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Large Block SAPGO Program*

Aerotriangulation with simultaneous adjustment of photogrammetric and geodetic observations is free from many of the former physical restrictions.

ABSTRACT: *The mathematical description of the* SAPGO *program has been presnted at prior meetings of the American Society of Photogrammetry. The computer program is designed to rigorously, yet efficiently, process large numbers of photographs with supporting geodetic and sensor information. Features of the program are automatic band-width computation, recursive partitioning algorithm for the solution of the normal equations matrix, and the use of direct access for all the data storage and retrieval. Since the first coding and testing of the program its adaptability has been demonstrated for practical aerotriangulation exercises. Modifications for special applications have been made on the UNIVAC 1108 computer at the Defense Mapping Agency Aerospace Center. This paper defines these modifications, with a subsequent description of the program utilization. The relationship of the number of photographs processed, band-width considerations, irregular strip configurations, and computer processing times are also discussed for a number of block aerotriangulation projects.*

INTRODUCTION

COMPUTER SOFTWARE to perform the simultaneous adjustment of large photogrammetric blocks have been developed at the University of Illinois. These programs are called SAPGO-MFL and -L. The common prefix SAPGO is used to associate all the programs to the same project[5] and the suffix-MFL signifies the *multiple focal length* version and -L signifies the *lunar* version. The primary difference between the two versions is the coordinate system in which the adjustment is performed. The SAPGO-MFL version uses a local space rectangular coordinate system and the -L version uses a selenocentric coordinate system.

The large block SAPGO programs have a unique structure which provides them with capabilities that are not available with current computer software. The two most outstanding capabilities are the lack of restrictions on block configuration and the efficiency of the programs. Test blocks have been processed which demonstrate each program's capabilities. A large photogrammetric block of 500 photographs with normal block configuration, and two blocks of 273 and 167 photographs with abnormal block configurations, have been processed using SAPGO-MFL. The Apollo 15 block of 625 photographs was processed using SAPGO-MFL. The ratio of the computer processing time to the wall-clock time, or the efficiency of the program, for all these blocks never exceeded 1.5; that is, each minute of central processor time requires at most one and one-half minutes of clock time.

PROGRAM DEVELOPMENT AND CHARACTERISTICS

The data storage and manipulation techniques developed for the SAPGO programs are

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responsible for the tremendous flexibility and efficiency of the programs. The use of direct access data files simplified the data storage problems and is responsible for the development of data manipulation schemes. These schemes sort incoming data and place it in direct access storage locations which are sequenced with the data processing scheme. Hence, as the processing begins, it is in a sequential order through the direct access data files.

DATA STORAGE

The use of direct access files allows a Fortran programmer to use temporary disk or drum storage as a simple extension of core storage. This technique is used in both of the large block SAPGO programs for all the mass data storage. Data Files are defined for pass point, exposure station, and reduced normal equations data. All of the data associated with each pass point define the pass-point data-file record length, likewise for the exposure station and reduced normal-equations files.

Direct Access Data Files. The direct access data files are reserved by using a special Fortran statement called DEFINE FILE. This statement reserves disk or drum storage for a temporary data file. Each record of that file may be accessed directly from the Fortran source program.

The DEFINE FILE i (j, k, U, N),
i. Unit Number.
j. Number of data records in the file.
k. Length of each file in data words.
U. Code which specifies the data to be unformatted.
N. Integer variable used to point to the next record after each READ or WRITE statement.

A record from a file is transferred into core by a standard Fortran READ or WRITE statement with a slight variation. The actual record number to be read replaces the format statement number and an apostrophe replaces the comma separating the file number and the record number. As an example:

```
DEFINE FILE 1 (10, 20, U, N1)
DIMENSION X (20)
.

.
I = 3

WRITE (1' I) X
.

.
I = 2
READ (1' I) X
```

The DEFINE FILE statement reserves ten records of unformatted data on unit one, with each record being 20 words long. The WRITE statement transfers the data from array *X* to the third record of unit one. The READ statement transfers the data from unit one, record two, to the array *X*.

Definitions of SAPGO Data Files. There are three basic divisions of data within SAPGO. These include pass point, exposure station, and the reduced normal equations data. The individual record of each direct access file is made up of all the data associated with that particular element. The direct access approach is required in each division because the natural collection of data does not correspond to the program processing sequence.

A *pass point* may be measured on several photographs and will have a set of image coordinates associated with each photograph. All the image coordinates and corresponding exposure station numbers for a given pass point are stored in a pass-point record. This record also contains the updated ground coordinates of the point, the total corrections applied, the actual point number, the type of point, and the weight matrix for that point.

