INITIAL TESTING OF A METHOD TO GEOGRAPHICALLY REGISTER AIRBORNE SCANNER IMAGERY THROUGH PARAMETRIC MODELING WITH IMAGE-TO-IMAGE MATCHING

Paul A. Pope, Frank L. Scarpace
Environmental Remote Sensing Center
University of Wisconsin
Madison, Wisconsin, U.S.A.
papope@students.wisc.edu
scarpace@macc.wisc.edu

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ABSTRACT
This paper presents the results from initial testing of a new method for georeferencing airborne multispectral scanner imagery. The method is called "parametric modeling with image-to-image matching" (PMIIM). The method takes an error prone estimate of the aerial platform's trajectory as input, and outputs a corrected trajectory. The corrected trajectory can then be used to georeference the airborne imagery through another ray-tracing code. The method was tested by synthesizing an airborne scanner image through the use of mathematically generated trajectory functions. A discussion of how spatial autocorrelation affects the method is discussed. Pre-processing steps and justification for the choice of input parameters is explained. The method was able to decrease the planimetric error from 34 meters to 21 meters. Avoiding the coupling between some of the exterior orientation parameters enabled the run time to be reduced dramatically, but incurred a decrease in planimetric accuracy.

1. BACKGROUND

This research concerns itself with addressing the problem of georeferencing multispectral imagery acquired primarily by a whiskbroom scanner with a large field-of-view carried aboard an airborne platform flying at a relatively low altitude. A previous paper has provided more details concerning the various methods described in the literature for addressing this problem, as well as the justification, objectives, design, and implementation of a new solution (Pope and Scarpace, 2000). Only a brief outline of this new philosophy is provided herein. This paper describes proof-of-concept testing of this new method through numerical modeling and accuracy assessment of the results.

Compared to frame-based (e.g. aerial photography) and line-based (pushbroom) imaging systems, the problem of georeferencing imagery acquired by a point-based (whiskbroom) scanner is the most difficult, due to the highly dynamic nature of the viewing geometry. Large planimetric distortions are incurred through the inter-play between the scanner dynamics, platform instability, and the terrain. Research to address this problem has given rise to two largely disparate approaches; parametric and non-parametric.

The first is the pursuit of parametric (geometric, deterministic) methods. Examples of these methods are photogrammetric (McGlone and Mikhail, 1985) and "direct georeferencing" (Schwartz, et al., 1993; Meyer, 1994). These methods may also be categorized as "hardware" solutions, since they rely on highly accurate and temporally fine measurements of the platform's trajectory (e.g. INS/GPS), or at least a trajectory "seed" which is iteratively improved through a least squares bundle adjustment. Also, parametric methods often require a digital elevation model (DEM) to obtain the highest planimetric accuracy.

The second is the pursuit of non-parametric (image-warping, empirical) methods. Examples of these methods are the piece-wise application of bi-variate mapping functions (Ji and Jensen, 2000), iterative Delauney triangulation (Chen and Rau, 1993), and multi-quadratic rectification (McGwire, 1998). These methods may also be categorized as "software" solutions, since they do not rely on any hardware-based measurements of the platform's trajectory. However, they often depend on a reference image or a map to aid in defining ground control points (GCPs). The manual definition of GCPs is known to be labor intensive. Automated image-to-image matching can aid in defining control.

A new solution has been developed which takes a "hybrid" approach and lies between these two extremes. It is fundamentally parametric (ray-tracing) in nature, but is autonomous in defining control and takes as inputs the *a priori* information typically used by both non-parametric and parametric methods. The proposed solution is to use a reference image (e.g. a digital orthophoto or satellite image) and a DEM to define a "virtual landscape" over which a mathematical model of the scanner and its airborne platform are "flown". A trajectory "seed" provides an initial estimate of the position and orientation of the platform as a function of time. The trajectory seed can be derived from direct measurements of the platform's position and orientation with time, or this information can be a calculated estimate of the actual flight path through the use of a few GCPs. The two georeferenced rasters and the input trajectory constitute *a priori* information required by the method.

