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Evaluation of Aircraft MSS Analytical Block Adjustment

Modified collinearity equations, constrained segmentation of strips, *a priori* weighting of parameters and constraints, and editing and evaluation statistics were employed.

Abstract: *A spatial block adjustment for aircraft multispectral scanner (*MSS*) data was implemented using modified collinearity equations, constrained segmentation of strips,* a priori *weighting of parameters and constraints, and editing and evaluation statistics. Tests were conducted, using three sidelapping strips of data, to compare single and multiple strip adjustments, to determine the effect of constrained segmentation of the strips, and to evaluate the determinacy of the* ω *and* ϕ *orientation angles. It is concluded that constrained segmentation does have a beneficial effect and that the determination of points by the intersection of two or more rays, made possible by the use of sidelapping strips, is more accurate, precise, and reliable than using only one strip. Inclusion of the* ω *parameter improves the results, although high correlations result among the orientation parameters. Due to the lack of significant terrain relief,* ϕ *was not recoverable.*

Introduction

Most recent work on the geometric rectification of aircraft MSS data, except for a few instances (Ethridge and Mikhail, 1977; Ethridge, 1977), has involved only single strips. While there are often economic and practical reasons for using only single strips, there are also advantages to the use of overlapping strips of data.

If sidelapping flights are used, then each ground point is determined by the intersection of two or more rays. This means that the elevation coordinate does not necessarily have to be supplied or assumed for points whose horizontal positions are to be determined, but can be determined from the adjustment. Also, the increased geometric strength makes the determination of planimetric coordinates more accurate. There may also be advantages in the redundancy of radiometric information, which could lead to more accurate digital classification. In fact, incorporation of geometric information into classification algorithms should lead to improvements.

Formulation of the Adjustment Procedure and the Evaluation Statistics

The block adjustment of sidelapping MSS data essentially follows the standard photogrammetric technique of block adjustment. The collinearity equations, modified for the scanner geometry, are used. The strips are divided into sections, in each of which the orientation parameters are modeled by polynomials. Each of these sections is analogous to a photograph in an aerotriangulation block adjustment. Constraints are written at the section boundaries in order to assure the continuity of the rectified data. Details of the mathematical development have been given in previous work done at Purdue (Baker and Mikhail, 1973, 1975; Baker *et al.*, 1975).

In order to evaluate the effectiveness of the various adjustment cases, three criteria are used: accuracy, precision, and reliability. Accuracy refers to how closely the results of the adjustment—in this case the ground coordinates—agree with values from sources taken to be correct (or superior). Precision refers to the stochastic variability of the estimated coordinates. The reliability of the results refer to the probability that the results are free of blunders to gross errors of specified magnitude.

Accuracy is evaluated by comparing calculated ground coordinates to check values, known *a priori* but withheld from the adjustment. The coordinate difference may be summarized by a global statistic, such as the mean squared error of the differences. It has been shown (Molenaar, 1971) that the mean

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squared check point errors are estimates for the average value of the diagonal elements of the covariance matrix of the ground points, provided that the *a priori* check point coordinates are without error and that the adjustment is unbiased. In the present investigation the check points were determined in the same manner as the control points so they are not without error. However, they still provide useful information for the evaluation of the adjustment.

An alternative to the mean squared check point error is the use of concepts from the area of statistics known as exploratory data analysis (Tukey, 1977). The idea of exploratory data analysis is to use statistics which give a good description of the data, are not dependent on restrictive assumptions, and are not affected by possible outliers in the data. The statistics are usually more qualitative than quantitative, but give a feeling for the basic properties of a data set. They also allow the detection of differences between data sets which would not normally be noticed. Differences between adjustments may be such that they are not detectable by statistics such as the mean squared error. For example, unless the variances of the computed coordinates are all equal, the mean squared error gives no indication of how the check point errors are distributed. Also, the presence of an outlier has quite a large effect on the mean squared error, because the larger the discrepancy is, the more influence it has on the estimate.

