation angles and the (X_0, Y_0, Z_0).

DLT

By merging (x, y) and (x_0, y_0) terms on the left side of equation 1, and re-arrange the right side of equation 1 based on the ground coordinates (X, Y, Z) of a point, the DLT representation of the rigorous camera model can be written in equation 2:

$$\begin{cases} x' = \frac{a_0+a_1X+a_2Y+a_3Z}{c_0+cX+c_2Y+c_3Z} \\ y' = \frac{b_0+b_1X+b_2Y+b_3Z}{c_0+cX+c_2Y+c_3Z} \end{cases} \quad (2)$$

where (x', y') is the position of a ground control point in the image space; (X, Y, Z) is the position of the same ground point in the ground coordinate system; a_i, b_i, c_i, and d_i are the parameters defining the DLT. The DLTZ parameters are combinations of the image exterior orientation parameters. For example, the parameter c_0 is equivalent to ($-m_{31}*X_0-m_{32}*Y_0-m_{33}*Z_0$). There are a total of 12 parameters in the DLT model; and six ground control points are required to calculate them.

It should be noted that depending on specific implementations, the numerators and denominators on the right side of equation 2 can be divided by the coefficient c_0 to normalize the DLT equation. This will make the coefficient c_0 a constant number of 1. RFMs for commercial satellite images are usually represented using the value of 1 for the constant coefficient in the denominators. In this study, c_0 is kept as a variable to be solved using the ground control points.

RFM

As stated earlier, RFM uses the ratio of two polynomials to represent the imaging geometry. A quadratic/ quadratic RFM is represented in equation 3:

$$\begin{cases} x = \frac{a_0+a_1X+a_2Y+a_3Z+a_4XY+a_5XZ+a_6YZ+a_7X^2+a_8Y^2+a_9Z^2}{b_0+b_1X+b_2Y+b_3Z+b_4XY+b_5XZ+b_6YZ+b_7X^2+b_8Y^2+b_9Z^2} \\ y = \frac{c_0+c_1X+c_2Y+c_3Z+c_4XY+c_5XZ+c_6YZ+c_7X^2+c_8Y^2+c_9Z^2}{d_0+d_1X+d_2Y+ad_3Z+d_4XY+d_5XZ+d_6YZ+d_7X^2+d_8Y^2+d_9Z^2} \end{cases} \quad (3)$$

where (x, y) is the position of a ground control point in the image space; (X, Y, Z) is the position of the same ground point in the ground coordinate system; a_i, b_i, c_i, and d_i are the parameters defining the RFM. Modern satellites use pushbroom scanners to acquire high-resolution images; thus such satellite images have much more complicated imaging geometry than images acquired using frame cameras. The denominators in the x and y representations of RFMs are usually not the same, which is different from the DLT model. It can be seen from equation 3 and 2 that the DLT model is a special case of RFM.

When RFM and DLT are applied to approximate the rigorous imaging geometry of frame-camera images, a large number of parameters need to be solved. Unlike a rigorous frame camera model that contains six parameters to be calculated from control points, a linear rational function model has 16 parameters and a quadric/quadric rational function model has 40 parameters. The DLT also has 12 parameters. This imposes two technical challenges. First, the computation of RFM/DLT using ground control points can be unstable (Hartley and Saxena, 1997; Hu, Tao, and Croitoru, 2004), which is caused by the correlation among the parameters. These parameters are correlated because they are mainly affected by the six exterior orientation parameters. Distortions from lens, atmosphere, earth curvature, and errors in camera may help alleviate the computational instability, but they are not determining factors. Computational instability is a common mathematic problem that is usually addressed using regularization techniques (Hartley and Saxena, 1997; Hu and Tao, 2001; Hu, Tao, and Croitoru, 2004; Neumaier, 1998; Tao, Hu, and Jiang, 2004).

The second challenge is that a relatively large number of accurate control points are required to calculate these RFM parameters. Without knowing the proprietary rigorous camera model of a satellite sensor, the solution has to rely on a large number of field collected control points. Further, when control points are to be collected in the field, its number may not be comparable to the number of virtual control points generated from rigorous camera models and ephemeris data as done for commercial satellite images. The latter is usually in hundreds. For historical aerial photographs, ground control points are normally collected from the existing map products, such as USGS digital orthophoto quarter-quadrangle (DOQQ). However, DOQQs were taken about 70 years later than historical aerial photographs. Due to the constant changes of ground features, measuring control points on historical images is difficult and subjects to low accuracy. This will result in declined accuracy of derived RFM/DLT models.