An image-to-image comparison is performed at periodic intervals along the flight path as follows. Scan lines are synthesized via ray-tracing for multiple combinations of perturbations in position and orientation about the trajectory seed. The synthetic scan lines are compared with the actual scan line to determine a set of best matches. The set of perturbations associated with the best matches are used to correct the trajectory seed. The corrected trajectory is then used in a separate process to georeference the airborne scanner imagery through parametric modeling. Output from the method is an irregularly distributed set of planimetric positions for all pixels, from which a geographically registered image can be formed. This new method is called "parametric modeling with image-to-image matching" (PMIIM).

2. OBJECTIVE

The objective of this research is to describe an initial proof-of-concept of the PMIIM method's ability to georeference airborne scanner imagery. The approach taken is to synthesize an airborne scanner image through mathematical modeling of a hypothetical aerial survey. A digital orthophoto is used as the reference image and serves as a model for the landcover (i.e. provides spectral information). A DEM serves as a model for the terrain (i.e. provides elevation information). The platform instabilities are known exactly since the trajectory motions are predefined functions of the exterior orientation parameters. Therefore, the planimetric position of every pixel in the image is also known exactly. Noise is added to the trajectory to reduce the accuracy of these data, as if the trajectory were being measured by a hardware system flying onboard the aerial platform. The noisy trajectory is used as the trajectory "seed" to the PMIIM method. The corrected trajectory output by the PMIIM method and the synthetic airborne image are then used in a ray-tracing method to georeference the airborne image. The corrected pixel locations are then compared to their known locations to provide an assessment of the planimetric accuracy of the PMIIM method. Modifications to the trajectory perturbations are used to investigate the sensitivity of the planimetric accuracy and compute times to these changes.

3. EXPERIMENTS

3.1 Computer Resources

The numerical experiments performed for this research were conducted on two types of machines. The first has a 600 MHz Pentium III CPU with 1,024 Mbyte of RAM running Linux V6.1. The second has a 200 MHz Pentium Pro CPU with 512 Mbyte of RAM running Linux V5.1. Data were read and written to a network harddrive over a 100 Mbit line.

Three computer codes were used in this research. These codes are written in the Interactive Data Language (IDL) V5.2 (Research Systems, Inc., Boulder, Colorado). The IDL codes, or "procedures" (*.pro files) are called "create_airborne_image.pro", "correlate_airborne_image.pro", and "correct_airborne_image.pro". The "create" code synthesizes an airborne scanner image from a reference image, a DEM, a scanner model, a trajectory, and the number of scan lines requested. Outputs are an airborne scanner image and a point file containing the planimetric location of each pixel. The "correlate" code implements the PMIIM method. Inputs are a reference image, a DEM, a scanner model, a trajectory seed, trajectory perturbations, a scan line skip value, and a minimum correlation value. The output is a corrected trajectory. The "correct" code georeferences an airborne image. Inputs are an airborne image, a DEM, a scanner model, and a trajectory. Output is a point file containing the planimetric location of each pixel.