In order to avoid these shortcomings, the check point discrepancies are analyzed using what Tukey (1977) calls the five number summary. This means specifying for the data set the two extreme points, the two quartile points, and the median. The five number summary is obtained for the check point discrepancies themselves and for their absolute values. The summary for the raw discrepancies gives an idea of bias, while the summary for the absolute values yields an estimate of accuracy comparable to the mean squared error.

It should be repeated here that the purpose of the Tukey analysis is not to draw final conclusions or to do rigorous statistical testing. Determination of distributions and establishment of confidence intervals for these types of statistics are often difficult or impossible. However, when used in situations such as this, with sufficient observations to insure that the "granularity" or discreteness of the data will not be a problem, these statistics can provide a useful insight into the quality of the results and any trends or tendencies present.

For analysis of the precision of the results of the adjustment, variance-covariance information on the orientation parameters and on the ground coordinates is used. In order to obtain a more global measure of the precision, the average variance or standard deviation of the triangulated points is used.

Statistical techniques for describing the reliability of an adjustment have been published in several places recently and will not be re-derived here (Förstner, 1976, 1980; Grün, 1978a, 1978b, 1980; Mikhail, 1979).

MSS Block Adjustment Tests

The data set used for the tests of the block adjustment algorithm was orginally flown for the NASA Large Area Crop Inventory Experiment (LACIE). It was taken over Hand County, South Dakota, using a Bendix 11-channel Modular Multiband Scanner at an altitude of 3050 metres (10,000 feet). The instantaneous field of view of the scanner is 0.0025 radians, with a total look angle of 100 degrees. The data set consists of three flight lines, each approximately 1450 lines long with 802 pixels per line. Sidelap between lines is approximately 70 percent.

The data were obtained from the Laboratory for the Application of Remote Sensing (LARS) at Purdue University. Control points were digitized from USGS 1:24,000 topographic maps, while image coordinates were obtained from a line printer display of channel three (0.50 to 0.54 micrometres). The ground coordinates were assumed to have standard deviations of twelve metres in X and Y and four metres in Z, after consideration of the planimetric accuracy of the map, the digitizing process, and the interpolation of elevations from contours. Image coordinates were given a variance of three pixels squared. The control and check point distribution is shown in Figure 1.

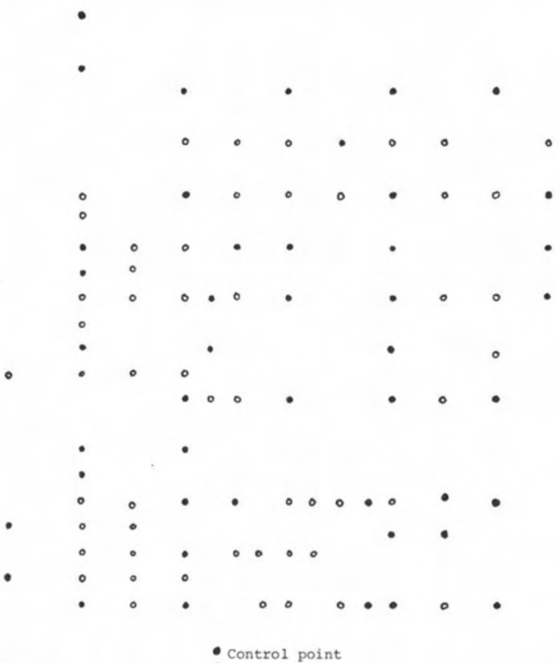

FIG. 1. Control and check point distribution for block adjustment tests.

Tests on the data were run using the program MSSBLK, written at Purdue. The program implements a rigorous least-squares block adjustment with *a priori* variances assigned to all parameters and constraints. The program also has the capability to perform the error propagation and reliability calculations described earlier.

Before the test cases were run, the data set was edited to eliminate any suspected blunders in the data. Preliminary editing runs were made using all points as control, running each strip separately and also all three simultaneously, using the *tau* criterion as described in Pope (1975). Using only one section per strip was not very effective, because any blunder present was spread over a large number of points. Division of the strips into three sections allowed blunders to be more easily located. It was also useful to run various other cases during editing because a blunder which may not be apparent in one configuration may appear in another, due to its changed location within the section or its changed relationship to other points. The use of multiple strips allowed some editing of the Z ground coordinates.

