CONTROLLING AERIAL PHOTOGRAPHY FROM TOPGRAPHIC MAPPING USING A MULTI-SENSOR BUNDLE ADJUSTMENT

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ABSTRACT:

Establishing ground control points for a photogrammetric topographic mapping project represents a significant cost, especially in remote or inaccessible areas. The goal then is to find methods to reduce this cost by minimizing the amount of ground control needed to achieve the desired level of accuracy. We evaluated an approach utilizing a simultaneous bundle adjustment which oriented a block of aerial frame photographs to a geometrically corrected SPOT stereo model. This approach was found to satisfy U.S. National Map Accuracy requirements for horizontal and vertical positioning with only 5 ground control points when compared to a conventional aerial triangulation of the photographic block. But these results are contingent on a number of factors, including the distribution of the control throughout the SPOT stereo model, the distribution of the tie points between the SPOT stereo model and the aerial photographs, the convergence angle between the SPOT images, and the amount of overlap between the aerial photographs and the SPOT images.

1. INTRODUCTION

A significant cost in any photogrammetric topographic mapping project is establishing the surveyed field control to scale and level the stereo models into the ground coordinate system. This can account for as much as 50% of the entire project's cost. The actual cost of establishing the control depends on the remoteness, harshness, and accessibility of the area being mapped. In order to properly orient a model, there needs to be at least two horizontal and four or more vertical control points in the model. Thus an economical approach to any project is to examine ways to reduce the number of control points needed to achieve the desired level of accuracy. The conventional approach to reducing this cost is to establish a sparse network of surveyed ground control and then densify the control through an aerial triangulation of the photographic block. In a typical project, this requires a minimum of eight horizontal and four vertical control points placed around the perimeter of the block, with additional horizontal control placed every 5 models and vertical control placed every 3 to 4 models. This network of control can be reduced further by incorporating Global Positioning System (GPS) observations into the adjustment to provide accurate estimates for the exposure stations' positions and orientation within the ground coordinate system.

This paper explores the feasibility of minimizing the ground control by orienting the block of aerial photography to geometrically corrected SPOT imagery in a simultaneous multi-sensor bundle adjustment. In this adjustment different orbital models are used to describe the position and orientation of the imagery within the object space. The images are organized in the bundle by sensor type and orbital event. For frame photography each orbital event is the moment of exposure, and the orbital model is the collinearity equations. SPOT imagery is collected using a linear array of detectors which scan across the terrain in the direction of flight. In a SPOT panchromatic image there are 6000 scan lines, and each scan line's position and orientation differs based on the oribatal path of the platform. The orbital model for the SPOT imagery accounts for the time dependent nature of the sensor through a modified version of the collinearity equations. Each continuous path of SPOT images is treated as a unique orbital event with its own set of twelve parameters which describe the sensor position, velocity, attitude, and attitude bias at an initial epoch. By solving for these parameters, and knowing the time mark for each scan line, the state vector for each scan line in the SPOT image can be determined.

Besides demonstrating that this approach can achieve the compilation accuracy necessary to satisfy United States National Map Accuracy Standards, we also intended to examine the various factors which affect the accuracy of the results, such as control point accuracy, number of control points, distribution of control points, the convergence angle between the SPOT images, and the distribution of tie points between the SPOT images and the aerial photography.

2. METHOD

2.1 Data

The project was located in northern Alabama in an area with flat to hilly terrain. The block of aerial photography was centered over Priceville, Alabama. The imagery used in the project included a stereo pair of SPOT Level 1A panchromatic images acquired on two successive dates, 28 Janurary and 29 Janurary 1988. Both images were acquired with the HRV 1 sensor with look angles of Left 13.4 degrees and Right 19.9 degrees, respectively. The aerial photographs consisted of a block of 27 1:24,000 scale frame photographs arranged in 4 east/west flight lines. These were acquired using a Wild RC-10 camera on 28 February 1991. The diapositives were scanned on a PS1 scanner at a resolution of 22.5 microns, and were stored in a JPEG compressed dat format. Flight lines 10, 9, and 8 entirely overlapped the SPOT stereo model, while flight line 7 only partially overlapped the SPOT images.