3.2 Study Site Description

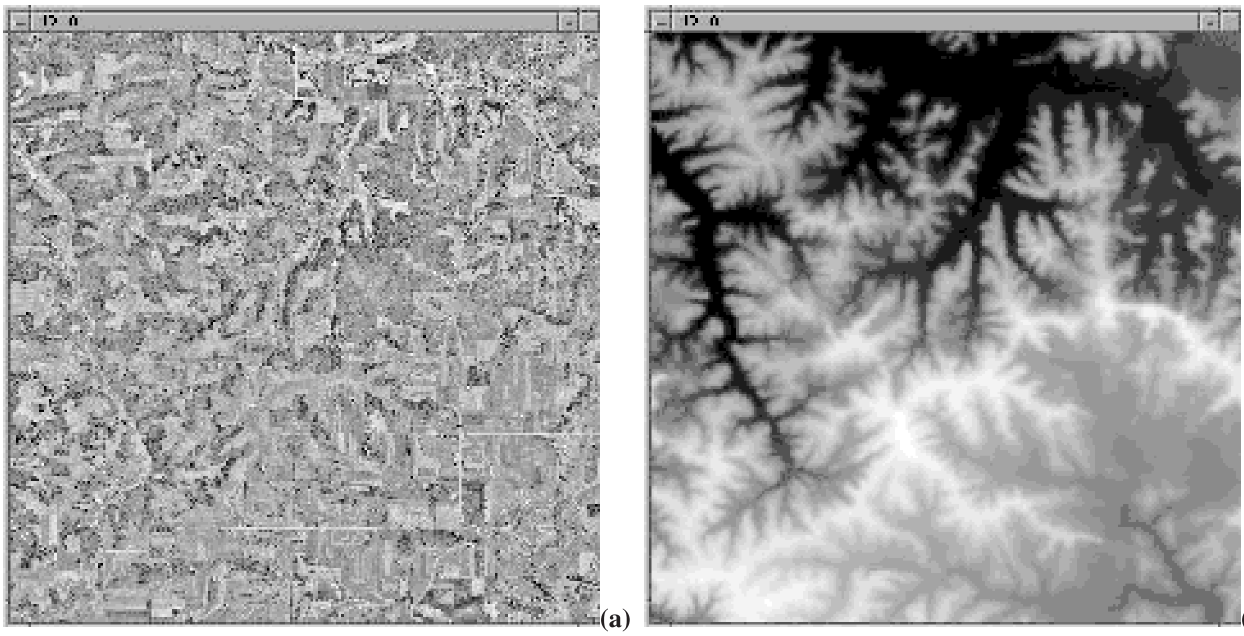
The study site for this work is an area located south of the town of Cross Plains, Wisconsin. This region is comprised of highly varying terrain due to a complex arrangement of fine-textured, dendritic erosional patterns. It is known as the "driftless area" because the southern extent of glaciation during the last ice age terminated just east of this region. The landcover is a variegated tapestry of tree covered hills and agrarian plots within the flatter valley areas.

3.3 Pre-processing

3.3.1 Reference Image and DEM Creation: The reference image and DEM required by this method were created from data provided to the authors by two different agencies. The reference image was created from panchromatic, digital orthophotos of the study area. The DEM was derived from another DEM of the study area. The digital orthophotos have a smaller ground sample distance (GSD) than the source DEM. Therefore, a nominal GSD of 10 meters was chosen for this study. This value lies between the GSD's of these two raster data sets, and is equal to the nominal GSD of other airborne scanner imagery of interest to the authors.

The digital orthophotos were obtained from the Wisconsin Department of Natural Resources. The format of these data is TIFF with ancillary TFW (georeference information) files. These images are tiled by township, have a GSD of 1 meter, are georeferenced to the Wisconsin Transverse Mercator (83/91) coordinate system (SCO, 1995), and have 1 byte per pixel quantization. A 1:24,000 scale digital elevation model (DEM) for this area was obtained from the United States Geological Survey (USGS). The 7.5" quadrant name of this DEM is "Cross Plains, WI". The format of these data is the Spatial Data Transfer Standard (SDTS). The DEM has a GSD of 30 meters, is georeferenced to UTM Zone 16 (NAD 1927), and has 2 bytes per pixel quantization. Elevations are in units of feet, and are referenced to the NGVD of 1929. The overlap between the digital orthophotos and the DEM were used to define study area extents expressed in WTM (83/91) coordinates. The upper left and lower right corners of the study area were set to (N 294,440 [m], E 540,400 [m]) and (N 284,400 [m], E 550,400 [m]), respectively.

