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Block Triangulation by ISP Comm. III

Summary of experimental research under the auspices of the International Society of Photogrammetry identifies new principles.

ABSTRACT: *The Commission III Working Group consisted of participants from U. S., Australia, England, Czechoslovakia, Netherlands and Canada with a total of nine organizations being involved. During the period 1964–68, each participant of the Group performed an independent adjustment of all or a portion of a 9 by 20-block of simulated near-vertical photography projected from approximately 11,000 meters above terrain, having an approximate scale of 1:65,000 and 60 percent all-around overlap. Two general groups of methods were used: (a) simultaneous adjustment of photographs; and (b) sequential adjustment. The first method produced more accurate results at a generally higher cost. However, sequential adjustments yielded results of high enough quality that further refinement in a simultaneous adjustment would not be necessary except for unusually large blocks where extremely high accuracy is required.*

INTRODUCTION

ANALYTICAL AERIAL triangulation and adjustment of strips and blocks were among the fields of interests specified in a resolution passed by Commission III at the 1964 Congress of the International Society of Photogrammetry. The Commission also called for the formation of a Working Group to undertake experimental research on block triangulation.

In accordance with this resolution Commission President, Mr. G. C. Tewinkel, appointed Mr. Charles Theurer as chairman of a Working Group formed to investigate and report on experimental research on block triangulation. The objectives of the Working Group were to be directed toward a practical solution of the problem. In line with these objectives, the Chairman contacted organizations which had operational analytical triangulation procedures and requested that they participate in the experimental studies. The overall plan was to suggest that each participant of the Group perform independent adjustments of a specific test block of aerial photography.

A block of simulated aerial photography was prepared and distributed to organizations indicating interest in the investigations. In this way complications which invariably accompany establishing ground control, reproduction and distribution of diapositives, plate coordinate measurement and refinement were avoided.

The Working Group included the following organizations and principal investigators:

1. Army Map Service, Washington, D. C., U.S.A. Mr. J. R. Barrett and Mr. V. E. Sellers.
2. ESSA, Coast & Geodetic Survey, Washington, D. C., U.S.A. Mr. Morton Keller.
3. Ohio State University, Columbus, Ohio, U.S.A. Dr. S. K. Ghosh.
4. International Institute for Aerial Survey and Earth Sciences (ITC), Delft. Dr. K. Kubik.
5. University of Illinois, Urbana, Illinois, U.S.A. Dr. H. M. Karara.
6. National Research Council of Canada. Mr. G. H. Schut.
7. Czechoslovakia, Prague, Czechoslovakia. Dr. V. Krátký.
8. Australian Photogrammetric Society. Mr. F. L. Bryant.
9. Geodetic Office of Survey Production Centre, R. E., Feltham, England. Mr. M. J. Miles and Mr. P. Verral.

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Reports from these nine participants in the Working Group have been received and analyzed. This paper constitutes a summary and analysis of the significant contributions of the Working Group participant's individual reports.

SIMULATED TEST BLOCK

A 9×20-block of simulated, near-vertical photography was made available to the Working Group participants.* This simulated block is composed of 180 fictitious photographs taken from approximately 11,000 meters above terrain containing up to 1,000 meters of relief. The camera focal length is 152.00 mm. resulting in an approximate photo scale of 1:65,000. Theoretically perfect (unperturbed) and perturbed plate coordinates are given to microns for an approximately rectangular array of 25 images per photograph. Plate coordinate perturbations consist of random normal deviates having a standard deviation of 6 microns plus a systematic displacement (20 microns maximum) to simulate radial lens distortion, film distortion, and other sources of systematic error. Theoretically perfect and perturbed positions are given for exposure centers and all ground points. Use of the complete set of data results in 9 strips having 60 percent side lap. Selection of odd-numbered or even-numbered flights provides 100 photograph and 80 photograph blocks, respectively, having 20 to 30 percent side lap. All forward overlap is 60 percent.

