Control Extension Utilizing Large Format Camera Photography

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ABSTRACT: Investigations were conducted at the University of New Brunswick into the accuracy obtainable for control extension utilizing Large Format Camera (LFC) photography taken from the Space Shuttle. Using ground control data obtained from the Surveys and Mapping Branch of Energy, Mines and Resources Canada, the locations of 118 ground control points (x,y,z) were identified on a strip of nine photographs taken during orbit 38 of Space Shuttle mission 41G, October 1984. The strip, of approximate scale 1:788,000, extends over a 400-km track from Empress to Rockglen in Saskatchewan, Canada. The ground control points used were road intersections for which coordinates could be obtained from terrestrial observations. Photograph coordinates were measured in an OMI AP-2C analytical plotter.

The following computations were carried out:

- image refinement (including use of observed reseau);
- analytical model formation;
- independent model aerotriangulation;
- bundle aerotriangulation; and
- space resection of single images, and subsequent reprojection of photo coordinates.

An RMS error of 15 m was attained for the derived ground coordinates and elevations by comparing computed and known values of check points. Conclusions are drawn regarding the performance of the LFC imagery as a means of control extension, and its application in support of mapping.

INTRODUCTION

WITH THE Space Shuttle now firmly established in its role as a multi-mission orbiter, together with its ability to act as a platform for the new generation of metric "space" cameras, the prospect of systematic photographic coverage of the Earth's surface from space is now a reality. Concomitant with this realization is the opportunity to investigate the utility of such photogrpahy for its many possible applications all over the world.

The aim of this paper is to give details of one such investigation carried out in the Department of Surveying Engineering, University of New Brunswick (UNB). Specifically, this study sought to establish estimates of the accuracy obtainable for control extension using photography from the Large Format Camera (LEC).

DATA ACQUISITION

THE PHOTOGRAPHY

The photography considered for these tests was acquired over Canada on Shuttle orbits 21, 37, 38, and 70. An evaluation of this photography showed Orbit 38 to be the most promising. The details of the photography chosen are as follows:

Frame numbers 674-682, Orbit 38 Shuttle Mission STS-41G
Date of photography: 7 October 1984
Forward overlap: 80 percent
Altitude: 241 km
Scale: 1:788,000 (approx.)
Strip coverage: 400 km by 180 km
Location: Empress to Rockglen, Saskatchewan, Canada
Film type: Black and White, Kodak 3412
Filter type: Minus blue (intra lens), antivignetting (front of lens)

The quality of the film diapositives was good, considering they were produced from third-generation negatives. Some degradation of image quality was evidenced by varying contrast across individual frames. To ensure that the photography could be used in conventional photogrammetric instruments, the film diapositives were printed in half frames of 23-cm by 23-cm format size, each containing the left or right half of a large format frame (46 cm by 23 cm). As shown in Figure 1, each half-frame included seven fiducial points, with points numbered 6 and 10 common to both. In the mensuration and image refinement stages that followed, all work was carried out on these half-frames.

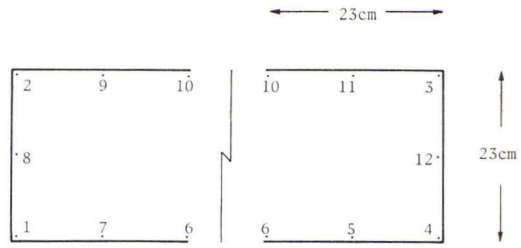

FIG. 1. Format of diapositives used in the investigation.

GROUND CONTROL POINTS

In the photographed area extensive use has been made of Inertial Survey Systems (ISS) to establish ground control. The sites chosen for virtually all these ISS points were adjacent to road intersections, with field measurements being made to the intersections for recovery purposes. In most cases the coordinates of the intersection of road center lines could be computed with a standard deviation of less than two metres.

Using their computed coordinates, road intersections were located on the relevant 1:50,000 National Topographic Series (NTS) map. By using the surrounding map detail, field notes, and large scale identification photography, each point was searched for on the LFC imagery. A total of 118 points were positively identified out of the nearly 600 points available.

Ground coordinates were found to be in two UTM zones (12 and 13). These coordinates were transformed to geodetic coordinates (ϕ, λ, h) then transformed to geocentric Cartesian coordinates (X, Y, Z). In addition, Transverse Mercator coordinates of all ground control points (GCPs) were computed for a single 6-degree zone covering the test area.