Tests were made on the standardized image coordinate residuals* and on the standardized ground coordinate residuals using the calculated value of the *tau* distribution at a significance level of 0.01. If image coordinates or ground coordinates were suspected of containing a blunder, they were given zero weight in the next run of the adjustment and the results were rechecked.

Once a cleaned data set was obtained, various factor tests were run. The main series of tests concerned the use of multiple strips and strip segmentation. Auxillary topics of interest included the assignment of elevations from overlapping MSS data, the effects of the inclusion of ω and ϕ (roll and pitch) orientation angles as parameters, and the effect of not constraining the section boundaries.

TEST RESULTS

RESULTS OF ACCURACY TESTS

Accuracy statistics derived from this series of tests are given in Table 1. The mean squared check point errors were used in an Analysis of Variance (ANOVA) procedure (Anderson and McLean, 1974) to determine if the use of multiple strips and multiple sections had a significant effect of the accuracy of the adjustment. The ANOVA was run with the pooled mean squared errors, using a log transformation to stabilize the variances of the observations. The pooled estimate was obtained by dividing the total sum of squares by the total degrees of freedom.

According to the ANOVA tests, both the number of strips and the number of sections involved are

TABLE 1. CHECK POINT ROOT-MEAN-SQUARED ERROR IN METRES AS A FUNCTION OF NUMBER OF STRIPS AND NUMBER OF SECTIONS

	Number of Sections											
	1			2			3			4		
Strips	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1	24.4	31.6	—	25.0	17.7	—	21.6	13.1	—	16.1	12.9	—
2	16.2	24.1	—	16.6	19.4	—	14.4	13.3	—	14.3	11.4	—
3	16.1	23.6	—	11.6	24.5	—	10.0	24.0	—	9.7	23.9	—
pooled	20.0	27.3	—	19.4	20.5	—	16.7	17.4	—	13.8	16.9	—
1 and 2	20.1	31.0	55.8	21.0	17.7	53.4	17.9	12.5	36.2	14.3	12.5	27.4
2 and 3	16.8	29.3	92.0	11.8	25.2	81.2	10.6	20.0	66.1	9.9	19.8	64.2
pooled	18.7	30.3	77.2	17.5	21.3	67.1	15.1	16.2	54.2	12.6	16.1	50.4
1,2,3	18.6	29.2	69.2	17.5	18.5	53.5	15.2	13.7	36.4	11.9	14.9	37.5

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* a standardized residual is equal to the residual divided by its standard deviation.

significant effects for all three coordinates, with significance of the F statistic ranging from 0.001 to 0.010. The Newman-Keuls test (Anderson and McLean, 1974) was used to determine which cases actually led to significant differences in the mean squared error.

In terms of the X (along strip) mean squared error, there was no significant difference between the results using one or two sections. However, increasing the number of sections per strip to three or four did reduce the mean squared error significantly. Using more than one strip made a significant difference, but there was no difference between using three or four strips.

For Y, the use of more than one section significantly reduced the mean squared error. The difference between using two or more than two sections was significant at $\alpha = 0.1$ but not at 0.05, while there was no difference between using three or four sections. There was no significant difference between the means for different numbers of strips, a contradiction of the results of the ANOVA although the significance of the ANOVA was only 0.1.

In Z the only significant difference was between the mean for one section and that using three or four sections, and that only at $\alpha = 0.1$. There were no significant differences at the 0.05 level.

The fact that using more than one section leads to higher accuracy in X and Y is not surprising, because this has been shown earlier in the case of single strip planimetric adjustment (Baker and Mikhail, 1975; Ethridge, 1977). However, these statistics seem to indicate that the use of multiple strips, that is, determining points by more than one ray, does not lead to higher accuracy. Because this was contradictory to intuition, further studies were made.

Table 2 shows, for cases using three sections and multiple strips, the root mean squared check point errors for points determined by one, two, and three rays. As can be seen, the more rays used to determine a point, the more accurately it is positioned in X, Y, and Z. The reason no significant difference was apparent for different numbers of strips in Table 1 was that, for these statistics, single and multiple ray points were used together in the calculation of the test statistics and the effects were absorbed.