The guide lines accompanying each data set were minimal. The test block was divided so that nine different sizes of blocks could have been ordered. Participants were requested to report:

1. Mathematical formulation
2. Details of adjustment procedures
3. Results and error analyses
4. Time and cost factors
5. Conclusions

Participants were free to choose any size block with any combinations of pass points, overlap, and ground control. It was suggested that at least one adjustment be made with minimum control to test and compare procedures.

* The simulated block was generated with a program prepared by the Autometric Operation of the Raytheon Company for the U.S. Army Engineering Topographic Laboratories (USAETL), and was provided through the courtesy of Autometric-Raytheon Co. (15).

ANALYTICAL TRIANGULATION PROCEDURES TESTED

In general, the procedures tested can be divided into two major groups: (1) simultaneous adjustment of photographs: and (2) sequential adjustment.

GROUP 1. SIMULTANEOUS ADJUSTMENT OF PHOTOGRAPHS

This group includes those triangulation procedures in which the desired parameters are adjusted as a result of one simlutaneous least squares adjustment of strips or blocks by direct or iterative methods (1, 2, 3, 4 in list of participants, above). From the mathematical standpoint, methods of this group are more rigorous and should provide the most accurate results. An outstanding difference between these methods and sequential procedures is the need for estimates of exposures station positions and orientations prior to the simultaneous adjustment of the strip or block. In addition, estimates for coordinates of all pass points may be needed depending on the approach taken. As a consequence, simultaneous adjustment of photographs should include a feasible method for acquiring the required estimated values.

Participants engaging in the simultaneous adjustment are listed in Table 1 where the type of equation and method for the solution of normal equations are also tabulated.

GROUP 2. SEQUENTIAL ADJUSTMENTS

This group includes procedures most easily visualized as analagous to the instrumental process of aerotriangulation (5, 6, 7, 8, 9, 11 in list of participants). Thus, sequential adjustments consist of analytic:

a. Relative orientation and computation of individual basic units† in arbitrary, independent coordinate systems.
b. Assembly of basic units into a common coordinate system (this step may be concurrent with *a* above).
c. Adjustment of the assembled system to known control points.

Mathematical approaches for sequential adjustments are categorized according to respective relative orientation procedures and the method employed for strip or block adjustment. Further subdivision of the relative orientation procedure is achieved by sub-

† Basic unit, as used in this report, refers in most cases to the traditional stereopair or model. However, it can include 1×3, 3×3 or $m\times n$ photographs.

classification according to type of equation, basic unit, method of basic unit assembly, and adjustment procedure. These characteristics are summarized in Tables 2a and 2b for the sequential adjustments.

Test Block Data Selected and Objectives Pursued

A total of 20 test blocks having variable dimensions and selected from different portions of the simulated block were tested. In addition, 35 different ground control point configurations were used for adjustment of the various test blocks. A total of 72 tests were performed with various combinations of these blocks and control configurations.

Tests performed by the working Group include:

1. Studies of the effects of varying the:
   a. number and distribution of ground control stations;
   b. ground control position weights;
   c. per-centage of photographic sidelap;
   d. degree polynomial used for block adjustment.
2. Studies of the effectiveness of incorporating horizon data as control to strengthen adjustment of strips and blocks.
3. Comparison of:
   a. results from a simultaneous adjustment of photographs with results from a sequential adjustment of a common block and control configuration using the same computer;
   b. strip extensions performed with a three-photo basic unit with those from a two-photo unit;
   c. two different strip adjustment programs utilizing polynomials. (Schlund and US C&GS).
4. Testing and verification of a direct simultaneous adjustment of a strip or block by solving the equation system with function minimization by conjugate the gradient method.
5. Block adjustment in three dimensions using a linear transformation in a simultaneous least squares adjustment of the entire block.
6. Adjustment of heights in a block by the method of linear adjustment of sections using a direct simultaneous least squares adjustment.