MENSURATION

Photograph coordinates were measured under 12x magnification in the OMI AP-2C analytical plotter at UNB. The instrument was run in monocomparator mode with each half-frame diapositive being mounted on the right photo carriage. The computer was programmed to drive the floating mark to each ground control point appearing in a particular photograph (Armenakis and Faig, 1986). The seven fiducial marks appearing in each half-frame and the four reseau marks surrounding each

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point were also observed. Three sets of measurements were taken on each diapositive, with a project total of approximately 4,500 observations being made.

COMPUTATIONS

Image Refinement

Each set of observed photo coordinates was processed using software developed to account for the effects of comparator errors, film deformation, and lens distortion. Projective transformation, based on the four reseau marks around each point, was employed to correct for film deformation. Thereafter, the corrected coordinates were transformed first to the fiducial coordinate system and then to the principal point origin and the remaining corrections were applied. A separate set of photo coordinates corrected for Earth curvature was also computed. There were used with Transverse Mercator ground coordinates in the single image transformations described later. The effect of atmospheric refraction is negligable for photography taken from altitudes at which the space shuttle orbits. Calibration data were obtained from the NOAA Calibration Report (Bossler, 1982).

The final step of this phase was to compare photo coordinates obtained from the three sets of measurements. The standard deviations of observations were found to be

$$\sigma_x = 5.5\ \mu m$$
$$\sigma_y = 6.0\ \mu m$$

Control Extension Procedures

The methods of control extension used in the tests were

- Independent model aerotriangulation using both "single model" and strip approaches;
- Bundle aerotriangulation; and
- Space resection, and subsequent reprojection of check point photo coordinates.

For the above procedures, the accuracy of computed ground coordinates was estimated by the Root Mean Square Error (RMSE) at check points. For tests using geocentric Cartesian ground coordinates, final adjusted coordinates were transformed back to the Transverse Mercator system and then compared to the known values.

Independent Model Aerotriangulation

Independent models were formed analytically using the well known program NRC 34. The models were formed using every fourth frame along the strip, which corresponds to 40 percent forward overlap, giving a base height ration (B/H) of 0.9. This combination was chosen as it afforded the maximum B/H while maintaining sufficient tie points between models. All points in a stereo pair were included in the relative orientation procedure. The maximum value and the RMS of the residual parallaxes for each model are shown in Table 1. These figures indicate the accuracy of model formation.

The above models were then used as input for the Stuttgart aerotriangulation program PAT-M-43 (Ackermann *et al.*, 1973). Adjustment of both single models and the entire strip of five models was carried out using the control configurations shown in Figures 2 and 3, respectively. Tables 2 and 3 show the results of these tests. In calculating the RMSE of check points, points

TABLE 1. MAXIMUM AND RMS RESIDUAL PARALLAXES FOR RELATIVE ORIENTATION

Frame Numbers	Model	Maximum V_{py} (μm)	RMS V_{py} (μm)
674-677	7477	15	4.2
675-678	7578	15	3.6
676-679	7679	15	3.7
677-680	7780	14	4.5
678-681	7881	14	3.9

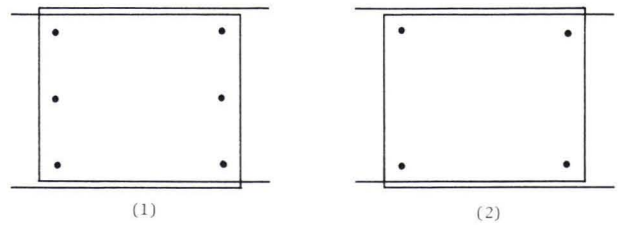

FIG. 2. Control patterns used in the single model tests.

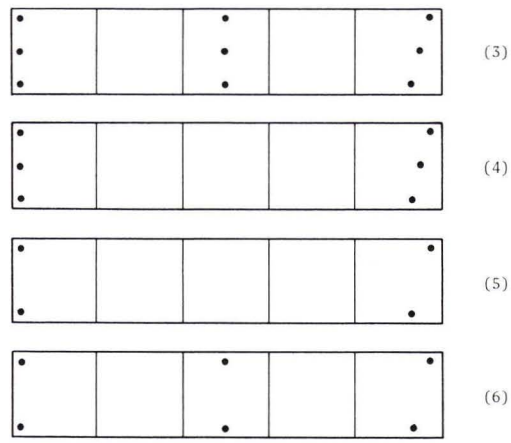

FIG. 3. Control patterns used in simultaneous adjustment of the strip.

which showed a discrepancy larger than three times the RMSE were excluded from the computation of the final values.