These data were pre-processed by using a hybrid GIS called TNT Mips V6.2 (MicroImages, Inc., Lincoln, Nebraska). The digital orthophotos and DEM were imported to the GIS. The digital orthophotos were mosaicked, resampled to a GSD of 10 meters using cubic convolution, and subset to match the study area extents. The output raster was used as the "reference image". The USGS DEM was resampled to a GSD of 10 meters using cubic convolution, elevations were rescaled from feet to meters, and the raster was subset to match the study area extents. The output raster was used as the DEM. The minimum and maximum elevation of this DEM are 253 meters and 373 meters above MSL, respectively. Each raster contains 10,000 rows by 10,000 columns of pixels. These raster data were then exported to simple array files (no header; rows stored sequentially), accompanied by ancillary georeference and size information files (Figure 1).



(a) (b)

Figure 1. The reference image (a) and the DEM (b) of Cross Plains, Wisconsin.

3.3.2 Spatial Autocorrelation Analysis: Spatial autocorrelation will reduce the ability of the PMIIM method to synthesize unique signals to be used in the image-to-image matching process. This will in turn reduce the ability of the method to resolve the necessary trajectory corrections. However, it can aid significantly in reducing the computational workload. A spatial autocorrelation analysis was conducted on the reference image by using a minimum correlation value of 0.7. The average lag value was 1.3 pixels with a standard deviation of 0.47 pixels. This means that on average a unique scan line (i.e. correlation value less than 0.7) is not encountered until 1.3 scan lines away from any particular scan line. This effect is symmetric about a scan line. Therefore, unique scan lines can be synthesized only if the average distance between their ground traces are 2*1.3 + 1 = 3.6 GSDs away from each other. This value is called the "spatial autocorrelation factor". The spatial autocorrelation factor will affect the scanner model and the trajectory perturbations used in the PMIIM method.

3.3.3 Scanner Model Design: The airborne scanner model mimics the characteristics of NASA's Airborne Terrestial Applications Sensor (ATLAS). This sensor is a whiskbroom, multispectral scanner and is flown aboard a Learjet (NASA, 2000). However, unlike the ATLAS sensor, only one band (channel) was modeled. Since the reference image is derived from panchromatic digital orthophotos, this band is essentially a panchromatic band. Relevant characteristics of ATLAS are provided in Table 1.

Name	Value	Units
Field-of-View (FOV)	72	Degrees
Instantaneous Field-of-View (IFOV)	0.0020	Radians
Samples per Scanline	640	Pixels
Scan Speed	6 - 50	Revolutions per Second (Scans per Second)
Scan Direction	-1	counter-/clockwise (+1/-1) about flight direction axis

Table 1. Characteristics of the ATLAS scanner.

Two scanner models are needed for this work. The first is called the "full resolution" scanner model, and is defined by the values in Table 1. The second is called the "reduced resolution" scanner model. This model is defined by a reduced number of samples per scanline, calculated by dividing the samples per scanline of the full resolution scanner model by the spatial autocorrelation factor. Therefore, the reduced resolution scanner model has 178 samples per scanline.

3.3.4 Aerial Survey Design: A hypothetical airborne survey was defined to acquire one flight line over the study area in a north to south direction down the center of the study area extents. The nominal GSD was set at 10 meters per pixel to match that of the reference image and DEM. Since the IFOV is 2.0 milliradians, the nominal flying height was set to 5,000 meters AGL. The average elevation of the DEM is 306 meters, so the nominal flying height was set to 5,306 meters above MSL. The flight line starts at the point (N 293,175 [m], E 545,400 [m], 5,306 [m] above MSL) and ends at the point (N 285,675 [m], E 545,400 [m], 5,306 [m] above MSL). The ground speed of the platform was set to 150 meters per second, which is close to the NASA Learjet's actual ground speed of 300 knots for an ATLAS aerial survey at this flying height (LMSO, 1997). The nominal scan line overlap was set to 0 percent, such that scan lines would abut each other. Therefore, the scan speed was set to 15 scans per second. The number of scan lines to be acquired was set to 750. Therefore, the flight line length was 7,500 meters and the acquisition time was 50 seconds.