The length of the pass-point record depends on the maximum number of photographs and SAPGO-L is 20. The larger number for the lunar version was required to handle the overlap of the orbits. The total record length for SAPGO-MFL is 51 words and SAPGO-L is 81 words.

The maximum number of points in a photogrammetric block is limited only by the amount of temporary disk or drum storage available. The amount of auxiliary storage is normally quite large; therefore, there is no limit to the amount of pass points that may be processed.

Exposure station data are divided into two files. The first file contains the ground coordinates, orientation elements, total corrections applied to each variable, actual exposure station number, and a pointer to identify which focal length to use. The second file contains the weight matrix for the exposure station parameters. The weight matrix is not needed as often as the other data; hence it is stored separately.

The reduced normal equations are of the general form $\mathbf{N}\dot{\delta} = \mathbf{D}$; where **N** is the reduced normal equation matrix, $\dot{\delta}$ is the matrix of vector corrections for each exposure station, and **C** is the constant term. The actual structure of **N** for a standard photogrammetric block is banded about the diagonal as shown

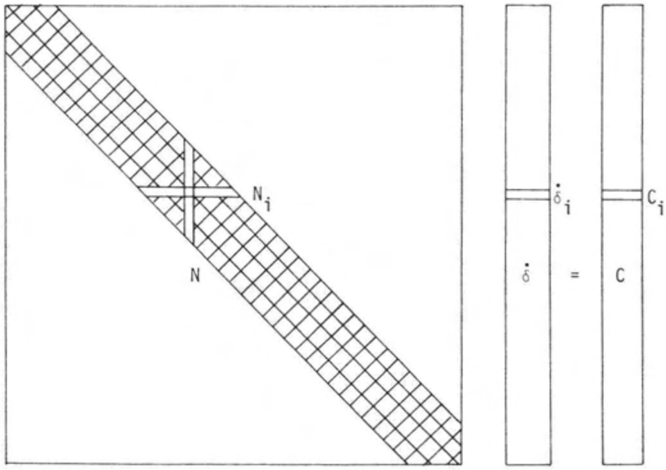

FIG. 1. Reduced normal-equations matrix.

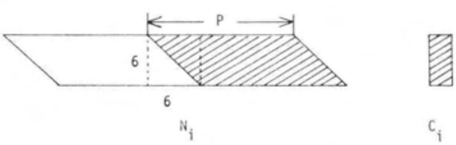

FIG. 2. Partition of the reduced normal-equations matrix for the i-th exposure station.

in Figure 1. This is one of the characteristics of N which implifies the matrix storage problem. The matrix **N** is also symmetric and its size is a multiple of the number of exposure stations. The six unknowns for each exposure station make a natural partition of **N** for storage and retrieval purposes in rows with six rows per partition.

The normal-equations matrix associated with the i-th exposure station is shown in Figure 2. The actual portion of the matrix that is stored is shown with the hashed lines. The partition N_i of N is stored as a 6×6 matrix and **C** as a 6×1 matrix. The bandwidth P is variable and may change with each block adjusted. Hence, the DEFINE FILE statement must reserve sufficient space to handle the maximum bandwidth anticipated. This waste of storage space is one of the disadvantages of the direct access storage scheme.

DATA SORTING

The sorting schemes used in SAPGO are responsible for the flexibility and efficiency of the programs. The sorting procedure arranges the exposure stations and pass points into a logical order. This minimizes the bandwidth of the reduced normal-equations matrix, which in turn reduces the processing time. The flexibility is attained by sorting the input data into pre-assigned storage locations. These locations are sequenced to follow the processing algorithm rather than the natural flow of input.

Sorting Exposure Stations and Pass Points. The logical order of the exposure stations is defined as the order that minimizes the bandwidth of the reduced normal-equations matrix. Correlation between exposure stations occurs if points have been measured on two or more photos. This fact aids the sorting scheme because only overlapping photographs are correlated.

The logical order of the pass points is defined by the logical order of the exposure stations. The pass points are sorted first according to their minimum logical exposure station number and secondly according to their maximum logical exposure station number.

The logical order of the pass points and exposure stations define their record number for the direct access data files. All of the computational steps within the program follow the logical order of the pass points and exposure stations.

A thorough discussion of the sorting of pass points and exposure stations to minimize the bandwidth is given in a previous publication.[4]

Data Manipulation Within SAPGO. The adjustment of a large photogrammetric block requires the processing of large amounts of data. The efficiency of the computational algorithm depends on the proper arrangement of data. This eliminates the need to search through data files or to duplicate storage of data. The sorting schemes used in SAPCO are designed around the computational algorithm, not around the collection scheme. This algorithm adapted for SAPCO was first proposed by Brown[1].