EXPERIMENTS

Data

The study area is located in Riverside County, California. The raw historical aerial photographs used were vertical photographs acquired in 1938. The frame format for the data set is 7.25 inches by 9 inches and there are 60% overlaps along a flight line and 30% overlaps between two adjacent flight lines. The general flight direction was east-west resulting in photo azimuths of about 90 or 270 degrees. Given the flight height of about 13750 feet above the ground and a focal length of 8.25 inches, the scales of the photographs were about 1:20000. The hardcopy frames were scanned with a dpi of 1200 producing a ground resolution of about 1.4 feet or 0.4 meter. Figure 1 shows the study area and an example of original raw aerial photograph overlaid with measured control points.

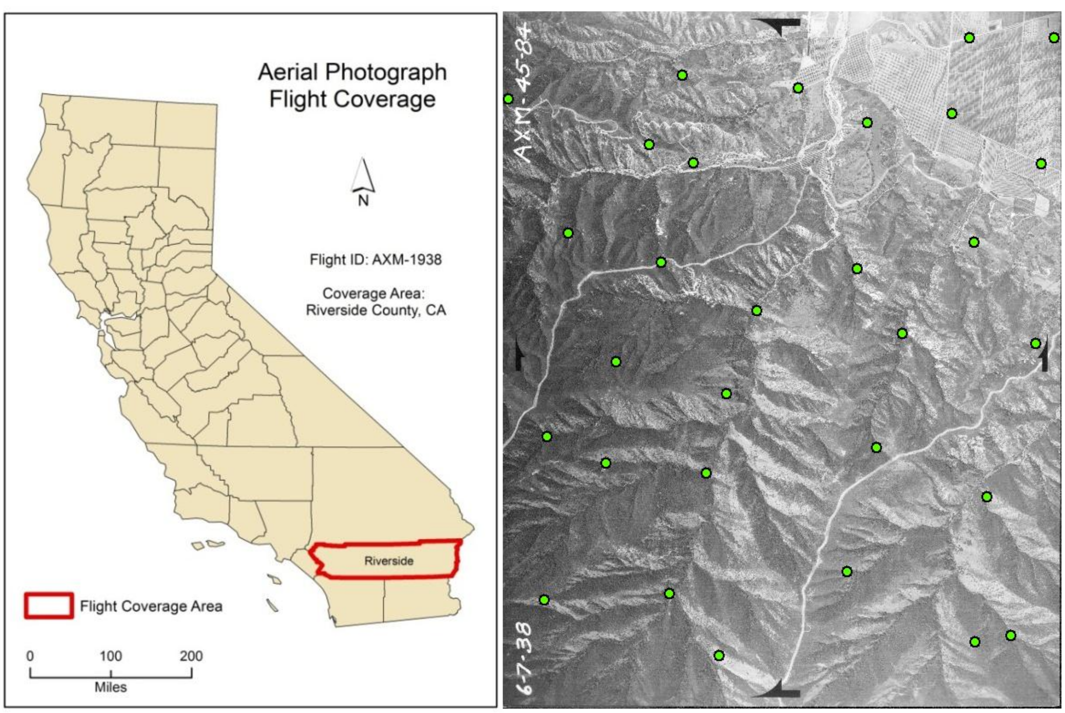

Figure 1. The study area (left) and an example of original aerial photograph (right) with measured control points (green dots).

Control points were collected from USGS DOQQ and DEM, which were acquired from the Cal Atlas Clearinghouse online. The DEMs are from the 2010 collection, and were downloaded in GRID format with a resolution of 1/3 arc second. The reference system of the DEM data was in the GCS North American 1983. The DOQQs have a spatial resolution of one meter. Both the 1993 black-and-white photos and the 1998 color infrared orthophotos from USGS were used for control point measurement. The coordinates system of the DOQQ data was the NAD 1983 UTM Zone 11 North. The horizontal position (X, Y) of control points were measured from DOQQs and the Z was read from the DEM data for position (X, Y). The DEM data were re-projected to the coordinate system of the DOQQ data for measuring the Z coordinate.

The DLT is a nonlinear model, which requires the estimation of variable values to begin solving the variables. In their study on RFM, Hartley and Saxena investigated using cubic rational function models in representing imaging geometry (Hartley and Saxena, 1997). They re-arranged the RFMs to a form of polynomial functions. The estimated starting values in solving their RFM were calculated as the normalized singular vector corresponding to the smallest singular value of the observation matrix constructed from the re-arranged polynomial functions. Generally, matrix singular value decomposition is computationally expensive. Tao and Hu proposed a method of solving RFM from control points. They started solving RFMs by setting denominators in their RFM to be a constant number of 1. To test their method, they used 100 well distributed control points selected from 7499 available ones (Tao and Hu, 2004).