Table 1. Simultaneous Direct Adjustment Summary Mathematical Procedures

Participant		Equations	System of Equations Solved by
No.	*Name*		
1	AMS	Modified Herget	Matrix Inversion
2	C&GS	Collinearity	Gauss-Cholesky Elimination
3	OSU	Collinearity	Matrix Inversion
4	ITC	Collinearity	Function minimization by Conjugate Gradients

Test Results

Test characteristics and results obtained using the simultaneous and sequential adjustments are summarized in Tables 3 and 4, respectively. Extreme caution should be exercised in attempts to compare results obtained by the nine participants. In addition to variable block dimensions and control point configurations, the number of check points utilized to calculate root-mean-square errors differs for practically all tests.

Additional items of interest output from simultaneous adjustments of photographs are: (a) standard deviations of unit weight s_o in plate coordinate residuals for the re-

Table 2a. Sequential Adjustments: Summary of Mathematical Procedures—Relative Orientation

Participant	Relative Orientation		
	Equation	*Basic Unit*	*Unit Assembly By*
5 5	Collinearity Collinearity	2-photo 3-photo	Successive Rotation & Scaling
6	Coplanarity	2-photo	Concurrent with Relative Orientation
7	Not Specified	2-photo	Successive Rotation & Scaling
8	Coplanarity	2-photo	Successive Rotation & Scaling
9	Coplanarity	2-photo	Not Specified
1	Coplanarity	2-photo	Concurrent with Relative Orientation

TABLE 2b. SEQUENTIAL ADJUSTMENTS: SUMMARY OF ADJUSTMENT PROCEDURES

Participant	*Adjustment Procedure*				
	Degree Equation			*Remarks*	*Iterations Required*
	Linear	*2nd*	*3rd*		
5 5		XY, Z XY, Z	XY, Z XY, Z	Strip adjustment, only Sequential XY and Z	Direct Solution
6		XY, Z XY	 Z XY, Z	Iterative block adjustment of strips Sequential XY and Z	Block Adjustment 6–10
7	XYZ			Linear, simultaneous block adjustment of strips in 3 dimensions. Iterative solution of normal equations	Strip: 4 Block: 6–10
8	Degree not specified in XY		Z	Horizontal block adjustment Followed by polynomial strip adjustment	Direct Solution
9	XYZ			Block adjustment by linear method of sections. Sequential XY and Z. Block height adjustment preceded by 2nd degree polynomial	Direct Solution
1		XY, Z	 XY, Z	Strip adjustment same as Participant 5. In block adjustment, strip tie points included in normal equations	Strip Adjustment Direct Solution

spective adjustments (where reported); and (b) iterations required for convergence. Note that values for s_o vary from 1.5 to 4.5 microns and are significantly different from applied perturbations having $\sigma_o = 6$ microns. Consequently, inconsistencies in simulated and/or applied perturbations are indicated. As the tests with unperturbed data yielded reasonable values for s_o of from 0.3 to 0.8 microns, the most likely cause of inconsistency is in the random normal deviates applied to plate coordinates.

COMPUTER STORAGE AND TIME REQUIREMENTS

Tables 5a and 5b show approximate data for storage and time requirements based on reported figures. The tabulated times *do not* reflect data preparation or manual analyses of results.* As nearly as this reporter can deduce, these times represent only the so called *central processor* time for which the highest rate is usually charged.

* Times/photo as given are averages for all runs where sufficient data were reported.

Maximum available core storage varies from approximately 7,000 words to 131,000 words, where word is a nominal value that can be interpreted differently for various computers. Times vary from of 0.06 to a maximum of 4.0 minutes per photograph. Observe that both of these extremes resulted from simultaneous adjustments of photographs. Also note that the minimum time was from an adjustment on the current generation of an extremely high-speed computer.