Another evaluation of the differences between the various cases can be gained by examination of the five number summary statistics for the test cases, given graphically in Figures 2 to 4. The line plotted for each adjustment case represents the total spread of the absolute value of the check point residuals in much the same way as a histogram would. The marks on each line show the 0, 25, 50, 75, and 100 percent points in the groups of residuals, for example, the size of the residual larger than 25, 50, or 75 percent of the group of residuals. Examination of the statistics in this form gives an idea of the spread of the absolute value of the check point residuals in much the samy way as a histogram would. The marks on each line show the 0, 25, 50, 75, and 100 percent points in the groups of residuals, for example, the size of the residual larger than 25, 50, or 75 percent of the group of residuals. Examination of the statistics in this form gives an idea of the spread of the results. For example, the difference between the 75 and 100 percent points is much larger than the other 25 percent intervals in all cases, suggesting greater variability toward the tails of the distribution or the possible presence of blunders. It can be seen that using a greater number of sections noticeably decreases the spread or variability of the check point residuals. This is a very desirable property, because it means that the results for the points are more consistent with one another.

The individual statistics, such as the median, can be used to compare the results of the individual adjustments, in the same way as the root mean squared error. Although rigorous statistical tests on the median are difficult, medians can give useful information on trends or general properties of the data. For example, the results of adjustments using strips two and three are in general worse (have a larger median) in Y and Z than the results of strips one and two. This may have been a function of strip geometry or of the particular control points appearing in these strips.

RESULTS OF PRECISION TESTS

Precision statistics are given in Table 3, which gives the average standard deviations of the check points, calculated as the square root of the average propagated variance. It can be seen that increasing the number of sections slightly increases the X, Y,

TABLE 2. CHECK POINT ROOT-MEAN-SQUARED ERROR IN METRES FOR SINGLE AND MULTIPLE RAY POINTS (ADJUSTMENTS USING THREE SECTIONS PER STRIP)

	Number of Rays							
	1		2			3		
Strips	X	Y	X	Y	Z	X	Y	Z
1	16.7	17.4	—	—	—	—	—	—
2	17.3	16.5	11.5	15.8	54.2	—	—	—
3	18.8	14.4	10.3	12.8	41.3	8.9	11.5	27.3

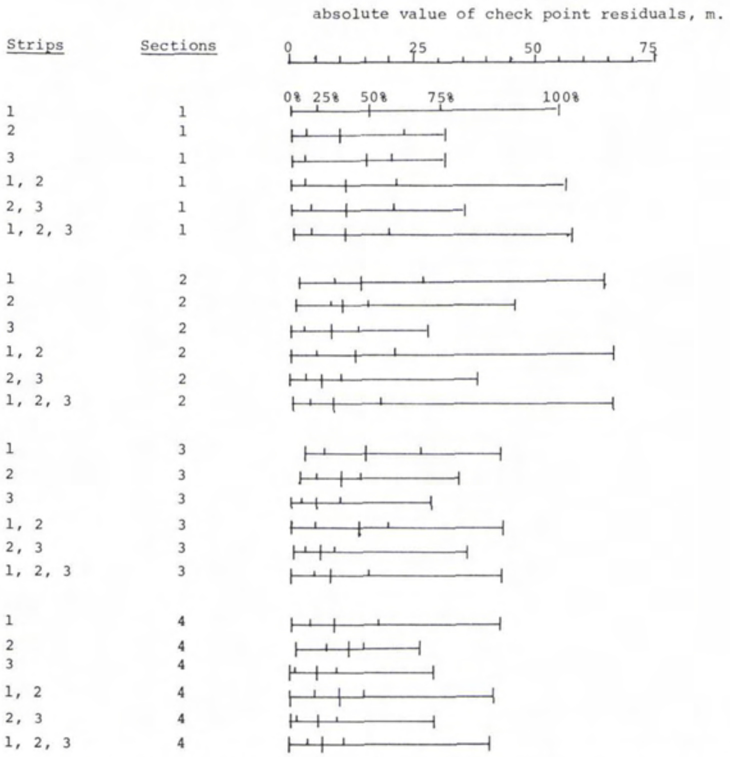

FIG. 2. Graphical representation of five number summary statistics for check point absolute X error.