3.3.5 Trajectory Generation: Two trajectories for the hypothetical airborne scanner mission were created. The first represents the "actual" trajectory, and is considered to be error free. The second trajectory represents the error prone measurement of the "actual" trajectory. This second trajectory will be referred to as the "measured" trajectory. Each trajectory consists of a file containing the x, y, z, roll, pitch, and yaw of the scanner at discrete points in time from 0 seconds to 50 seconds at 1/15 second intervals (i.e. one record per scan line). Parameters governing the trajectory generation were estimated from examination of the exterior orientation parameter variations observed during actual aerial surveys and forming a "worse case scenario" (Ethridge and Mikhail, 1977; Zhang, Albertz, and Li, 1994; Breuer and Albertz, 1996; Schlapfer, 1998). The "actual" trajectory was generated from sine functions. The frequency was set to 1 cycle every 10 seconds such that 5 cycles were completed in the 50 seconds it took to complete the flight line. Phase shifts were added such that the exterior orientation parameters were out-of-phase from each other by 30 degrees. The amplitude of the position parameters was set to 50 meters. The amplitude of the orientation parameters was set to 2 degrees. The "measured" trajectory was generated by adding correlated noise to the "actual" trajectory through the use of first-order autoregressive (AR1) functions (Wei, 1994). The mean of the AR1 functions was set to 0. The standard deviations of the AR1 functions were set equal to the change in exterior orientation parameter values which would give rise to a planimetric error of 3 GSDs (30 meters) for level flight at a scan angle of 36 degrees when applied independently (Roy et al., 1997). These values are provided in Table 2.

Exterior Orientation Parameter Error	Value	Units
σX	30.000	Meters
σY	30.000	Meters
σZ	41.292	Meters
σRoll	0.2248	Degrees
σPitch	0.3438	Degrees
σYaw	0.4731	Degrees

Table 2. Change in exterior orientation parameter values giving rise to a planimetric error of 3 GSDs.

3.3.6 Airborne Scanner Image Creation: An airborne scanner image was created by using the "create_airborne_image.pro" code with the reference image, DEM, full resolution scanner model, and actual trajectory as inputs. The number of scan lines requested was 750. This took approximately 7 minutes on the 600 MHz machine. The outputs were an airborne scanner image and a point file containing the planimetric location of each pixel. This point file is called the "actual" location point file and was set aside for use in planimetric accuracy assessment. The airborne scanner image was resampled via cubic convolution to match the number of pixels in the reduced resolution scanner model. This image is called the "reduced resolution" airborne scanner image.

3.3.7 Scan line skip and minimum correlation: The scan line skip value was set such that the sinusoidal variations in the exterior orientation parameters could be adequately captured by the PMIIM method. Since the phase shift was set to 30 degrees and the frequency was set to 1 cycle every 10 seconds, at least one sample of the trajectory must be taken every 1.2 seconds to resolve the peaks of these sinusoidal functions. Since the scan speed was set to 15 scans per second, the scan line skip value was set to 18 scan lines. With the scan line skip value set to 18, and 750 scan lines in the synthesized airborne image, then 42 records will be contained in the corrected trajectory file output by the PMIIM method. The minimum correlation value was set to 0.7, since this represents a nominal value for image-to-image cross correlation work.

3.3.8 Trajectory Perturbations Formation: The range and increment of perturbations for each exterior orientation parameter must be set such that the PMIIM method can resolve the corrections which must be applied to the measured trajectory. The noise within the measured trajectory is assumed to be known, since this would be governed by the accuracy of the hardware used to record the trajectory. Therefore, the perturbation ranges for each exterior orientation parameter were set to twice the values in Table 2 such that a 95% confidence interval exists for capturing the noise in the trajectory. The perturbation increments were set such that the change in exterior orientation would effect a 3.6 GSD change in the line-of-sight intersection point for level flight at a scan angle of 36 degrees when applied independently. The perturbation increment values maybe calculated by dividing the values in Table 2 by 3, and then multiplying by 3.6. The exterior orientation perturbation ranges and increments are provided in Table 3.