The problem in sorting photogrammetric data is in the way it is collected. Normally, photogrammetric data are collected in a sequential order down a strip of photographs. If a point is common between two strips, then all the data for that point is not available until the second strip is processed. This eliminates the use of sequential data files for SAPCO storage, because all the data for one point on two long strips could not be collected together.

Third-generation computers offer a direct access technique for the storage of data. Using this technique, which was described earlier, the loading of the data files is simplified. Data for a small number of pass points are accumulated in memory storage. Before a pass point on a photograph is added to the list of pass points, a check is made to locate a pass point already in core, but not located on the photograph being processed. When such a point is located, it is stored in its direct access location and the new point is transferred to its location.

The best way to explain the process is to go through a step-by-step analysis of the actual process using a flow chart. The arrays presented in Figure 3 symbolize the array used in the program. These arrays are defined as:

MASTER ID ARRAY. The logical list of actual pass point numbers. The location of a pass point number in this array defines the record number of the pass point on the direct access disk storage.

CORE ID ARRAY. List of actual pass point numbers located on the photograph currently being processed. The location of a pass point number in this array defines the location of the image coordinates for that point in the model arrays.

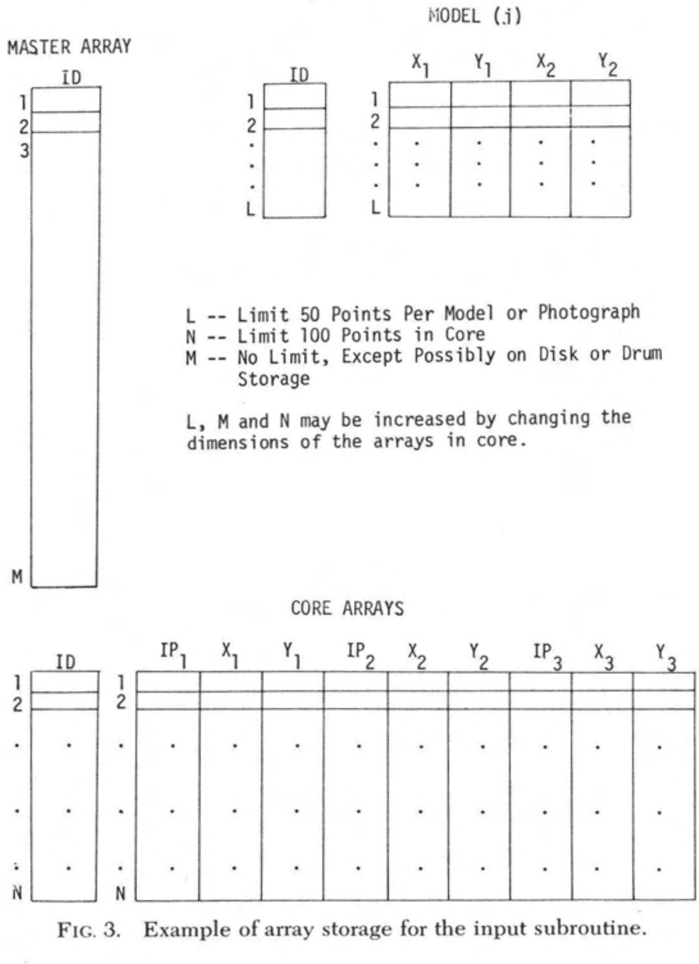

FIG. 3. Example of array storage for the input subroutine.

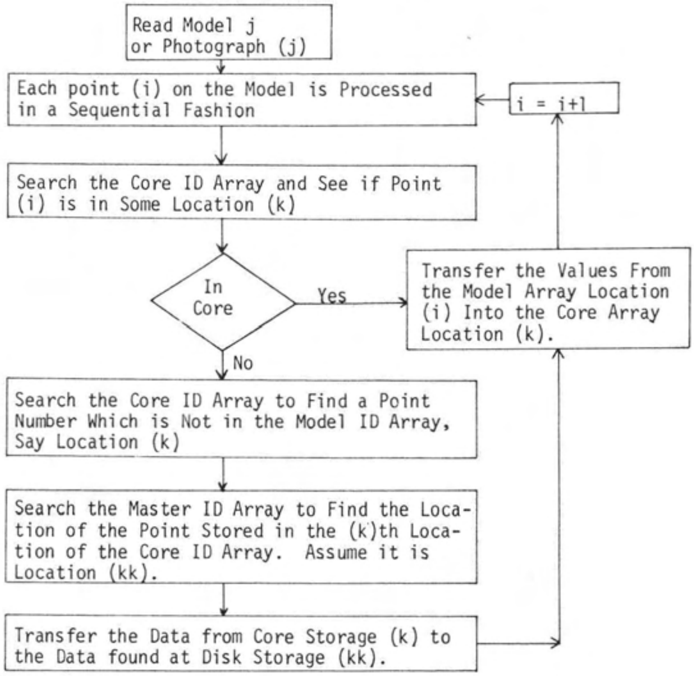

FIG 4. Flow chart for image coordinate sorting.