Comparisons among procedures are meaningless due to the variable characteristics of the computer systems. However, Participant 1 performed both the sequential and the simultaneous ajdustment of photographs of a common block on the same computing system. This pair of runs (Tests 2 3, and 4, Table 3; Tests 53, 55 and 57, Table 4) provides a valid comparison and reveals that the sequential method requires about one third the computer time needed for the simultaneous adjustment of photographs. This comparison constitutes the only sound, specific conclusion to be reached from data in Tables 5a and 5b.

TABLE 3. ROOT MEAN SQUARE ERRORS IN DISCREPANCIES; SIMULTANEOUS ADJUSTMENTS OF PHOTOGRAPHS

Participant	*Test No.*	*Tie Point*		*No. Check Pts.*	*RMSE* meters*				*Iterations*	*So Microns*
		Horiz.	*Vert.*		*Sx*	*Sxy*	*Sy*	*Sz*		
1	1	5	5	478	.57	.77	.52	.69	1	
	2	18	18	465	.56	.77	.52	.68	1	
	3	24	24	459	.57	.76	.51	.68	1	
	4	99	99	384	.51	.69	.46	.66	1	
2	5	8	14	96		.95		1.41	2	1.6
	6	8	14	96		.95		1.41	1	1.6
	7	16	20	90		.68		.70	1	2.8
	8	16	20	90		.67		.76	1	3.5
	9†	8	14	96		.95		.41	2	1.9
	10	4	4	106		.89		1.19	1	1.6
	11	8	8	102		.81		.55	1	1.9
	12	8	9	101		.81		.58	1	1.9
	13	8	13	97		.82		.52	1	2.0
	14	4	9	101		.86		.79	2	1.7
3	15	4	4	21	.6	.8	.6	1.2		
	16†	4	4	21	.6	.9	.7	.5		
	17	4	4	22	.9	1.1	.6	.6		
	18†	4	4	21	.9	1.1	.6	.6		
	19	4	4	27	.7	1.1	.8	3.3		
	20†	4	4	27	.6	.9	.7	.5		
	21	4	5	27	.6	1.0	.8	1.3		
	22	4	4	59	.9	1.2	.8	11.9		
	23†	4	4	59	.8	1.3	1.0	1.2		
	24	4	5	58	.9	1.1	.7	.7		
	25	4	4	27	.7	1.1	.8	3.3		
	26††	4	4	27	.6	1.0	.8	.6		
	27	4	4	59	.9	1.3	.9	11.9		
	28††	4	4	59	.8	1.1	.8	1.3		
4	29	15	15	45	.8	1.1	.7	.6	200	4.2
	30	10	15	90	1.1	1.4	.8	1.3	200	4.6
	31	10	15	130	1.4	1.7	.9	1.5	150	4.5

* RMSE (root mean square error) = $(\Sigma v_n^2/n)^{1/2}$ where v_n = true value − adjusted value, and n = number of points checked.

† 60% Side lap.

†† Horizon data used for control.

SUMMARY OF CONCLUSIONS

Major conclusions reached by participants can be summarized as follows:

1. Simultaneous adjustment of the one test block on the same computer produced RMS Errors 37 and 64 percent smaller in planimetry and heights than were obtained with a sequential adjustment (Tests 2, 3, 4, Table 3; Tests 53, 55, Table 4). Three times the computer time was required for the simultaneous adjustment.
2. Use of 60 percent sidelap improves vertical accuracy (Test 5, 9, Table 3).
3. Strong perimeter control is more effective than addition of interior points in a block (Tests 5, 7, Table 3).
4. Increasing position weights from 2 to 3 improved fit to control points but did not alter the accuracy of computed additional points.
5. The conjugate-gradient method of function minimization requires moderate time on a medium sized computer and resulted in realistic discrepancies for a 3×20 block (Tests 29, 30, 31, Table 3).
6. Use of horizon data as control, improves accuracy in both medium sized blocks (15 to 28 photos) and 13-photograph strips. (Tests 26, 28, Table 3).
7. The three-photo basic unit yields a significantly less warped strip than the corresponding strip triangulated with a two-photo basic unit for the case of minimum control. Use of the three-photo unit produces no significant improvement if redundant well placed ground