Bundle Aerotriangulation

Mean photograph coordinates were the basic input for the bundle triangulation program GEBAT (El Hakim, 1979). This program allows the inclusion of additional parameters in the solution. These parameters are the coefficients of a harmonic function, which is used to model the effects of residual systematic errors in photo coordinates.

Adjustment of the strip was carried out using, again, the control configurations shown in Figure 3. Results of these tests are given in Table 4.

Single Image Processing

The final phase of testing involved single photographs only. Analytical space resections of photographs 677 and 678 were carried out using the three control configurations shown in Figure 4. After each resection, the photo coordinates of check points were "reprojected" onto a plane at the mean terrain height of the control points used in the resection. The use of a mean terrain elevation for reprojection of photo coordinates necessitates that the ground coordinates be expressed in a plane coordinate system. As explained earlier, photo coordinates corrected for Earth curvature were used in these tests.

The assumption of a mean terrain height inevitably causes errors in derived ground coordinates. To assess the magnitude of these errors for this set of data, the reprojection was again carried out using known elevations of the check points. Results of these tests are shown in Table 5 and 6.

DISCUSSION OF RESULTS

Planimetric Accuracies

Results in Table 3 (Independent Model) and Table 4 (Bundle) indicate that planimetric accuracy varies very little from the use of four corner control points only to three bands of three horizontal control points for adjustment of the strip. (See control

TABLE 2. RMSE AT CHECK POINTS AFTER SINGLE MODEL ADJUSTMENTS

Model	Control Pattern	Number of Check Pts	Root-Mean-Square Errors: Ground Scale in metres X	Y	POSN	Z	Image Scale in mm x	y	posn	z
7477	(1)	20	10.8	9.9	14.7	15.7	0.014	0.013	0.019	0.020
	(2)	22	10.9	10.1	14.9	16.2	0.014	0.013	0.019	0.021
7578	(1)	32	9.5	9.4	13.4	16.0	0.012	0.012	0.017	0.020
	(2)	34	10.0	10.8	14.7	13.6	0.013	0.014	0.019	0.017
7679	(1)	29	10.9	9.7	14.6	14.5	0.014	0.012	0.019	0.018
	(2)	31	11.4	9.8	15.0	16.4	0.014	0.012	0.019	0.021
7780	(1)	29	9.1	9.4	13.1	15.5	0.012	0.012	0.017	0.020
	(2)	31	10.7	9.3	14.2	16.1	0.014	0.012	0.018	0.020
7881	(1)	22	10.4	8.1	13.1	9.6	0.013	0.010	0.017	0.012
	(2)	24	9.4	9.5	13.4	10.0	0.012	0.012	0.017	0.013
Weighted			10.1	9.3	13.7	14.4	0.013	0.012	0.017	0.018
Mean			10.5	9.9	14.5	14.6	0.013	0.013	0.018	0.019

TABLE 3. RMSE AT CHECK POINTS AFTER INDEPENDENT MODEL ADJUSTMENT OF THE STRIP

Control Pattern	Number of Control Points	Number of Check Points	Root-Mean-Square Errors: Ground Scale in m X	Y	PLAN	Z	Image Scale in mm x	y	posn	z
(3)	9	88	9.9	9.1	13.4	15.5	0.013	0.012	0.017	0.020
(4)	6	91	10.5	10.8	15.0	19.5	0.013	0.014	0.019	0.025
(5)	4	93	12.1	10.7	16.1	24.4	0.015	0.014	0.020	0.031
(6)	6	91	11.0	10.1	15.0	17.1	0.015	0.013	0.019	0.022

TABLE 4. RMSE AT CHECK POINTS AFTER BUNDLE ADJUSTMENT OF THE STRIP

Control Pattern	Number of Control Points	Number of Check Points	Root-Mean-Square Errors: Ground Scale in m X	Y	PLAN	Z	Image Scale in mm x	y	posn	z
(3)	9	95	9.3	8.8	12.8	16.1	0.012	0.011	0.016	0.020
(4)	6	98	10.9	9.9	14.8	17.3	0.014	0.013	0.019	0.022
(5)	4	100	10.8	9.3	14.3	19.5	0.014	0.012	0.018	0.025
(6)	6	98	9.5	9.8	13.6	16.5	0.012	0.012	0.017	0.021

