PHOTOTRIANGULATION: A REVIEW AND A BIBLIOGRAPHY

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ABSTRACT

This paper reviews the development of phototriangulation. A comprehensive classification of phototriangulation methods found in the literature is made. The main concepts of phototriangulation are highlighted and two distinct but not mutually exclusive approaches to aerotriangulation today - bundle adjustment and independent models - are discussed; representative accuracies from projects around the world are presented. Various applications are also enumerated. The paper contains a selected but classified bibliography.

1. INTRODUCTION

Aerotriangulation has witnessed a phenomenal development since its advent about half a century ago. It is probably true that no other single technological innovation has undergone so much change within so short a time. Although aerotriangulation methods can be classified into three major categories there are no less than thirty variations of these methods, some of which are briefly described in Table 1. These variations constitute an expression of adaptability to the following factors: (i) availability and limitations of current instrumentations (ii) economic considerations (iii) preference for a particular methodological approach (iv) limitations imposed by computational (computer) facilities as well as computational (programming) abilities and (v) accuracy and application requirements. It is the objective of this paper to review various aspects of phototriangulation methods and their applications in surveying and mapping.

2. RADIAL-LINE TRIANGULATION

The practice of aerotriangulation probably started with radial line methods which are based on very simple geometric properties of the aerial photograph. For example angles measured in the plane of the vertical photograph about the principal point are true horizontal angles, since radial lens distortions have no effect on such angles and tangential distortions are considerably small. The vertical photograph then became an angle-measuring device. This concept was first developed by Scheimflug and later expounded by Finsterwalder Gruber, Bagley, Collier and Hotine (Hallert [92]). The primary principles involved in the practice of radial methods are those of resection and intersection by which a two-dimensional trig. network may be extended between control points graphically. Moreover, the equipment required are modest. The simplicity of the application of radial line methods has encouraged further development of radial-line triangulation from the easy-to-do graphical radial line plotting to relatively more complicating procedure of mechanical slotted template, stereo-template and Jerie's analogue computer methods all of which are imitations of graphical procedures. Jerie's [93] analogue computer is more flexible and accurate than conventional methods. Whereas stereo-template techniq ue is an adaptation of third order stereoplotters such as Multiplex, which are not designed for precise stereotriangulation, to accomplish radial triangulation by using stereotemplates constructed from stereomodels in plan. In 1955, Konecny [95] performed radial triangulation with convergent photography and by 1962, Reolofs [98] has executed radial triangulation in mountainous country.

Perhaps one of the most exciting developments in radial triangulation is the arrival of numerical methods, which make use of measured image coordinates in the solution of a mathematical model (a duplication of the principles of resection and intersection according to Hallert's, [90] model). Turnip [103] and Wolf [105] improved on Hallert's model by eliminating the necessity to locate the line of flight as the axis of reference. Mikail [97] introduced the least squares approach to numerical radial triangulation by using redundant observations. Hallert [91] initiated the concept of numerical stereoradial method. Wolf and Lloyd [106a] however advocate the use of triplets as a basic computational unit for numerical methods. Although numerical radial triangulation is no more widely practised, its merit lies in the improved accuracy it provides over contemporary methods of radial line triangulation, briefly described in Table 1.

3. MECHANICAL AEROTRIANGULATION

Another stage of development in aerotriangulation witnessed the use of stereoplotters with multiple bank of projectors such as Multiplex or the Belplex. Adjacent models were successfully oriented to each other on the projectors to form a continuous stereo-triangulated strip. Two-projection type of stereoplotters such as Wild B-8, Holden [243] with some extra devices were also employed for triangulating a strip but their use was short-lived owing to the development of universal instruments, such as Wild A 7, stereoplanigraph C 8 and Zeiss stereoplanigraph with base-in base-out capabilities (Zeiss parm) and devices for precise recovery of exterior orientation. The introduction of such instruments gave birth to the practice of two stereotriangulation procedures namely Aeropolygon, Bradt [232], ASP [111] and Aerolevelling, (see Table 1), Adler [312] eventhough the theory behind these two methods have been enunciated in 1935 by Von Gruber [36]. The resulting strip or block from aeropolygon or aerolevelling may be adjusted graphically or computationally by polynomials. The concept of using distances and azimuth to control a strip was first introduced by Karara [190] and subsequently utilized by Bradenbeger [184], Colcord [185] and Ghosh [189] in a method called Independent Geodetic Method for developing suitable polynomials for adjusting strips from aeropolygon or aerolevelling.