The DLT model has a direct relation with the rigorous camera model; and its parameters are the combinations of the six exterior orientation parameters. In this study, the initial values of the DLT parameters were estimated from the estimated six exterior orientation parameters. The position of the camera (X_0, Y_0) was estimated as the mean center of the control points. The value of Z_0 was estimated to be the addition of the average elevation of ground control points and the flying height of the aircraft. A value of 0 was used for the rotation angles around x-axis and y-axis given the fact that these photographs were vertical photographs. The rotation angle around the z-axis was estimated from the flight direction.

Results

Within the study area, a block of six adjacent aerial photographs covering the City of Corona were used to evaluate the DLT model. The coverage is featured with forested mountain areas, agriculture field, and urban developments. The area has a large topographic variation; and relief displacements are large and need to be corrected for accurately transforming these photographs to a ground coordinate system. In addition, urban development has significantly changed the ground features in this area, which imposes difficulty in collecting control points.

30 control points were measured on each of the six photographs to calculate their respective DLT models. Additionally, 15 check points were measured on each photograph for assessing the accuracy of the derived DLT models. Table 1 listed the root mean square errors (RMSE) of the check points for the six photographs. For comparison purpose, 2nd order polynomials were used on the same set of control points to perform 2D transformations in geo-referencing the six photographs. The RMSEs of the same set of check points on the geo-referenced photographs are at the level of 60 to 70 meters.

Table 1. Check point RMSE from DLT

Photograph ID	RMSE from DLT (meter)
045_061	5.39
045_063	5.93
045_064	5.43
035_071	7.29
035_073	7.81
035_075	6.67

The National Map Accuracy Standards state that 90 percent of all points tested must be within one-fiftieth of an inch on the map. At a scale of 1:20,000, one-fiftieth of an inch on the map would be 33.33 feet or 10.16 meters on the ground. Of these six photographs, four photographs had one check point with an error larger than 10.16 meters out of the total of 15 check points. The other two photographs have all 15 check points with error smaller than 10.16 meters. It shows that the accuracy of the orthorectified historical photographs meet the mapping standard based on the evaluation of 15 check points each.

Figure 2 illustrates the comparison between an orthorectified photograph and USGS DOQQ as well as the comparison between two adjacent orthorectified historical photographs. The left image shows an orthorectified photograph on top of its corresponding DOQQ. The labeled regions (a_1, a_2, a_3, and a_4) show the matched ground features. Also can be seen from the overlaid image is the change of land cover over a period of about 70 years, such as citrus orchards appearing in the newer DOQQ data. The image on the right shows the two overlaid orthorectified historical photographs. The labeled areas (b_1, b_2, b_3, and b_4) also show the matched ground features. It should be noted that the tone of the top photograph was reversed to demonstrate the difference between these two photographs as it is illustrated that bright features from the bottom photograph are linked to dark ones from the photograph on top. The visual inspection shows that the orthorectified historical photographs have great geometric quality and consistent accuracy across different photographs.