Exterior Orientation Perturbation	Minimum	Maximum	Increment	Units
ΔX	-60.000	60.000	36.000	Meters
ΔY	-60.000	60.000	36.000	Meters
ΔZ	-82.584	82.584	49.550	Meters
ΔRoll	-0.4496	0.4496	0.2697	Degrees
ΔPitch	-0.6876	0.6876	0.4126	Degrees
ΔYaw	-0.9462	0.9462	0.5677	Degrees

Table 3. Exterior orientation parameter perturbation values.

The number of perturbation increments per exterior orientation parameter is 5. Therefore, the PMIIM method must conduct 5^6 = 15,625 perturbations of the input trajectory at each of the 42 scan line skip locations along the flight line.

3.4 Results

3.4.1 Without trajectory correction: The "correct_airborne_image.pro" code was used to correct the pixel locations of the full resolution airborne scanner image by using the full resolution scanner model, DEM, and measured trajectory as inputs. This took approximately 23 minutes to run on the 200 MHz machine. The output point file was then accuracy assessed by comparing (differencing) it with the actual location point file. The RMSE was 33.669 meters. The planimetric error statistics are provided in Table 4.

Component	Minimum	Maximum	Median	Mean	Std. Dev.	Skewness	Kurtosis
ΔX	-166.107	200.486	2.018	2.030	27.520	0.1114	1.084
ΔY	-99.621	100.925	-2.416	2.307	27.082	0.06902	0.1103

Table 4. Planimetric error statistics, in units of meters, for the case of no trajectory correction.

3.4.2 With trajectory correction: The "correlate_airborne_image.pro" code was used to correct the measured trajectory by using the reference image, DEM, reduced resolution airborne image, reduced resolution scanner model, scan line skip equal to 18, minimum cross correlation equal to 0.7, and the exterior orientation perturbations of Table 3 as inputs. This took approximately 5.7 hours to run on the 600 MHz machine. This implies a computation rate of 1,919 trajectory perturbations per minute. The "correct_airborne_image.pro" code was used to correct the pixel locations of the full resolution airborne scanner image by using the full resolution scanner model, DEM, and corrected trajectory as inputs. This took approximately 23 minutes to run on the 200 MHz machine. The output point file was then accuracy assessed by comparing (differencing) it with the actual location point file. The RMSE was 20.961 meters. The planimetric error statistics are provided in Table 5. A plot of the actual and corrected trajectories is provided in Figure 2.

Component	Minimum	Maximum	Median	Mean	Std. Dev.	Skewness	Kurtosis
ΔX	-116.457	53.987	-3.786	-3.064	19.150	-0.1975	0.1365
ΔY	-90.654	96.765	2.654	2.4647	13.001	-0.2758	0.7543

Table 5. Planimetric error statistics, in units of meters, from PMIIM correction of a noisy input trajectory.