The ground control was collected from two different sources. For the standard aerial triangulation ground control was established through a differential GPS survey using one roving receiver. In this survey the ground control points were set up at prominant photo-identifiable locations. The control was referenced to the State Plane 1983, Alabama West Zone coordinate system. For the triangulation, the standard deviation of this control was set at 0.25 feet. The ground control used in the multi-sensor triangulation was collected from 1:24,000 scale United States Geological Survey (USGS) 7.5 minute topographic maps. To collect this control, the map sheets were registered into a design file using an affine transformation of the neat line corners. The registration was accomplished with less than 0.3% RMS error. The ground control points were located at the center line of road intersections, and were digitized to a precision of 1 centimeter in the design file. The points were then transformed into latitude/longitude coordinates referenced to the World geodetic System 1984. Elevations for the control points were interpolated from the maps' contours. Standard deviations for the X,Y,Z coordinates of the control were set at 10 meters.

2.2 Data Analysis

Several runs of the multi-sensor triangulation were made to test the effect of different configurations of ground control and tie points on the accuracy of the solution. The bundle adjustment used was the Trifid Multi-Sensor Triangulation for SPOT and aerial photography.

The first run used 11 ground control points distributed throughout the SPOT model. None of the control was measured on the aerial photographs. Tie points between the SPOT images were collected at an interval of approximately every 1000 pixels, and both SPOT images were tied to each aerial photograph in the block with between 12 - 16 tie points per photograph. Diagnostic points were also collected. The second run used the same configuration as the first run, but was limited to only 5 ground control points. The control was distributed with one point at each corner of the SPOT stereo model, and one point in the center of the model. The third run changed the configuration by limiting the tie points between the SPOT images and aerial photographs to just the corners of the block. The fourth run changed the configuration by limiting the tie points between the SPOT images and the aerial photographs to just the upper left corner of the block. In the final run, the same configuration as the first run was used, but this time only included a single SPOT image in the simultaneous adjustment.

Two conventional aerial triangulations were run. Their results were used as baselines to which the multi-sensor triangulation results were compared. The first triangulation used 16 GPS derived control points, while the second used 19 control points collected from the USGS quadrangles which covered the project area. In both triangulations, 6 - 8 pass points were collected per model, along with 4 - 6 tie points per strip.

2.3 Data Collection

The multi-sensor project setup was accomplished using Intergraph's ImageStation Photogrammetric Manager (ISPM) software. The setup involved weighting the sensor parameters, extracting initial estimates for the SPOT ephemeris from the SPOT leader files, organizing the images into their proper orbital configurations, setting the convergence criteria for the adjustment, and setting the object grid parameters.

Point mensuration was accomplished using Intergraph's ImageStation Digital Mensuration (ISDM) software. The same Interior Orientation (IO) parameters were used in each run of the multi-sensor triangulation. The IO measurements were taken automatically using ISDM's image correlation, and were based on a conformal transformation model using 3 fiducial marks. (The fourth fiducial mark could not be read in the scans.) The sigma for the IO solution on each photograph varied from 5 to 25 microns.

The control and tie points were collected monoscopically, and these measurements were processed through a least squares refinement whenever the points were collected between images with the same spatial resolution. This refinement allowed for precise measurements to the sub-pixel level. Measurements on the SPOT images were stored as pixel coordinates (row/column), while measurements on the aerial photographs were stored as photo coordinates (x, y). As the ground control was measured on the SPOT images, the software refined a set of drive parameters using a two-dimensional warp. The initial estimates for the aerial photographs' exposure stations within the geocentric reference system were computed from the SPOT drive parameters when the photographs were tied into the solution.

The primary problem encounterd in the point mensuration was identification of common points between the SPOT images and the aerial photography. Differences in the radiometric quality of the imagery as well as the spatial resolution (10 meters versus 0.5 meters) caused difficulties in precise pointing to common features. To achieve the best precision, we adopted a procedure where the common points between the SPOT images and aerial photographs were visually matched based on centerline intersections, while the common points between images from the same sensor were matched using the least squares refinement.

When the multi-sensor triangulation was run, any tie or control point with an image residual greater than 1 pixel was either witheld from the solution, or remeasured. Output from the triangulation included an error propagation of the control and tie points, statistics on the diagnostic points which were collected, and image residuals for each point measurement. While these were used to evaluate the triangulation results, the primary output was a three-dimensional cube of regularly spaced ground-image coordinate pairs located on five elevation planes. This grid was referenced to the WGS 84 coordinate system. It can then be transformed into the desired coordinate sytem to which the topographic map will be compiled. From this grid, a 3rd-order polynomial projective transformation in three dimensions is computed, but only the terms of the full model which apply to the particular sensor are active. This transformation is used to resample the images into epipolar aligned stereo models for compilation of topographic features.