MODEL ARRAYS. Contain the x and y image coordinates for the photograph being processed.

CORE STORAGE ARRAYS. Contain the image coordinates and exposure station numbers for each pass point currently being processed and stored in memory.

The flow chart in Figure 4 gives the sorting of all the pass points on model or photograph (j). One interesting point in the scheme is that at any one time the core storage arrays does not have more points than the maximum number of pass points found on any one photograph or model. This may be demonstrated by observing Figure 5. If model 1-2 is being processed, points 1-10 are transferred to memory in the first 10 locations of the core storage arrays. As model 2-3 is being proccessed, points 6-10 are in memory, but points 11-15 are not. Instead of creating additional memory storage for points 11-15, they are transferred into the memory locations occupied by points 1-5 after these points have been transferred to direct access storage.

The combination of sorting scheme and direct-access storage has given SAPGO the following capabilities:

- There is no limit to the number of pass points or exposure stations that may be processed except where the available temporary disk storage is limited.
- There is no maximum limit to the number of pass points per photograph.
- Photographs may be processed in any order.
- Points may be duplicated on a photograph (two cards with the same image coordinates for one point) or even photograph data may be loaded more than once.
- A large photogrammetric block may be divided into separate sub-blocks and adjusted separately; then for the complete block solution, the sub-block data may be stacked end to end.

A similar type of sort is used constantly in the program to keep the exposure station data current in core. As point i is being processed, it has an exposure station associated with it. Rather than read all the data associated with each point, a group of exposure stations are kept in core all the time. The number of exposure stations in core is equal to the bandwidth and are kept current by the scheme described earlier.

If the number of exposure stations in core is equal to the bandwidth, the exposure station data is called into core once for each computational cycle. That is, the points are arranged in such an order that a point-by-point processing also produces a photograph-by-photograph processing.

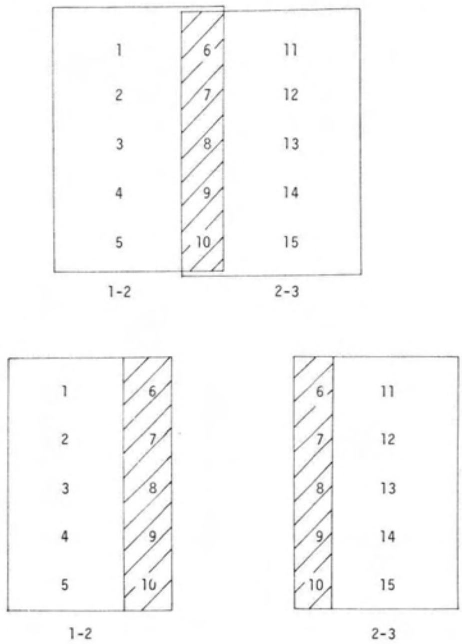

FIG. 5. Example of common points on two stereomodels.

SOLUTION OF REDUCED NORMAL EQUATIONS

The solution algorithm chosen for the SAPGO programs is the standard recursive partitioning algorithm. It has been discussed in previous papers[3] so it will not be repeated at this time. The algorithm is a simple variation of the fundamental Gauss elimination method of solving linear equations. It recognizes the fact that the zero elements located outside of a diagonal band in a banded matrix remain zero throughout the elimination process.

The algorithm was programmed using direct-access data files for the storage and manipulation of data. These data files are prepared to simplify the data handling process in conjunction with the solution algorithm.

PROGRAM TESTING

There are currently two versions of SAPGO for large photogrammetric blocks in use and a third version is being developed. Each version is limited in the number of strips it can process but is not limited by the number of exposure stations or pass points. The different versions are required to accommodate a wider range of photography and to expand its operational capability. Each version has a common program structure so that the tests performed on one version need not be repeated for each version. The primary difference in the versions is the input data. These differences are tabulated in Table 1.

There are several programs capable of a simultaneous photogrammetric block solution available for the photogrammetrist. They all produce similar results and have the same basic mathematical model. The objective of the SAPGO program tests is to demonstrate the unique capabilities of the SAPGO programs.