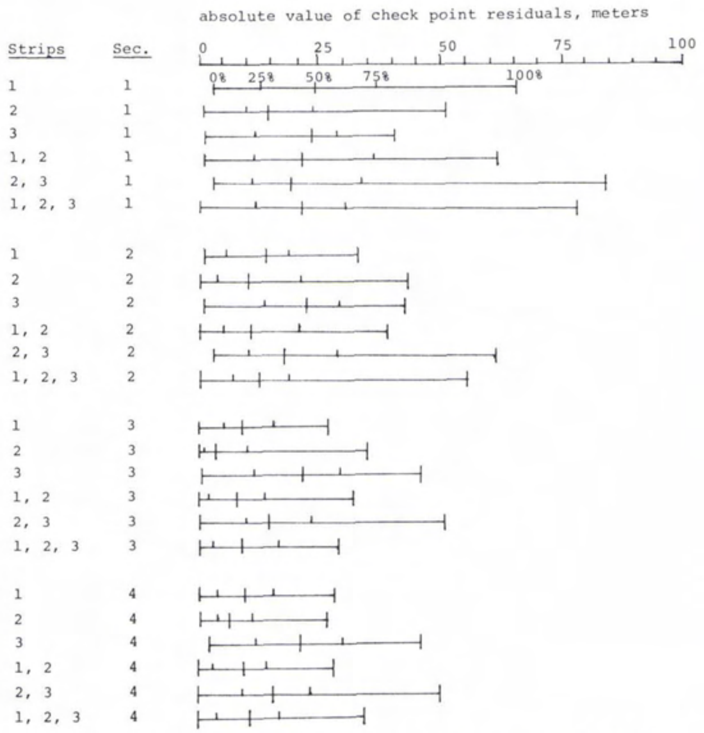

FIG. 3. Graphical representation of five number summary statistics for check point absolute Y error.

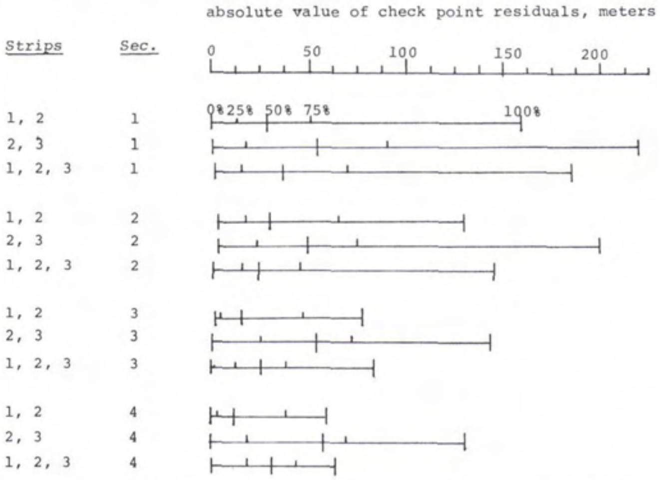

FIG. 4. Graphical representation of five number summary statistics for check point absolute Z error.

and Z standard deviations. Using more strips decreases the X standard deviations slightly and the Z standard deviations significantly. Going from one strip to two strips increased the Y standard deviation, while using three strips decreased it again.

As was the case for the mean squared check point errors, some of these results are contrary to expectations. Again, analyzing the statistics in terms of points determined by one, two, or three image rays provides more insight into the problem.

Table 4 shows the average check point standard deviations for point with one, two, or three image rays, from the test cases using three sections per strip. It can be seen that increasing the number of rays which determine a point leads to a significant reduction in X and Z standard deviations. The large increase in Y standard deviations in going from one ray to two rays is due to the fact that, when using two rays, Z is also being determined. Due to the flight direction of this data set, the errors between the Y and Z ground coordinates are significantly correlated (for two ray points, typically 0.6 to 0.9). This correlation leads to a decrease in the precision of the Y coordinate, compared to the case where Z is not solved for. When the three rays are used, correlation is not signficant and the Y standard deviation is lower than it was for the single ray case.