TABLE 4. ROOT-MEAN-SQUARE ERRORS IN DISCREPANCIES SEQUENTIAL ADJUSTMENTS

Participant	*Test No.*	*No. Check Pts.*	*Grd. Control Points*		*Degree Polynomial*			*RMS meters*				*Remarks*
			XY	*Z*	*XYZ*	*XZ*	*Z*	*Sx*	*Sxy*	*Sy*	*Sz*	
6	32	195	6	18		2	2				.94	Strip Mean (*UTM Coordinates*)
	33	195	6	18		2	2				.93	Block Mean
	34	195	8	24		2	3	.99	1.35	.92	.90	Strip Mean
	35	195	8	24		2	3	.95	1.30	.89	1.35	Block Mean
	36	195	8	24		3	3	.90	1.46	1.15	.85	Strip Mean
	37	195	8	24		3	3	.88	1.44	1.12	.85	Block Mean
	38	195	6	18		2	2				.91	Strip Mean
	39	195	6	18		2	2				.90	Block Mean
	40	195	8	24		2	3	.95	1.42	1.05	.92	Strip Mean
	41	195	8	24		2	3	.91	1.38	1.04	.91	Block Mean
	42	195	8	24		3	3	.76	1.12	.83	.85	Strip Mean
	43	195	8	24		3	3	.71	1.07	.81	.86	Block Mean
7	44	400	14	14	1st			.75	1.40	1.18	.95	Secant Plane
	45	400	14	14	1st			.75	1.42	1.20	1.03	UTM
	46	400	18	18	1st			.69	1.25	1.04	.94	Secant Plane
	47	400	24	24	1st			.61	1.01	.80	1.07	UTM
	48	400	24	24	1st			.61	.99	.78	.87	Secant Plane
8	49	400	9	32	Not Specified		3	.92	1.45	1.11	.54	UTM Coord.
9	50	1		18		1	2	Not given			.9	Height Adjustment,
	51	—		12		1	2	Not given			.7	only
1	52	400	18	18		2	2	.82	1.03	.62	1.87	Strip Mean
	53	400	18	18		2	2	.90	1.21	.80	2.03	Block Mean
	54	400	24	24		2	2	.75	1.10	.64	2.24	Strip Mean
	55	400	24	24		2	2	.84	1.19	.84	2.41	Block Mean
	56	300	99	99		2	2	.71	1.00	.70	1.77	Strip Mean
	57	300	99	99		2	2	.78	1.13	.83	1.89	Block Mean

TABLE 5. SUMMARY OF COMPUTER STORAGE AND TIME REQUIREMENTS

(a) Direct Simultaneous Solutions

Participant	*Maximum Core Storage Available (words)*	*No. Photos Processed*	*Time Minutes/Photo*
1	32,000	50	2.3
2	131,000	90	0.06
3	32,000	210†	4.00
4	16,000	60	0.95

(b) Sequential Solutions

Participant	*Maximum Core Storage Available (locations)*	*No. Photos Proc.*	*Approximate Time Minutes/Photo*			
			Rel. Orien. Unit Assemb.	*Adjustment*	*Other*	*Total*
1	32,000	50				0.8
5	≃40,000	100				
6	8,190	100	0.30	0.20		.50
7		100	0.20	1.40		1.60
8	32,000 3,000–8,000	100	0.03	2.70		2.73
9	7,168	100	0.70	1.20	1.10††	3.00

† Includes 10 separate runs of from 10 to 49 photo blocks.

†† Extra run for gross error detection.

control points are available and higher-degree adjustments are performed (Participant 5).