For each triangulation, stereo models from flight lines 9 and 7 were epipolar resampled using a cubic convolution interpolation. The resampling aligned the images parallel to the operator's eye base and removed any y-parallax from the models. The software also computes real time drives for the Hand-Held-Controller as the operator roams through the model. The object grids were converted to a polyconic projection referenced to the North American Datum of 1927 (NAD 27) prior to the stereo resampling.

From each stereo model a set of spot elevations were manually collected from both strips. These were collected at the center line of road intersections and served as a sample set to compare the accuracy of the stereo models from each triangulation run against the baseline of the conventional aerial bundle adjustment using GPS derived ground control. The X,Y,Z coordinates of the spot elevations were all transformed into the State Plane 83 coordinate system using the NADCON datum transformation.

3. RESULTS

The following tables provide a summary of the triangulation results and the comparisons of the spot elevations collected from the stereo models. Table 1 lists the error propagation of the tie points for each multi-sensor triangulation. This provides an indication of the internal consistency of the adjustment.

Table 1: Error Propagation of tie points in the multi-sensor triangulations. Average standard deviations in meters.

	Latitude	Longitude	Height
Run #1	4.391	4.725	9.025
Run #2	5.734	6.146	11.195
Run #3	10.762	5.381	43.523
Run #4	4.394	4.483	9.162
Run #5	7.789	8.720	20.850

In comparing the internal precision of each multi-sensor bundle adjustment there is about a 30% decrease in the internal consistency when we decreased the number of control points to a minimal configuration. In the fourth run where we used the same amount of control, but limited the tie points to the corner of the block, there was no significant change. In the third adjustment where we included only a single SPOT image in the adjustment we saw a dramatic decrease in the height precision, and to a lesser degree in the latitude. We saw this same increase when we limited the tie points to the upper left corner of the block in the last bundle adjustment.

Table 2 provides a breakdown of the diagnostic point statistics generated for each multi-sensor triangulation. This provides an indication of the absolute accuracy of the adjusted image-to-ground projections. No significant pattern is seen when comparing each triangulation, and at first glance it appears that none of the runs would satisfy the United States Map Accuracy Standards for a 1:24,000 scale map. But it is important to remember that the control coordinates of the diagnostic points were also digitized from the USGS map sheets, and have an accuracy themselves of >10 meters.

Table 2: Diagnostic Point Statistics for multi-sensor triangulations. Expressed as Linear 90% in meters.

	Latitude	Longitude	Height
Run #1	16.691	25.040	16.694
Run #2	17.089	23.138	20.849
Run #3	13.383	24.110	16.038
Run #4	16.615	25.053	23.644
Run #5	13.049	21.194	16.390

Table 3 contains a comparison between the the spot elevations measured on the stereo models from the first multi-sensor triangulation and the baseline spot elevations collected from the GPS controlled stereo models. These statistics show how well the SPOT controlled solution can be used in placė of a conventional aerial triangulation. The two solutions match in X, Y, and Z within the constraints of the National Map Accuracy Standards. The difference between the two solutions is a fairly consistent shift, but we can also see that the shift varies between Strip 7 and Strip 9. We believe that this is caused by the limited overlap between the photographs in Strip 7 and the SPOT images.

Table 4 shows the differences in the spot elevations collected from stereo models generated using the GPS controlled stereo models, and those generated using the USGS map sheet controlled stereo models. We wanted to make these comparisons to see how the multi-sensor triangulation solutions compared to a conventional aerial triangulation which used control collected from a less accurate map source. We can see that the aerial triangulation using control from USGS maps provides a slightly better solution than the multi-sensor triangulation.

Table 3: Differences in X,Y,Z coordinates of spot elevations collected from multi-sensor triangulated stereo models and GPS controlled stereo models. Units are in feet.

	Strip 9	Strip 7
Mean X	24.70	3.39
Mean Y	22.27	32.65
Mean Z	4.43	9.46
Std Dev X	5.20	4.12
Std Dev Y	8.50	8.06
Std Dev Z	6.07	5.14
CE 90%	20.82	19.41
LE 90%	9.98	8.46

Table 4: Differences in X,Y, Z coordinates of spot elevations collected from the USGS map controlled stereo models and the GPS controlled stereo models. Units are in feet.