TESTS WITH GENERATED DATA

The tests with generated data were designed to demonstrate the efficiency and accuracy of the large block SAPGO solution. Four photogrammetric blocks were generated at a photographic scale of 1:25,000 and a focal length of 6 inches. There were two blocks of 100 photographs and two of 500 photographs. The data generator incorporated in the SAPGO-P program provides all the photogrammetric data necessary for a block solution in

TABLE 1. COMPARISON OF INPUT DATA FOR SAPGO-MFL AND -L.

PARAMETER	SAPGO-MFL	SAPGO-L
Camera Systems	20	1
Exposure Station Position	LSR, USR or Geographic	Selenocentric or Selenographic
Orientation Elements	LT Angles, USR Orientation Matrix or USR Angles	USR Angles or USR Orientation Matrix
Adjusted Coordinate System	LSR	Selenocentric
Ground Control	LSR, USR or Geographic	Selenocentric or Selenographic

LSR—Local Space Rectangular
LT—Local Tangent
USR—Universal Space Rectangular (Geocentric)

TABLE 2. PARAMETERS OF THE PHOTOGRAMMETRIC BLOCKS GENERATED FOR SAPGO-P.

DATA SET	1	2	3	4
Focal Length	152.0 mm	152.0 mm	152.0 mm	152.0 mm
Photographs	100	100	500	504
Strips	4	4	5	12
Points/Photograph	9	25	9	9
Points	225	833	1100	1050
Control Points	16	32	48	44

TABLE 3. PERTURBATION OF VARIABLES IN THE GENERATED BLOCKS FOR SAPGO-P

Variable	Perturbation	Variable	Perturbation
X^c	5M	X	0.001 M
Y^c	5M	Y	0.001 M
Z^c	5M	Z	0.001 M
ω	20″	x	0.006 mm
ϕ	20″	y	0.006 mm
κ	20″		

the proper sequence for the program. The description of the four data sets is given in Tables 2 and 3. The perturbation of each variable was kept small so that one iteration was sufficient for the block solution.

The central processor time (or CPU time) required for each step of the adjustment process is recorded for each data set in Table 4. The accuracy of the block solution was examined by comparing the derived values of the pass points to the actual values for the data generator. The standard error and circular error of these comparisons are also presented in Table 4. The 6-micrometer perturbation at photographic scale produced a 0.15-meter pertubation at ground scale. This was very close to the computed standard error of the ground coordinates except for data set four.

The efficiency of the block solution was one of the significant results of the SAPGO test. The ratio of CPU time to clock time never exceeded 1: 1.5. This small ratio is extremely important before a very large photogrammetric block reduction, which requires several hours of CPU time, could be accomplished.

Data sets 1 and 2 were identical except for the number of pass points. Data set one had nine points per photograph, but data set 2 had 25 points per photograph. The increase in the number of points improved the accuracy of the derived pass points and significantly increased the CPU time required. The CPU time required to build the normal equations and to update the parameters was directly proportional to the number of pass points in the

TABLE 4. STANDARD ERROR OF THE DERIVED PASS-POINT COORDINATES IN METERS AND A BREAKDOWN OF THE CPU TIME REQUIRED FOR ONE ITERATION OF THE SAPGO-P SOLUTION.

DATA SETS	1	2	3	4
σ_x	0.15 M	0.14 M	0.10 M	0.24 M
σ_y	0.18 M	0.13 M	0.11 M	0.25 M
σ_z	0.54 M	0.34 M	0.29 M	0.45 M
σ_{xy}	0.24 M	0.19 M	0.14 M	0.36 M
Check Points	209	801	1052	1006
Bandwidth	10	10	12	26
CPU Time to Build Equations	29^s	1^m7^s	2^m31^s	2^m42^s
CPU Time to Solve the Normal Equations	54^s	46^s	5^m13^s	19^m20^s
CPU Time to Update the Parameters	24^s	58^s	$2^m\ 8^s$	2^m33^s
Total CPU Time	1^m47^s	2^m50^s	9^m52^s	24^m16^s

photogrammetric block. A 25-point pattern for data set 3 approximately doubled the total CPU time, but for data set 4, it changed the total CPU time to approximately 32 minutes instead of 24.

The importance of the bandwidth was demonstrated by a comparison between data sets 3 and 4. The number of pass points and exposure stations were approximately the same but the bandwidth was doubled. This quadrupled the CPU time required to solve the normal equations.

TESTS WITH LARGE ABNORMAL BLOCKS

The tests for program SAPGO-MFL were designed to demonstrate the capability of performing a simultaneous solution of photographs obtained with several different camera systems. The different camera systems normally implies that the photographs are taken at different times of the year with different flight patterns and altitudes. The ability of the SAPGO-MFL version to accommodate all these differences is one of the outstanding capabilities of this program.