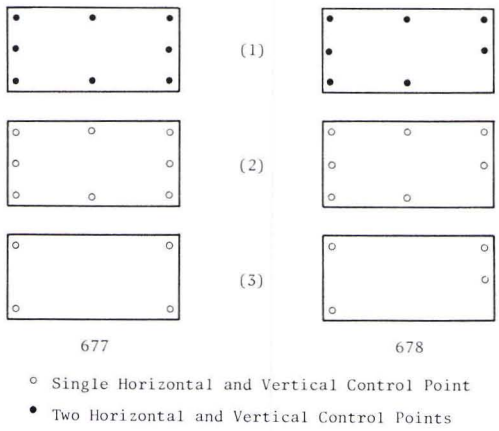

FIG. 4. Control patterns used in the single photograph transformations.

patterns 5 and 3, respectively, in Figure 3.) This is consistent with well recognized aerotriangulation characteristics.

Comparing Table 2 with Tables 3 and 4 indicates that the simultaneous adjustment of strips can yield planimetric accuracies compatible with those obtained by the adjustment of individual models.

From Tables 5 and 6 it is clear that single image tranformations yield results that are less accurate than those for stereo image processing. A decrease in accuracy is not surprising as the discrepancies used to calculate the RMS values result from the transformation of only one set of image coordinates, unlike the other computational methods. The assumption of a mean terrain height for image point reprojection causes significant accuracy loss, even in the relatively flat terrain covered by the photographs. Also it is quite possible that errors arise from the approximate nature of the Earth curvature correction, in which vertical photography is assumed. Comparison between the results of diffeent control configurations indicate only a slight accuracy loss when moving from dense to corner-only control.

VERTICAL ACCURACIES

Tables 3 and 4 show quite close correspondence in terms of vertical accuracies obtained. As expected, the distribution of control has a far greater effect than for planimetry. The best height accuracies are achieved with a band of three control points situated at each end and midway along the strip. A decrease in accuracy is evident when the end control is reduced to corners only. Larger degradation in accuracies are caused with the use of control at the ends of the strip only. From the results it could be concluded that the bundle adjustment with additional parameters shows less sensitivity to increased separation between control points (Figure 3: patterns 4 and 5).

Comparing Table 2 with Tables and 4 shows that with control every two to three models (or four to five photographs), the vertical accuracies of simulaneous adjustments match those of individual model adjustments.

TABLE 5. RMSE AT CHECK POINTS AFTER SINGLE IMAGE PROCESSING (USING PROJECTION ONTO A PLANE AT MEAN CONTROL POINT ELEVATION)

Frame #	Control Pattern	Number of check pts	Root-Mean-Square Errors: Ground Scale in m X	Y	POSN	Image Scale in mm x	y	posn
677	1	46	16.5	15.5	22.6	0.021	0.020	0.029
	2	52	18.8	16.3	24.9	0.024	0.021	0.032
	3	56	19.2	17.6	26.0	0.024	0.022	0.033
678	1	42	15.3	14.4	21.0	0.019	0.018	0.026
	2	49	15.7	14.2	21.2	0.020	0.018	0.026
	3	52	16.9	15.0	22.6	0.021	0.019	0.027
Weighted	1		16.0	15.0	21.9	0.020	0.019	0.028
	2		17.4	15.3	23.2	0.022	0.020	0.029
Mean	3		18.2	16.4	24.4	0.023	0.021	0.030

TABLE 6. RMSE AT CHECK POINTS AFTER SINGLE IMAGE PROCESSING (USING PROJECTION AT KNOWN CHECK POINT ELEVATIONS)

Frame #	Control Pattern	Number of check pts	Root-Mean-Square Errors: Ground Scale in m X	Y	POSN	Image Scale in mm x	y	posn
677	1	50	14.5	13.6	19.9	0.018	0.017	0.025
	2	58	12.8	14.7	19.5	0.016	0.019	0.025
	3	62	16.5	15.2	22.4	0.021	0.019	0.028
678	1	47	13.1	11.7	17.6	0.017	0.015	0.022
	2	54	14.9	12.0	19.1	0.019	0.015	0.024
	3	57	16.1	15.4	22.3	0.020	0.020	0.028
Weighted	1		13.8	12.7	18.8	0.018	0.016	0.024
	2		13.8	13.4	19.3	0.017	0.017	0.025
Mean	3		16.3	15.3	22.4	0.021	0.019	0.028

CONCLUSIONS AND RECOMMENDATIONS

Overall, the results obtained can be regarded as excellent, considering the fact that all control and check points were untargetted natural features.