4. SEMI-ANALYTICAL METHODS

The 50's also saw the humble development of semi-analytical methods of Independent Models as an imitation of aeropolygon procedure; the only difference being that in semi-analytical method, independent models obtained from the stereoplotter are linked successfully one to another through a three dimensional similarity transformation which represents the projective relation between the preceding model space system X, Y, Z and the subsequent model space system x, y, z in eqn. (1)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = SM \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix} \qquad (1)$$

where the unknown parameters are

S = scale factor

M = orthogonal matrix of rotation K, Φ, Ω

X_o, Y_o, Z_o = translatory elements.

The linkage operation to form a strip or block and the subsequent adjustment are performed on the high speed computer. This approach which constitutes a compromise between analogue and fully analytical methods is undoubtedly the most popular of all aerotriangulation methods. This is so by virtue of the fact that semi-analytical methods can be executed by a combination of relatively less expensive non-universal instruments such as Wild A8 or Kern PG2 and the highspeed computer or even a mini-desk computer with a basic memory of 10k words. The implication is that semi-analytical methods are within reach of small mapping organisations in terms of cost and ease of operations.

4.1 Perspective Centre

In semi-analytical methods of Independent Models it is customary to make use of the common perspective centres between adjacent models in conjunction with three more pass points to provide sufficient geometric strength for the connection of successive models to form the strip or block. Accordingly various methods for perspective centre determination have been developed, Fereday [212], Thompson [225], Williams and Brazier [226] and Ligterink [217]. The necessity for accurate determination of perspective centre has also been established by Brazier [211] and Savage [224].

4.2 Strip or Block Adjustment

Polynomials were first used for the adjustment of strip, block or sections, Schut [200], [202], Schermehorn [196] and Thompson [204]. Inspite of theoretical objections polynomials have remained popular with many mapping organisations on account of their simplicity, ease and economy, computation wise and also for their faily good accuracy performance which is adequate for topographic mapping. Similarity transformation eqn. (1) has however taken over from polynomials as the standard procedure for strip or block adjustment with independent models. The mathematical model of observation equations

$$L_a = f(X_a) \qquad (2)$$

represented by eqn. (2) is used and this results in the linearized observation equations by Taylor's series expansion

$$V = BX + L \qquad (3)$$

where V = vector of residuals

$B = \frac{\partial f}{\partial x}$

X = vector of parameters update

L = misclosure vector.

By minimising sum of squares of weighted residuals we obtain the normal equations, eqn. (4)

$$(B'WB)X + B'WL = 0 \qquad (4)$$

where W = weight matrix of observations for model coordinates.

Important innovations in the use of similarity transformation may be enumerated as follows:

(i) the an block planimetric block adjustment approach, Boniface [183], Vande Hout [207], which is exemplified in PAT-M4 Computer program, Ackermann [176a];

(ii) the introduction of the Rodrigues Matrix to replace the orthogonal matrix M in eqn. (1), Thompson [206b] and Ackermann [176a],;

(iii) the planimetric-height iteration demonstrated per excellence in PAT-M 43, Ackermann [176a] in which seven parameter similarity transformation is solved for in groups of four and three parameters; this procedure is faster and requires less storage capacity than the classical seven parameter approach and

(iv) the admission of observation on parameters - particularly known and unknown ground coordinates.

4.3 Semi-Analytical Bundle Adjustment

Semi-analytical methods are usually associated with Independent Models vis-a-vis similarity transformation until Maarek [193] developed a procedure which this author chooses to call Semi-Analytical Bundle. Models coordinates obtained through analogue methods are transformed into photo coordinates which are in turn refined for systematic errors computationally, before bundle type of adjustment which will be discussed in the appropriate sections. The sources and methods of compensating for these systematic errors will now be discussed.

5. IMAGE ERRORS

One of the major demerits of semi-analytical methods is their inability to computationally account for systematic errors in the measured image coordinates. This is why Maarek's [193] approach to semi-analytical bundle adjustment constitutes a "maverick" in the group of semi-analytical methods. Five major sources of image errors which cause a departure from the idealized collinearity concept are depicted in Fig. 1. These errors may be classified into three distinct types. The first type are of the first order and are due to instrumental fault and or operator's blunders. They are usually detected by calibration of the instrument and by repeated measurements. There are however a few computer algorithms for automatic detection of gross errors or blunders, Davis [266], Osaikhuiwu [299], Forstner [11] and Bouloucos [262].