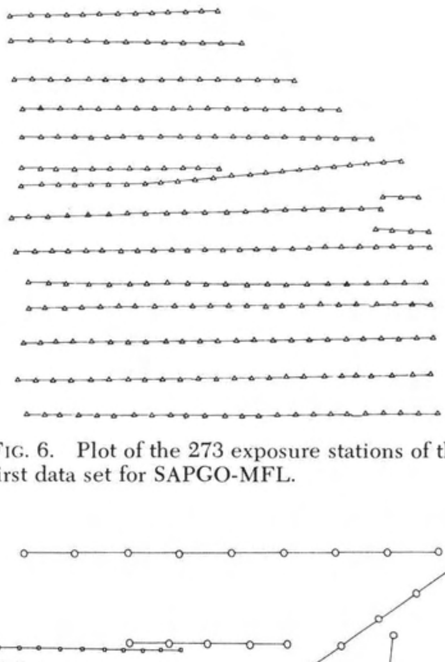

FIG. 6. Plot of the 273 exposure stations of the first data set for SAPGO-MFL.

FIG. 7. Plot of the 167 exposure stations of the second data set for SAPGO-MFL.

The two data sets chosen to test SAPGO-MFL were actual photogrammetric blocks. The first data set contained 273 exposure stations with six different camera systems. The flight lines were parallel to each other and their flying heights were very similar. A plot of the exposure stations for this block is presented in Figure 6.

The second data set was a very challenging photogrammetric block for any program. It contained 167 exposure stations, 2 sets of perpendicular flight lines and one diagonal, 4 different camera systems and 2 different flying heights. A plot of the exposure station positions is presented in Figure 7.

The ground control for these blocks was provided from 1:50,000 AMS map source. Photo-identifiable points were used as the horizontal control and the map elevations of pass points in the blocks were used as the vertical control. Additional horizontal control was provided on the north and east side of each block from previous aerotriangulation projects. The map-derived horizontal control was assigned a standard error of ±40 meters and the previously derived points were assigned a standard error of ±10 meters. The vertical control consisted entirely of map elevations. The contour interval of the map source was 10 meters, so all the vertical points were assigned a standard error of ±5 meters.

The most difficult portion of the adjustment process for these two data sets was the determination of the logical sort of the exposure stations. In both blocks no attempt was made to determine the logical sort of the exposure stations that yielded the minimum bandwidth. Rather, the objective was to sort the exposure stations in such a way as to yield a bandwidth within the maximum allowable for program SAPGO-MFL. It required several passes through program BANDWIDTH[4] with different exposure station sorts before a useable bandwidth was attained. The number of passes through the program was affected by the complexity of the block configuration.

The parameters for these two data sets are given in Table 5, along with some analysis of the results. Unfortunately, these data sets

TABLE 5. RESULTS OF THE BLOCK ADJUSTMENT OF THE TWO DATA SETS FOR SAPGO-MFL.

DATA SET	1	2
Cameras	6	4
Photographs	273	167
Points	1771	1457
Strips	16	19
Bandwidth	32	34
Horizontal		
±10 M	40	45
±40 M	85	61
Vertical		
±5 M	125	106
Residual Error of Image Coordinates	12 μm	16 μm
σ_x Image	20 μm	20 μm
σ_y Image	20 μm	20 μm
Circular Error $m_{\phi,\lambda}$	±3.0 M	±4.4 M
Vertical m_h	±2.5 M	±3.8 M
Total CPU Time/ Iteration	23^m	15^m

μm, micrometers; M, meters; m, minutes.

were not located over some test range; consequently a thorough analysis of the derived data was not possible. The circular error and vertical error presented in the table were determined by comparing common data points between different strips. The coordinates of the points used in the comparison were computed from the derived exterior orientation parameters of the photographs.

Even without a rigorous evaluation of the derived data, these data sets demonstrate a very unique capability of the SAPGO programs in processing material at different photographic scales and block configurations.

APOLLO 15 PHOTOGRAMMETRIC BLOCK

The test data for the SAPGO-L version was the Apollo 15 photogrammetric block. There were approximately 1,760 photographs in the complete block, but only 625 were required to produce full stereo coverage over the complete area. This was the size of the final block solution. The area covered by this block included 200 degrees of longitude and 45 degrees of latitude. A plot of exposure station positions is given in Figure 8. This plot shows the convergence of the orbital strips on each end and the maximum separation in the middle. It includes only the final 625 photographs that were adjusted with SAPGO-L.