8. Tests on the same computer revealed no significant difference between the Schlund and the US C&GS methods of strip adjustment (Participant 5).
9. The iterative block adjustment of Participant 6 converged rapidly (8 to 10 iterations) because each iteration was started with two outside strips containing planimetric control. Experiments with this same adjustment confirm that increasing the degree of the adjustment equations does not necessarily improve results and may cause increased discrepancies (Tests 34, 36 and 35, 37, Table 4). Under certain conditions, a higher-degree adjustment does improve results as illustrated by Tests 41 and 42 where a systematic third-degree variation in scale was corrected by introducing a third-degree planimetric adjustment.
10. The simultaneous, three-dimensional, linear block adjustment (Participant 7, Tests 44, . . ., 48) converged in 5 to 10 iterations using a Gauss-Seidel iterative solution of the normal equations. Note that results obtained with this linear adjustment are comparable to those produced by adjustments with polynomials.
11. A block height-adjustment by the method of linear adjustment of sections (section = 2 adjacent, 2-photo units), yielded results sufficiently accurate for contouring at a 10-meter interval with 1:60,000 photography in which lateral control is spaced at 45- to 50-kilometer intervals (Test 50, Table 4). Ground control at 10-model intervals in analytic strip triangulation provides results in height control equal in accuracy to that obtained by a complete block adjustment (Test 51, Table 4).

If the efforts of the Working Group are considered as a unit, several interesting conclusions can be drawn. First, readers should avoid making specific, direct comparisons between different procedures on the basis of the reported results—too many variables exist between the testing procedures to reach other than very general conclusions.

Secondly, if one selects the maximum root-mean-square errors of discrepancies from the entire series of tests, the height accuracy achieved is 1/8,000 of the average flight elevation (11,000 meters) and planimetric accuracy is 1/40,000 of the least dimension (60,000 meters) of the 100 photo block. Where the minimum values of root-mean square-errors are considered, these ratios are 1/20,000 and 1/70,000, respectively. If one accepts the hypothesis that the simulated model does provide a reasonable facsimile for a real block of photography, then fully analytic triangulation systems are quite feasible for small-scale mapping projects where the photography and ground control are of high quality. In making this evaluation due regard should be given to evidence indicating inconsistencies in the simulated data or in the random normal perturbations applied to plate coordinates (see Test Results).

Thirdly, as one would have expected, the method of simultaneous adjustment of photographs produced more accurate results at a generally higher cost. The exception to this cost differential was a simultaneous adjustment of photographs performed on a very large and fast computer (Part. 2, Table 5). As such computers become more common, this time differential will be of less consequence. In this respect, additional work should be devoted to iterative solutions of large systems of normal equations as applied to the block adjustment. Also, efforts should continue to be pursued in further development of the conjugate-gradient method of function minimization as applied by Participant 4 of the Working Group.

However, the bookkeeping problems and need for sequential methods to provide estimates still remain. If such sequential adjustments result in the same excellence as exhibited in the examples furnished by this Working Group, then the need for further refinement in a simultaneous adjustment of photographs would not be warranted except for unusually large networks where extraordinary accuracy is required.

Finally, the simulated data block appears to be an excellent vehicle for experimental research in analytic triangulation and block adjustment. For example, a simulated block would be the ideal form of data for use in research directed toward establishing realistic specifications for the observed quantities used in analytic photogrammetry. This is an area not yet fully explored for fully analytic triangulation and adjustment systems and deserves further attention.

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Articles for Next Month

Peter Bock and *J. G. Barmby*, Survey effectiveness of spacecraft remote sensors.
J. M. Burnham and *P. R. Josephson*, Color plate stability.
Clifford J. Crandall, Radar mapping in Panama.
W. P. MacConnell and *Peter Stoll*, Evaluating recreational resources of the Connecticut River.
P. M. Merifield et al., Satellite imagery of the Earth.
R. K. Moore, Heights from simultaneous radar and infrared.
Paul E. Norman, Out-of-this-world photogrammetry.
J. T. Parry et al., Color for coniferous forest species.

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