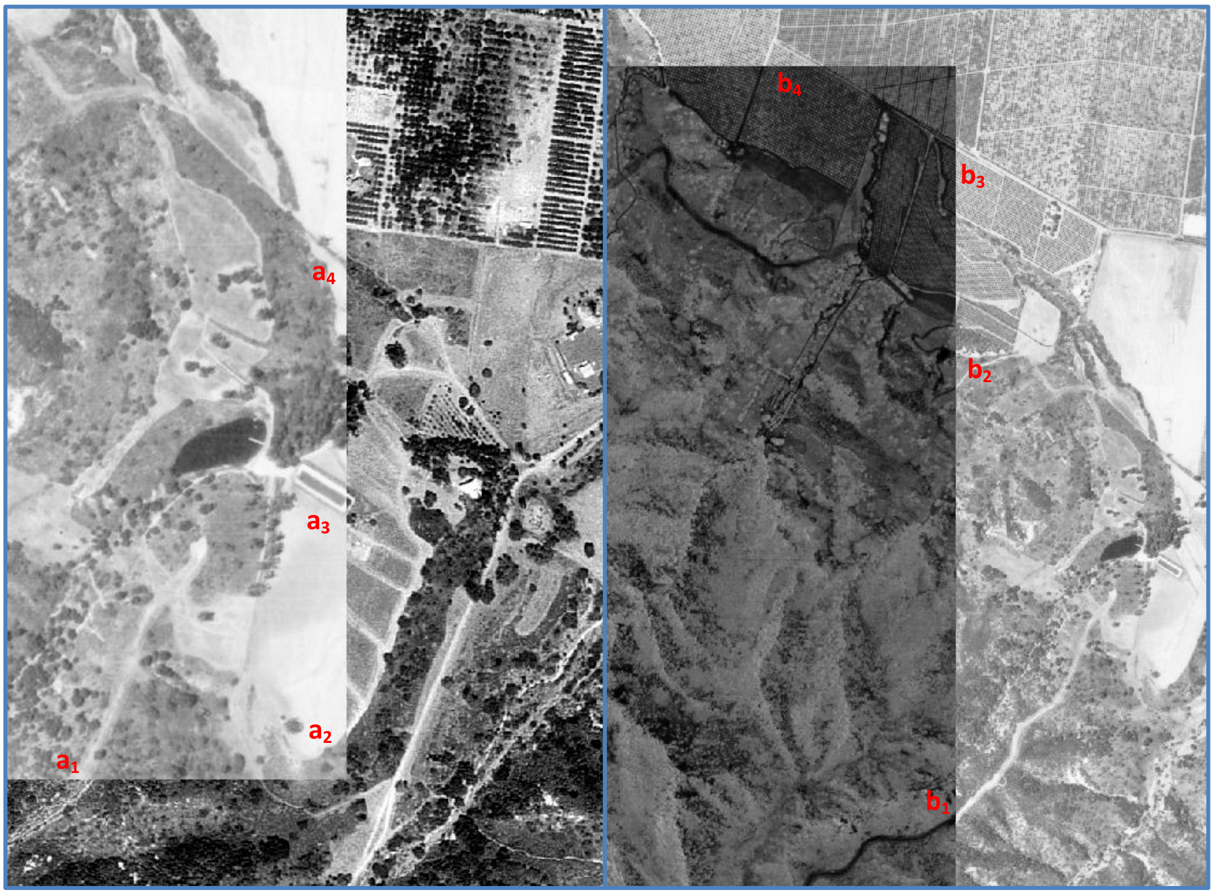

Figure 2. Comparison of orthorectified photograph and USGS DOQQ (left) and comparison between two adjacent orthorectified photographs.

Another accuracy evaluation was performed using a digitized road. A road was digitized independently from the orthorectified aerial photographs, the geo-referenced photographs resulted from the 2D polynomial transformations, and the USGS DOQQ. These three digitized lines of the same road are displayed in Figure 3 to illustrate the positional discrepancies. Using the DOQQ as the reference, the road line from orthorectifed photographs is obviously more accurate than the one digitized from the geo-referenced photographs. It demonstrates the accuracy superiority of the orthorectified photographs over the geo-referenced photographs.

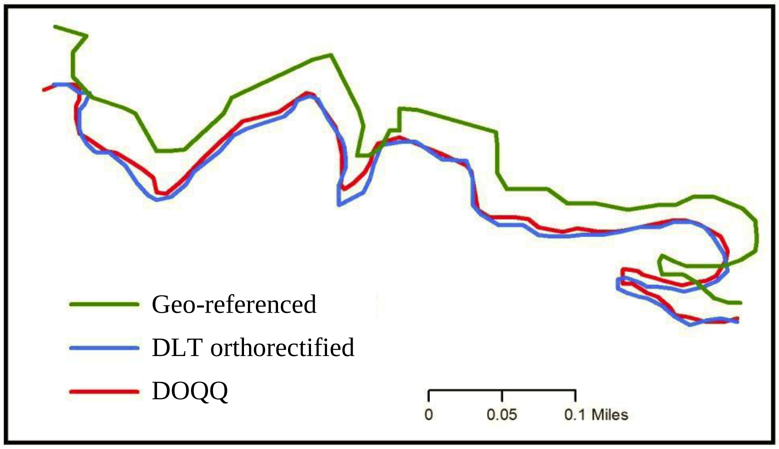

Figure 3. A comparison of digitized roads from different photo sources.

CONCLUSIONS

This study evaluated the DLT method in orthorectifying historical aerial photographs. The resulted ortho photos in this study met the National Map Accuracy Standards at a map scale of 1:20000. The control points used to solve DLT models were collected from existing USGS map products, namely DOQQs and DEMs. It is expected that the collected control points would have lower accuracy than control points collected in field using methods such as traditional surveying and GPS. However, massive field data collection would be very expensive and thus unaffordable for projects working with a large number of photographs. As demonstrated in this study, a relatively large number of control points can be collected from existing map products to provide a great data redundancy in solving the DLT models. This data redundancy can compensate for the lower accuracy of the control points collected from existing map products. The generated orthophotos showed great geometric quality. This approach makes it practical in orthorectifying massive historical aerial photographs.

In the future, generic RFM could be evaluated in representing imaging geometry for historical frame camera photographs. In addition, coordinates used in solving DLT/RFM models could be normalized to improve the computational stability in calculating model parameters. The current study only examined individual DLT models. In the future, bundle adjustment of multiple DLT models and generic RFM models could be investigated to identify more efficient and accurate methods in orthorectifying historical photographs.

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