There were three unique problems with this data set: (1) the convergence of the orbits on each end of the block; (2) the lack of measured ground control; and (3) the total area covered. The convergence on each end of the block caused a point to be located on as many as 18 photographs. In a normal photogrammetric block the maximum expected number of photographs for a point to be located in is 9. The SAPGO-L version was designed to handle 20 photographs per point.

The control for the block consisted of the exterior orientation data for each exposure station. The position of each exposure station was provided by NASA and the orientation elements were provided by the Defense Mapping Agency Aerospace Center (DMAAC). Table 6 gives all the Apollo 15 block parameters, including the standard errors assigned to the exterior orientation parameters. The position elements were the weakest of the exterior orientation parameters; consequently, only the center strip was held to 200 meters in latitude and longitude and 50 meters in height. The remaining strips were allowed to adjust to the center strip. Two other

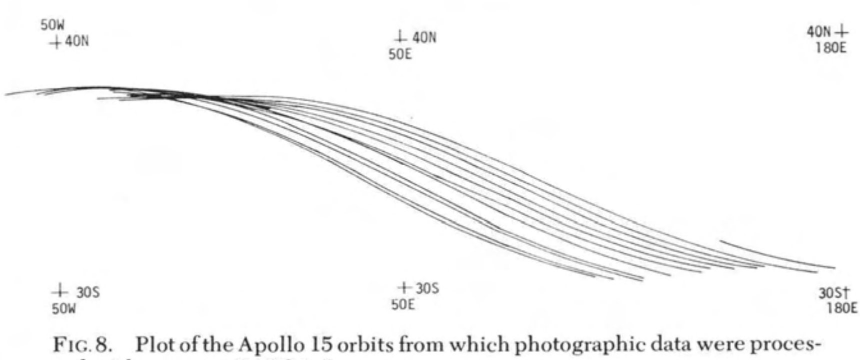

FIG. 8. Plot of the Apollo 15 orbits from which photographic data were processed with program SAPGO-L.

TABLE 6. PARAMETERS OF THE APOLLO 15 DATA SETS FOR SAPGO-L.

DATA SET	1	2	3
Photographs	426	438	630
Pass Points	3319	3469	4933
σ_x	±20 μm	±20 μm	±20 μm
σ_y	±20 μm	±20 μm	±20 μm
Bandwidth	32	26	32
Control Orbit			
σ_ϕ	±200 M	±200 M	±200 M
σ_λ	±200 M	±200 M	±200 M
σ_h	±200 M	±200 M	±50 M
All Others			
σ_ϕ	±2000 M	±2000 M	±2000 M
σ_λ	±2000 M	±2000 M	±2000 M
σ_h	±2000 M	±2000 M	±2000 M
All Orbits			
σ_ω	±25″	±25″	±25″
σ_ϕ	±25″	±25″	±25″
σ_κ	±25″	±25″	±25″

TABLE 7. CENTRAL PROCESSOR TIME (CPU) FOR EACH STEP OF ONE ITERATION OF THE APOLLO 15 BLOCK SOLUTION USING SAPGO-L.

DATA SET	1	2	3
Photographs	426	438	630
Pass Points	3319	3469	4933
Bandwidth	32	26	32
CPU Time to Build Equations	6^m46^s	6^m35^s	10^m20^s
CPU Time to Solve Equations	16^m23^s	15^m58^s	34^m45^s
CPU Time to Update Parameters	$5^m\ 6^s$	4^m47^s	7^m32^s
Total CPU Time/Iteration	28^m48^s	27^m22^s	52^m37^s
σ_{xy}	±12 μm	± μm	±10 μm

data sets of the Apollo material were processed. Sub-blocks of the complete data set were utilized. The control strip of these blocks had the height held to 200 meters.

Table 7 presents the central processor times (CPU) for each data set and the standard error of the image residuals for each solution. Again, the ratio of CPU to clock time was small. The maximum ratio for these three data sets was 1:1.5.

The evaluation of the Apollo 15 block data was a very difficult task. A relative evaluation was determined by deriving all the pass-point coordinates from the derived exterior orientation parameters of each strip. The derived pass point coordinates from each strip were then compared. These comparisons are presented in Table 8. The weighted average of these comparisons is 26 meters in latitude, 21 meters in longitude and 33 meters in height. These figures indicate how well the different strips were tied together as well as an estimate of the original identification and mensuration accuracies.

Additional information about the Apollo 15 block adjustment can be obtained from the DMAAC special project report[2].