Another interesting result to note is that the precision depends mainly upon the number of rays determining a particular point, and is not greatly affected by the number of strips used in the adjustment. This is evident from examination of the columns of Table 4. It would be expected that the increase in redundancy due to the use of more than one strip would cause an increase in precision for all points, including those not determined by more than one ray.

The precision of individual points is also affected by the location of the point along the scan line. The Y standard deviation varies from 14.5 to 19.5 metres in the case of single ray points imaged at the center and at the edge of the scan line, respectively. The X standard deviation is affected only slightly.

RESULTS IN RECOVERY OF ELEVATIONS

One of the main reasons for trying to obtain elevation information from the MSS data is to eliminate the need to assign elevations to each pixel if any geometric processing is to be done (unless the terrain is considered flat). These elevations must be obtained from some external source such as a digital terrain model (DTM) of the imaged area. This is an expensive process, even assuming that a suitable DTM is already available for the area. Use of elevations obtained directly from the MSS data would probably prove less expensive; however, for the use of such elevations to be feasible, they must be accurate enough for the purpose.

According to Baker and Mikhail (1975), the maximum allowable height assignment error without geometric degradation of the results is that which results in a planimetric error of one pixel or less after processing. This maximum elevation error, Z_e, is given as a function of flying height above terrain ($Z_c - Z_j$), resolution of the scanner γ, and the scan angle from vertical, θ.

$$Z_e = 2 \gamma (Z_c - Z_j) / \sin 2 \theta$$

For the data set under consideration and for a scan angle of 45°, where the elevation error tolerance is critical, $Z_e = 15.25$ metres. Even for a scan angle of 30° $Z_e = 17.61$ metres, while the best root mean square error (RMSE) obtained was 36 metres. So, the conclusion must be reached that elevations

TABLE 3. AVERAGE CHECK POINT STANDARD DEVIATION IN METRES AS A FUNCTION OF NUMBER OF STRIPS AND NUMBER OF SECTIONS

	Number of Sections											
	1			2			3			4		
Strips	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
1	14.8	18.8	—	15.5	19.5	—	16.1	20.1	—	17.6	21.6	—
2	15.4	18.5	—	16.0	19.0	—	16.5	19.6	—	17.5	20.6	—
3	14.8	19.4	—	15.4	20.2	—	15.9	20.9	—	16.5	21.6	—
pooled	15.0	18.9	—	15.6	19.6	—	16.2	20.2	—	17.2	21.3	—
1 and 2	13.6	19.0	48.4	14.2	19.6	49.4	14.7	20.1	50.8	15.8	21.4	53.0
2 and 3	13.0	25.7	63.8	13.7	26.6	65.4	14.2	27.4	67.7	14.8	28.3	69.6
pooled	13.3	22.4	56.1	14.0	23.1	57.4	14.4	23.8	59.2	15.3	24.8	61.3
1,2,3	12.6	19.8	46.1	13.4	20.5	47.0	13.7	20.9	48.2	14.6	22.1	49.8

from MSS data are not sufficiently accurate for elevation assignment in this case. It is very possible, however, that future refinements in technique will increase accuracy to a usable level.

RESULTS FROM USING ω AND φ AS PARAMETERS

In a single strip solution, inclusion of ω as a parameter had little effect. Because the data were roll stabilized, only a small amount of ω should be present. The check point RMSE and the average standard deviations of the ground points were hardly affected. Correlation between orientation parameters was not a problem.

In a test using all three strips with three sections each, there was a significant reduction in *Z* RMSE, from 36.4 metres to 27.2 metres, with no change in *X* and *Y*. There was little change in the average standard deviations. Correlation between the orientation parameters again was not a problem.

The effects of using φ as a parameter were also investigated in a run with three strips, three sections each, and with the φ and X_c (*X* position of the perspective center) parameters loosely constrained. No benefits in terms of check point RMSE or average standard deviation were gained. Correlation between the φ and X_c constant terms increased up to ten times, while the standard deviation of the φ constant term was about 1 degree. This was expected, because the relief in the test area is only about 40 metres and determination of φ is precise for scanner imagery only in areas of high relief.