	USGS To GPS
Mean X	28.44
Mean Y	7.33
Mean Z	3.21
Std Dev X	4.90
Std Dev Y	4.05
Std Dev Z	6.26
CE 90%	13.63
LE 90%	10.29

Table 5 shows a comparison between the spot elevations collected from the stereo models created from the first and fourth multi-sensor triangulation. We saw that the differences between the two solutions was insignificant. This was expected based on the error propagation and diagnostic point statistics. Table 6 shows the results of comparing the spot elevations collected from the stereo models of the third and fifth multi-sensor triangulation. The Circular Error is comparable to the other runs and the Linear Error is larger. But what is more striking is the much larger shift in the X and Z components than in the other multi-sensor triangulation results.

Table 5: Comparison of the spot elevations taken from the first and fourth multi-sensor triangulation results. Units are in feet.

Mean X	0.75
Mean Y	1.20
Mean Z	3.52
Std Dev X	0.55
Std Dev Y	1.35
Std Dev Z	1.63
Circular Error 90%	3.13
Linear Error 90%	2.68

Table 6: Comparison of the spot elevations taken from the third and fifth multi-sensor triangulation results as compared to the GPS controlled stereo models. Units are in feet.

	Run #3	Run #5
Mean X	68.58	65.46
Mean Y	26.22	16.34
Mean Z	32.42	30.55
Std Dev X	2.60	11.06
Std Dev Y	8.16	16.89
Std Dev Z	7.58	8.41
CE 90%	18.38	18.37
LE 90%	12.47	13.83

4. CONCLUSIONS

Both conventional triangulations produced more accurate results than any of the multi-sensor triangulations. The conventional aerial triangulation using the GPS surveyed points as the ground control provided the most accurate solution from which to compile the topographic maps. The RMS error of the control points in this triangulation was 0.558, 0.445, and 0.237 feet in X,Y, and Z, respectively. But to achieve this level of accuracy required 14 control points. We were also able to achieve better results in a conventional aerial triangulation using control points collected from a USGS 1:24,000 scale topographic map sheet. Using 19 ground control points, we achieved an RMS error in the control of 17.056, 20.664, and 14.43 feet in X,Y,and Z, respectively.

But based on the comparison of the spot elevations collected from both the conventional and multi-sensor triangulation generated stereo models, we saw that the aerial photography can be controlled to support topographic mapping within U.S. National Map Accuracy Standards. For a 1:24,000 scale map, the National Map Accuracy standards for horizontal positioning is 40 feet CE 90%, and the height accuracy is 10 feet LE 90% given a 20 foot contour. If we attempt to map at a 1:10,000 scale from the 1:24,000 scale photography, we can still attain the horizontal positioning necessary, but the height accuracy is outside the standards, assuming a 10 foot contour interval. These levels of accuracy were attainable using only 5 well distributed ground control points within the SPOT stereo model, and just tie points to the aerial photographs.

But in order to attain this level of accuracy the project must be set up with the following factors:

(1) The project must use SPOT stereo pairs, and the aerial photographs need to be tied to both SPOT images through common tie points. If just a single SPOT image is used, or if the photographs are tied to just one of the SPOT images the accuracy in Latitude and height are degraded significantly.

(2) The SPOT stereo pair must have a sufficent convergence angle between their look angles. At lower convergence angles, the solution of the Z component of the stereo models is degraded.

(3) At a minimum, it appears that the block of aerial photography needs to be tied to the SPOT imagery around the perimeter of the block. This was evident from the significant decrease in accuracy when we just tied one corner of the block to the SPOT imagery, and the lack of any significant change when we just tied the corners of the block to the SPOT imagery. The decrease in accuracy in Strip 7 also indicates that the accuracy of this approach will decrease as the block extends away from the SPOT imagery.

In areas where existing, up-to-date topographic maps of suitable scale exist, it would be more cost effective to digitize the control from the maps and create the stereo models for compilation through a conventional aerial triangulation. But in areas where the maps do not exist, or are not current, this multi-sensor approach can provide a method of creating accurate stereo models for compiling small-scale topotgraphic maps. This was just a preliminary study. Further study will include applying the approach to smaller scale photography, using a more accurate control point source, and bridging a larger block of photography between two SPOT stereo models.