TABLE 8. COMPARISON OF COMMON POINTS BETWEEN REVOLUTIONS, IF THEIR COORDINATES ARE DERIVED FROM THE ADJUSTED EXTERIOR ORIENTATION PARAMETERS IN SAPGO. THE TABLE WAS TAKEN FROM THE DMAAC APOLLO 15 REPORT[2].

Strips Compared	$\sigma\phi$	$\sigma\lambda$	σh	Number of Points
4 *vs.* 16	11	10	15	12
16 *vs.* 22	24	19	31	307
27 *vs.* 22	28	21	37	236
27 *vs.* 33	25	21	32	220
38 *vs.* 33	28	25	37	262
38 *vs.* 44	29	21	33	224
50 *vs.* 44	29	30	43	227
50 *vs.* 60	34	23	30	96
70 *vs.* 63	23	17	26	274
72 *vs.* 63	22	17	27	195
72 *vs.* 70	21	17	31	361
Weighted Average	26	21	33	2413

$\sigma_A = \frac{\Sigma n_i \sigma_i}{\Sigma n_i}$: Formula for computing weighted average.

CONCLUSIONS

The SAPGO programs for large block triangulation remove most of the physical restrictions placed on block triangulation. There is no limit to the number of pass points or exposure stations in a photogrammetric block, no limit to the number of points per photograph, no block configuration restrictions, no limit on the number of control points, and they can handle up to 20 camera systems. The major restriction is placed on the maximum number of strips or the bandwidth of the reduced normal equations. This current limit is 16 strips or a bandwidth of 34. The number of strips are small but there is no limit to the number of photographs per strip.

The SAPGO program is capable of being modified to meet any large block triangulation requirement on a wide variety of digital computers. It is currently operational on a UNIVAC 1108, and IBM 360/75 and a CDC 6500. If a computer has a direct-access storage capability with at least 32 K single precision 32-bit words of core storage, then a version of SAPGO could be prepared for it.

A new version SAPGO-G is currently being developed. This version will be capable of using independent geodetic observations as additional control for the block triangulation. The independent observations are required to keep the bandwidth of the reduced normal equation within the photogrammetrically imposed limits.

The recursive partitioning algorithm is also being modified to increase the number of strips or bandwidth that can be adjusted. Unfortunately, this change will also affect the efficiency of the program. As the bandwidth is increased, the ratio of CPU to clock time will increase, and the efficiency will decrease.

Acknowledgment

This research project was initiated in September 1968 through a research grant from the University Research Board at the University of Illinois. Since April 1969 this project has been supported by the US Army Research Office—Durham, North Carolina. This project is directed by Dr. K. W. Wong from the University of Illinois.

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BOOK REVIEW

Zoom Lenses, by A. D. Clark, American Elsevier Publishing Company, Inc., New York, and Dallmeyer Ltd., London, 1973, 90 pages; 6 × 10 inches, hardcover, price $17.

This is the seventh in a series of monographs written by students at Imperial College as part of the work for the M. Sc. degree in applied optics. When a thesis is chosen as suitable for publication, it is expanded and rewritten, new material is added, and publication generally occurs some years after the student obtained his degree.

This monograph is well organized, with contents well chosen. Very little material has been published on zoom lenses, and as a result the text contains many illustrations and much information supplied by manufacturers. The work is certainly a contribution in a neglected area of lens design and application, and gives a reader insight on the properties and potentials of zoom lenses. Many of the comments are parochial to England, but zoom lenses from many different countries are discussed.

My own experience with zoom lenses has not been broad, and I thus feel that not many ASP members have had much involvement with them either. A photogrammetrist who must obtain reliable quantitative information from photographs may never use zoom lenses. A few exceptions can be recognized, however. Zoom stereoscopes are used to match photocontrol points between photos of widely different scale. Moreover, the Bausch & Lomb *Zoom Transferscope* permits matching a new photograph to a published map for updating corrections.

All types of aberrations that affect the ability to form a perfect image are discussed. Unfortunately, as the focal length of a lens or magnification of a zoom lens is changed, variations occur in all aberrations, but in modern designs, the effects have been reduced to a practical minimum.

The zoom lens has found extensive applications in television where ultraprecise image quality is not of prime importance. There is little mention of distortion, which is a rather important photogrammetric quality, aside from this quotation: "Distortion causes the magnification ratio of the lens to vary with lateral image position. Thus, in the case of barrel distortion the magnification decreases with increasing field angle and, in the case of pincushion distortion, the magnification increases with field angle."

The reader needs little depth of optical knowledge as all mathematical expressions are simple optical formulas. At the present state of the art, the author indicates that many types of zoom lenses in use today may have reached the limits of modification and improvement.

—William P. Tayman