A test was also made, again using three strips with three sections each, on the effect of not constraining the orientation parameters at the section boundaries. Relaxation of the constraints improved the RMSE in *X* from 15.2 to 11.1 metres and in *Z* from 36.4 to 35.3 metres, while not affecting *Y*. Average standard deviations of the ground points did increase slightly, as did those of the orientation parameters. Values of the orientation parameters at the section boundaries were calculated and compared, and showed very significant differences which would lead to unacceptable discontinuities in the rectified MSS data. It must therefore be concluded that the constraints are necessary.

CONCLUSIONS

EFFECT OF NUMBER OF SECTIONS

The number of sections into which the strips are divided has a significant effect on the accuracy and precision of the adjustment. Increasing the number of sections, up to a point, decreases the check point RMSE and average standard deviations in all three coordinates. The decrease becomes smaller as more sections are used, until the redundancy of the adjustments becomes so small that the results start to degrade.

TABLE 4. AVERAGE STANDARD DEVIATION IN METRES FOR SINGLE AND MULTIPLE RAY POINTS (ADJUSTMENTS USING THREE SECTIONS PER STRIP)

	Number of Rays							
	1		2			3		
Strips	X	Y	X	Y	Z	X	Y	Z
1	16.2	20.2	—	—	—	—	—	—
2	16.0	20.5	11.6	26.2	57.4	—	—	—
3	15.7	20.0	11.5	26.3	57.3	9.5	12.1	29.9

EFFECT OF NUMBER OF STRIPS

Increasing the number of strips used in the adjustment also has a beneficial effect on accuracy and precision. This is due to the determination of points in the overlap area by two or more rays. There is little effect on points in the adjustment which are not in the overlap area and are determined by a single ray.

RECOVERY OF ELEVATIONS

Computation of elevations from overlapping aircraft MSS data is a possibility. The RMSE in Z is typically three times that in X and Y. Although this is not accurate enough to use for pixel elevation assignment for further geometric processing, further refinements in techniques may make this possible.

EVALUATION OF RELIABILITY

Reliability of MSS block adjustment is a function of the number of rays per point and the location of the image in the scan line. In order for errors to be detected, at least three image rays for each point are necessary.

USE OF ω AS A PARAMETER

Inclusion of ω as a parameter leads to significant correlations between the orientation parameters and to increased standard deviations for them. However, when it is included in an adjustment the Z RMSE is reduced.

USE OF ϕ AS A PARAMETER

Inclusion of ϕ as a parameter gives no benefits in terms of check point RMSE or average standard deviations, while causing very significant correlations between the orientation parameters and higher standard deviations for them. Therefore, it should be excluded.

USE OF CONSTRAINTS BETWEEN SECTIONS

Relaxation of the boundary constraints between sections gives more accurate results in X and Z. However, the large differences in the values of the parameters at the section boundaries would lead to unacceptable discontinuities in the rectified data.

USE OF EVALUATION STATISTICS

The use of several types of statistics to evaluate and compare the accuracy, precision, and reliability of various adjustment cases instead of using only the check point RMSE gives a better appreciation for the effectiveness of each adjustment case and also allows for more meaningful comparisons between cases. This is especially important when comparing completely new algorithms which may differ in unexpected or subtle ways.

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Forthcoming Articles

James E. Anderson, The Use of Landsat-4 MSS Digital Data in Temporal Data Sets and the Evaluation of Scene-to-Scene Registration Accuracy.

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Siamak Khorram and *Heather M. Cheshire*, Remote Sensing of Water Quality in the Neuse River Estuary, North Carolina.

William H. Klein, An Aerial Photo Stereo Teaching Aid.

James P. Ormsby, *Bruce J. Blanchard*, and *Andrew J. Blanchard*, Detection of Lowland Flooding Using Active Microwave Systems.

James P. Verdin, Monitoring Water Quality Conditions in a Large Western Reservoir with Landsat Imagery.