Systematic errors due to lens distortion, film distortion, earths curvature and atmospheric refraction are second order effects. Notable contributions in the mathematical modeling of second order systematic errors, have been made by Betram [41], Saastamoinen [62], [63] and Schut [66] on refraction; Brown [44], [45], [46], Conrody [48], and Washer [67] on lens distortion; Lampton [56] and Ziemann [68], [69], [70] on film distortion. The research performed by Brown [46] and Merchant [59] are also invaluable contributions to the understanding of image geometry in the aerial camera system.

Third order effects are exemplified by lack of film flatness, anomalous image deformation through film transport, atmospheric turbulence, printing and processing effects (See Fig. 1). This group of image errors are very difficult to account for computationally owing to lack of adequate mathematical models. Emperical formulas commonly referred to as "additional parameters" are normally adopted for compensating third order effects which are usually presented as residual systematic errors after block adjustment. The use of reseau marks has also been adopted as an effective means for removing local anomalous film distortion around the measured image point, Robinson [61], Sadler [64] and Ziemann [68]. An attempt has also been made by Andrade [40] to model atmospheric refraction due to air turbulence around the entrance node of the aerial camera by using the "boundary layer theory". Further more El Hakim and Faig [272] have experimented on the compensation for systematic errors by using spherical harmonics whilst Kraus and Mikhail [287] have successfully used advanced least squares collocation for predicting residual systematic errors.

6. ANALYTICAL METHODS

The effective corrections of measured image coordinates for systematic errors forms one of the strong foundations for achieving high accuracy in analytical methods. Out of the four distinct analytical methods described in Table 1, only numerical radial triangulation lacks this foundation. Kenefick and others [192] reported an experience with analytical approach to Independent Geodetic Method. Strips and blocks formed after corrections for systematic errors were effected on image coordinates. A block of 4 strips (67 photos at scale 1:6000) was bridged using X-Y horizontal controls comprising of distances and azimuths. The same block was also adjusted using conventional method. Independent geodetic method not only produced comparable accuracies with conventional method, but overall savings in providing mapping controls amounted to 33 percent compared to conventional method. Two other analytical methods Independent Models and Bundle Adjustment will now be discussed in some details.

6.1 Analytical Method of Independent Models

The primary distinction between semi-analytical and fully analytical approach to Independent Models is that in fully analytical approach relative orientation is performed analytically using the image coordinates corrected for systematic effects. The analytical relative orientation is traditionally based on the coplanarity concept although Bender [144], Keller and Twenkel [191] have shown that relative orientation can also be performed with collinearity concept. Strip or block formation, and adjustment operations are the same as those of semi-analytical method of independent models. The use of eqns. (1), (2), (3) and (4) for these operations may be regarded as classical procedure. (Note that in eqn (1), X, Y, Z are now the object space coordinates in strip or block adjustment). There are however four deviations from this classical procedure.

The first deviation relates to the concept of weight constraints discussed by Case [151] and utilized by Ackermann [176a] in the development of PAT M-43 and also by Blais [261] in SPACE-M program. By this concept photogrametric model coordinates, perspective centre coordinates as well as terrestrial coordinates (known and unknown) are regarded as observations and therefore weighted accordingly and simultaneously adjusted. There are three implications of this rigorous approach which in the authors opinion is only justified in a fully analytical method of Independent Models. The first is that the ground controls are no longer regarded as perfect. Secondly, it is possible to detect gross errors at the ground control points. The third implication has to do with the addition of more observation equations to eqn. (3) to complete the adjustment (see eqns. (5) and (6))

$$\overset{pc}{V} = \overset{pc}{X} + \overset{pc}{L} \quad \text{(for perspective centre)} \tag{5}$$

$$\overset{s}{V} = \overset{s}{X} + \overset{s}{L} \quad \text{(for ground coords.)} \tag{6}$$

Eqns. (3), (5), (6) may be combined into one observation eqn. (7)

$$\bar{V} = \bar{B}\bar{X} + \bar{L} \tag{7}$$

minimising $\bar{V}'\bar{W}V$, sum of squares of weighted residuals we obtain the normal equations, eqn. (8)

$$(\bar{B}'\bar{W}\bar{B})\bar{X} + \bar{B}'\bar{W}\bar{L} = 0 \tag{8}$$

where

$$\bar{W} = \begin{bmatrix} W & 0 & 0 \\ 0 & \overset{pc}{W} & 0 \\ 0 & 0 & \overset{s}{W} \end{bmatrix}$$ = Combined weight matrix of model coords (W), perspective centre coords ($\overset{pc}{W}$) and ground coords ($\overset{s}{W}$).