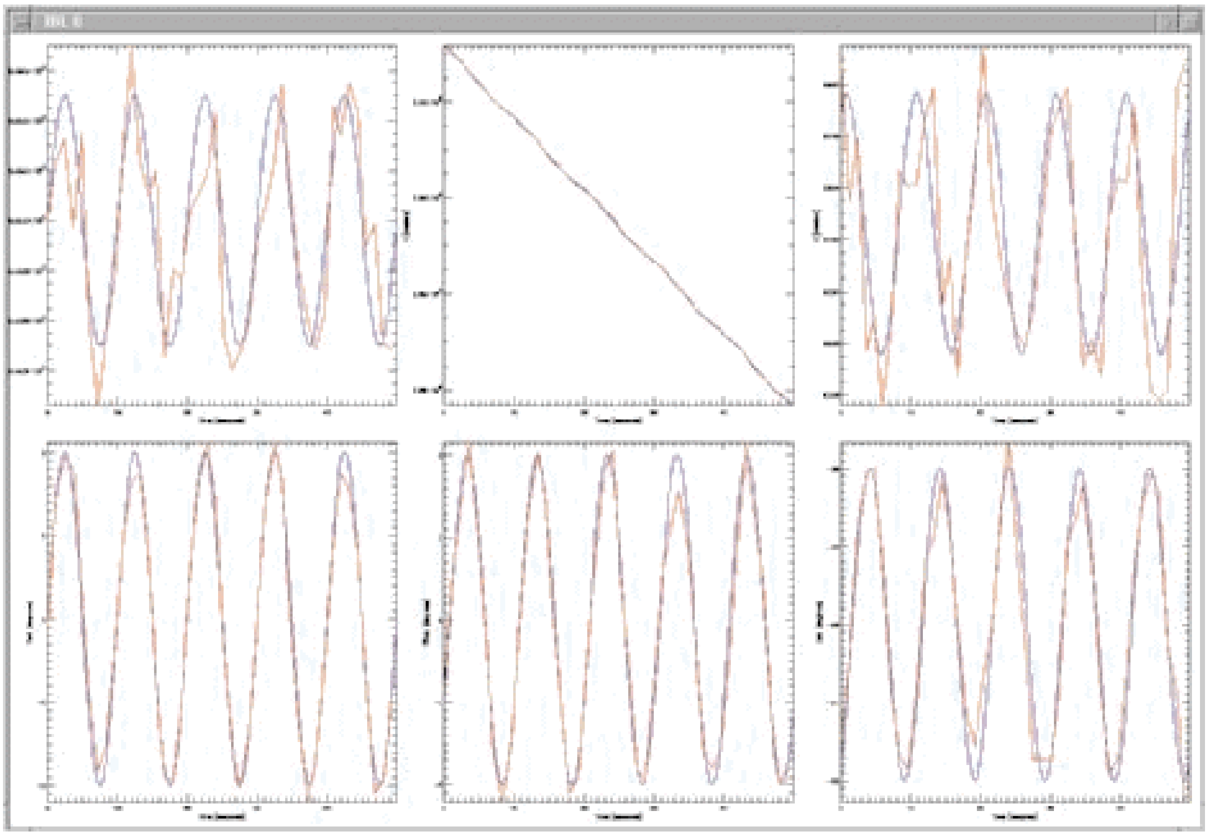


Figure 2. A plot of the actual (blue) and corrected (red) trajectories. The top row of plots (from left to right) are x, y, and z versus time. The bottom row of plots (from left to right) are roll, pitch, and yaw versus time.

3.4.3 Neglecting roll and pitch corrections: The six exterior orientation parameters are not all independent. Planimetric errors induced through roll action can be mimicked through x and/or y motions. Planimetric errors due to pitch can be also be achieved through x and/or y and z motions. Therefore, perturbations in roll and pitch were set to zero and the PMIIM method was used to correct the trajectorys of the remaining four exterior orientation parameters. Note that the number of perturbations per scan line skip value was reduced from 15,625 to 5^4 = 625. The "correlate_airborne_image.pro" code was used to correct the measured trajectory by using the reference image, DEM, reduced resolution airborne image, reduced resolution scanner model, scan line skip equal to 18, minimum cross correlation equal to 0.7, and the exterior orientation perturbations of Table 3 (modified as explained previously) as inputs. This took approximately 30 minutes to run on the 200 MHz machine. This implies a computation rate of 875 trajectory perturbations per minute. The "correct_airborne_image.pro" code was used to correct the pixel locations of the full resolution airborne scanner image by using the full resolution scanner model, DEM, and corrected trajectory as inputs. This took approximately 23 minutes to run on the 200 MHz machine. The output point file was then accuracy assessed by comparing (differencing) it with the actual location point file. The RMSE was 32.442 meters. The planimetric error statistics are provided in Table 6.