Preflight analysis of LFC parameters contributing to planimetric and heighting errors had been carried out by Mollberg (1979). From this analysis, the expected accuracies for the techniques utilized in these tests are 10.6 metres for planimetric position and 13.3 metres for elevation. Of the results, those which most closely approximate the conditions of the preflight analyses are the Single Model tests. Accuracies obtained are 13.7 metres for planimetric position and 14.4 metres for elevation.

When comparing the above results, the following points should be considered:

- The estimated accuracies are for "relative" positioning. The RMSE values obtained are for "absolute" positioning. Thus, ground control inaccuracies and small observational blunders may be contained in the empirical results.
- All control and check points were untargetted natural features, chosen "from the ground" not "from the imagery."

The diapositives used were fourth generation. Murai and Matsuoka (1985), in their tests of the Zeiss Metric Camera Imagery (Spacelab 1), cite their use of second-generation film as a cause of a decrease in accuracy with respect to that obtained by Konecny using first-generation material.

With regard to LFC imagery supporting topographic mapping, the following criteria are pertinent:

- Map accuracy standards require that for well defined features the standard error for planimetric position shall not exceed 0.3 mm on the map, the standard error of contours shall be within one-third the contour interval, and that the standard error of spot heights shall not exceed one-fifth the contour interval.
- Regarding contouring during analog map compilation, a generally accepted rule-of-thumb is that contours can be produced at an interval of approximately five times the spot height standard error. Contours derived using digital techniques could have an interval equal to three times the spot height standard error, given suitable data sampling.
- Experience has shown that the standard error of the horizontal and vertical control used for map compilation should not exceed 0.1 mm at map scale and 0.1 contour interval, respectively.

Applying these criteria to the RMS errors obtained it could be concluded that, under the conditions of these tests, LFC data has application in

- Determining planimetric position of well defined features to an accuracy of 14 m;
- spot heighting to an accuracy of 15 m;
- contouring with a minimum interval of 75 m using anolog means, or 50 m using digital techniques;
- producing photo maps at scales of 1:50,000 and smaller;
- providing horizontal control for map compilation at scales of 1:150,000 and smaller, and
- providing vertical control for contouring at a 150-m interval.

Line maps must also adhere to the specifications set for map content. Therefore, the interpretability of the image must also be considered in arriving at the largest map scale that can be compiled. No such test was performed in this investigation.

Of particular importance are the implications with respect to ground control requirements for LFC projects. In these tests it was found that, over an area covering 400 km by 180 km, six control points distributed around the perimeter provided a good compromise between accuracy and economy. This is a significant finding for countries with sparce geodetic control.

Tests conducted elsewhere indicate that a substantial increase in accuracy can be achieved by employing a very dense control point field. For example, at the Politecnico de Milano, Togliatti and Moriondo (1986) attained a 7-m RMS error for planimetric position and elevation when a model area covering 110 km by 180 km was adjusted to 24 ground control points. Such a proposition may not be practical for the poorly mapped regions of the Earth, which could benefit the most from space photogrammetry. This investigation has also shown the feasibility of acquiring ground control after the photography has been obtained. Coordinating natural features clearly visible on the photogra-

phy would afford accuracies as good, if not better, than those achieved in these tests. This would ensure that points are established at optimum locations with minimum effort, and where cloudless imagery exists.

Concluding then, these tests verify the theoretical expectations of the LFC system, in particular its geometric fidelity (Doyle, 1979; Mollberg, 1979), and the predictions made six years ago based on the investigation of the Skylab S-190A and S-190B imagery (Derenyi, 1981). Having proven its technical ability to support activities such as worldwide mapping projects, what is needed then for successful future employment of the system is the necessary economic and political momentum.

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