Eqn. (8) has given rise to a large system of normal equations in which the normal coefficient matrix is symmetric, patterned, sparse, positive definite and banded; the band width is defined as the maximum distance from the diagonal to the last non-zero elements of any row in the normal coefficient matrix. By taking advantage of the structure of this matrix, a partitioning procedure of the matrix into submatrices yields the reduced normal equations. In PAT-M-43 the models, pass points and control points are ordered in their optimum sequence to achieve a minimum band width in the reduced normal equations, the solution of which is obtained by an algorithm called HYCHOL (HYper-CHOLesky direct method for a solution of a system of equations using submatrices as units for a Cholesky solution. It is particularly efficient for banded or banded/bordered matrix), Ackermann [176b]. SPACE-M, Blais [261], however uses Cholesky's square root algorithm for the direct solution of the reduced normal equation after obtaining an automatic minimum band width. Ackermann's [176a] experience with the poor performance of iterative solution of systems of normal equations, particularly conjugate gradient methods which will be discussed under bundle adjustment, influenced his choice of direct method. (See Table 2 for other softwares for Independent models).

The second deviation from classical procedure is the use of additional parameters to compensate for systematic image errors (third order effects) in block adjustment with Independent Models. The need for special treatment of systematic image errors effects in the block has been confirmed by Ackermann [311], [176a] who has demonstrated the general effectiveness of Least Squares collocation for interpolation in improving the accuracy obtained by block adjustment with independent models. However, Ackermann [311] has found that Least Squares Collocation is limited in effectively dealing with such systematic image errors in the block; for example, maximum residual errors were hardly reduced by collocation. Ebner and Schneider [187] used the concept of "additional parameters" to compensate for third order systematic image errors due to model affine deformation, twisted models and perspective centre errors. Although these image errors are regarded as unknown parameters which may be common to any groups of models or to all models in the entire block, they are also treated as observations with appropriate weights so as to obliterate the possibility of an ill-conditioned normal equations due to highly correlated unknown parameters. According to Ebner and Schneider [187] the accuracy of adjusted block coordinates is said to improve up to a factor of three by using the concept of "additional parameters".

The third deviation from classical procedures in analytical independent models is the use of triplets which was first demonstrated by Mikhail [218]. An overlap of one photograph is required in using triplet, rather than stereopair as a basic unit in block triangulation. Mikhail [218] holds that there is a reduction in the number of units and therefore in the number of parameters in the Block; for n photos in each of s strips, the number of parameters for bundle method is 6ns, for conventional method of stereopairs 7(n-1)s and for triplet method 3.5(n-1)s or 3.5ns when n is odd or even respectively, Marks and Mikhail [129]. Triplet method which is also used at National Oceanic Surveys, Keller and Twinkel [191], has yielded accuracies comparable with those obtained by bundles and stereopairs, Marks and Mikhail [129].

The fourth deviation from classical procedure relates to the use of auxiliary data in analytical Independent Models. This will be discussed in another section.

6.2 Bundle Adjustment

The evolution application and potential of bundle adjustment has been fully discussed by Brown [147]. Only a brief description of the meth⸱⸱ is presented here with some particular emphasis on the problem of solving large system of normal equations.

Classical bundle adjustment (see Table 1) is performed by making use of image coordinates corrected for first and second order systematic effects in the formation and solution of linear observation equation (10) and normal equations (11). This solution is conventionally obtained by minimising sums of squares of weighted residuals, using Lagrange's multipliers. Note that both equations are based on Collinearity equations (9)

$$x = -f \frac{(X-X_o)m_{11} + (Y-Y_o)m_{12} + (Z-Z_o)m_{13}}{(X-X_o)m_{31} + (Y-Z_o)m_{32} + (Z-Z_o)m_{33}}$$

$$y = -f \frac{(X-X_o)m_{21} + (Y-Y_o)m_{22} + (Z-Z_o)m_{23}}{(X-X_o)m_{31} + (Y-Z_o)m_{32} + (Z-Z_o)m_{33}} \qquad (9)$$

where x, y, = photo coordinates in the image space

m's = orthogonal rotation matrix in K, ϕ, ω

X, Y, Z, = ground coordinates in the object space

X_o, Y_o, Z_o, = ground coordinates of exposure station.