Component	Minimum	Maximum	Median	Mean	Std. Dev.	Skewness	Kurtosis
ΔX	-126.262	78.222	-1.576	-2.693	23.130	-0.2157	0.1151
ΔY	-90.262	97.403	-3.109	-6.524	28.567	-0.1272	-0.02276

Table 6. Planimetric error statistics, in units of meters, for the case of neglecting roll and pitch corrections.

4. DISCUSSION

The numerical modeling test results indicate that the PMIIM method has the ability to correct an error prone trajectory so that it can be used to georeference airborne scanner imagery. Using the error prone trajectory without correction (the "do nothing scenario") yields a planimetric RMSE of approximately 34 meters. Note that this is consistent with the 3 GSDs (30 meters) of noise introduced to the actual trajectory to form the measured trajectory. Using the PMIIM method to correct the trajectory, the planimetric RMSE was reduced to approximately 21 meters. Taking advantage of the coupling between the roll and pitch with the other exterior orientation parameters reduced the compute time from approximately 6 hours on a 600 MHz machine to only 30 minutes on a 200 MHz machine. However, the RMSE was not reduced significantly (32 meters), though the minimum and maximum errors did decrease. This is most likely due to the fact that corrections to the pitch cannot be ignored in areas of significant terrain relief.

The spatial location of the largest planimetric errors occurs near the edges of the scan in areas of high relief (i.e. occultation problems), and where there is large under and over-sampling. Under and over-sampling are excessive in this numerical simulation, as is the level of noise compared to the amplitudes of the position exterior orientation parameters. Imagery from an actual flight usually contains much less of these effects. Also, most scanning systems implement roll correction, which would most likely eliminate the need to correct the trajectory for that exterior orientation parameter. Another adverse effect maybe that the spatial autocorrelation factor only represents an average autocorrelation lag length. There are parts of the image for which the lag is zero (i.e. every scan line is not significantly correlated). These facts may explain why there are sporadic mismatches between the corrected trajectory and the actual trajectory (Figure 2). This in turn led to a reduction in planimetric RMSE which was only equal to about 1 GSD. Finally, we expected that the planimetric error in the cross-track direction is usually less than that in the along-track direction since there is an approximation to perspective viewing geometry in the cross-track direction, as opposed to the parallel viewing geometry in the along-track direction. However, it is interesting to note that in this study the planimetric error in X (Easting) is larger than the planimetric error in Y (Northing), since the cross-track and along-track scanning directions are nominally associated with the X and Y directions, respectively.

This research also reveals one of the major impediments to using a parametric method. That is, the labor involved in creating the inputs to such a method. This is apparent from the number of pre-processing steps described previously. Also, this method will probably find its greatest utility when applied to imagery from an airborne scanner survey in which no trajectory information has been recorded (e.g. historical imagery), or for which only relatively inaccurate and temporally coarse trajectory information is ava.ilable. This method most likely would not be able to enhance the trajectory accuracy available from highly accurate and temporally fine trajectory measurements, such as those available from INS/GPS systems.

5. FUTURE WORK

This research has investigated the initial testing of a new method to georeference airborne scanner imagery. Although a successful proof-of-concept of the PMIIM method has been accomplished, other numerical simulations would be interesting. Testing of the PMIIM method’s sensitivity to variations in spatial autocorrelation and trajectory noise could address some of the concerns expressed in discussing the results of these experiments. Some questions which might be addressed in the future are "Will reducing the spatial autocorrelation factor lead to better results?", "Can similar results be obtained through smoothing the input trajectory?", and "What is the result of using only every 18th record of the input trajectory and splining in between records?". However, more applications oriented results can be obtained by applying the PMIIM method to the problem of georeferencing actual airborne scanner imagery. The authors are presently engaged in applying the PMIIM method to real ATLAS imagery. Future work will describe the results of using the PMIIM method to georeference real imagery, provide a more in-depth accuracy assessment and statistical analysis, and a comparison with traditional techniques.

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