f = camera constant

$$V + \overset{ee}{B\Delta} + \overset{se}{B\Delta} + E = 0 \qquad (10)$$

$$\begin{bmatrix} \dot{N} & \bar{N} \\ \bar{N}' & \ddot{N} \end{bmatrix} \begin{bmatrix} \overset{e}{\Delta} \\ \overset{s}{\Delta} \end{bmatrix} + \begin{bmatrix} \dot{u} \\ \ddot{u} \end{bmatrix} = 0 \qquad (11)$$

where $\dot{N} = \overset{e}{B}{}'W\overset{e}{B}$ $\qquad \dot{u} = \overset{e}{B}{}'WE$

$\bar{N} = \overset{e}{B}{}'W\overset{s}{B}$ $\qquad \ddot{u} = \overset{s}{B}{}'WE$

$\ddot{N} = \overset{s}{B}{}'W\overset{s}{B}$ $\qquad$ W = weight matrix of photo coords x,y

$\overset{e}{\Delta}$ = correction vector to approx. Ext. orientation elements

$\overset{s}{\Delta}$ = correction vector to approx. survey coords.

E = misclosure vector from eqn (1)

$\overset{e}{B}$, $\overset{s}{B}$ = design coefficient matrices of $\overset{e}{\Delta}$, $\overset{s}{\Delta}$ respectively.

Equ. (11) may be expressed concisely as

$$N\Delta = U \qquad (12)$$

there is however a departure from classical bundle adjustment. The concept of constraints, Case [151], both functional and weight constraints, may be introduced to admit observations on exterior orientation parameters and ground survey coordinates. This yields two more observation eqns (13) and (14)

$$\overset{e}{V} - \overset{e}{\Delta} + \overset{e}{E} = 0 \quad \text{(ext. orientation)} \qquad (13)$$

$$\overset{s}{V} - \overset{s}{\Delta} + \overset{s}{E} = 0 \quad \text{(ground survey coords.)} \qquad (14)$$

The resulting normal equations from eqns (10), (13) and (14) are given in eqn. (15) by minimising the sums of squares of weighted residuals using Lagranges multipliers;

$$\begin{bmatrix} \dot{N}+\overset{e}{W} & \bar{N} \\ \bar{N}' & \ddot{N}+\overset{s}{W} \end{bmatrix} \begin{bmatrix} \overset{e}{\Delta} \\ \overset{s}{\Delta} \end{bmatrix} = \begin{bmatrix} \dot{u} - \overset{ee}{wE} \\ \ddot{u} - \overset{ss}{wE} \end{bmatrix} \qquad (15)$$

This development may be extended to the concept of self calibration by admitting observation of the unknown parameters of the interior geometry. Eqn. (10) will therefore be replaced by eqn. (16) plus one other observation eqn. (17)

$$V + \overset{e}{B}\overset{e}{\Delta} + \overset{s}{B}\overset{e}{\Delta} + \overset{i}{B}\overset{i}{\Delta} + E \qquad (16)$$

$$\overset{i}{V} - \overset{i}{\Delta} + \overset{i}{E} \quad \text{(for int. geometry)} \qquad (17)$$

The normal equations for self calibration may be obtained from eqns. (13), (14), (16) and (17) by minimization process. Thus we have eqn. (18)

$$\begin{bmatrix} \overset{e}{B}{}'W\overset{e}{B}+\overset{e}{W} & \overset{e}{B}{}'W\overset{s}{B} & \overset{e}{B}{}'W\overset{i}{B} \\ \overset{s}{B}{}'W\overset{e}{B} & \overset{s}{B}{}'W\overset{s}{B}+\overset{s}{W} & \overset{s}{B}{}'W\overset{i}{B} \\ \overset{i}{B}{}'W\overset{e}{B} & \overset{i}{B}{}'W\overset{s}{B} & \overset{i}{B}{}'W\overset{i}{B}+\overset{i}{W} \end{bmatrix} \begin{bmatrix} \overset{e}{\Delta} \\ \overset{s}{\Delta} \\ \overset{i}{\Delta} \end{bmatrix} + \begin{bmatrix} \overset{e}{B}{}'WE - \overset{e}{W}\overset{e}{E} \\ \overset{s}{B}{}'WE - \overset{s}{W}\overset{s}{E} \\ \overset{i}{B}{}'WE - \overset{i}{W}\overset{i}{E} \end{bmatrix} = 0 \qquad (18)$$

It should be noted that the normal coefficient matrix from eqn. (15) gives a sparse but banded-diagonal matrix while eqn. (18) yields a banded-bordered matrix. The concept of bordering a normal coefficient matrix was proposed by Brown [147] for"block-invariant" parameters (that is parameters which are common to all photos in the block or strip) such as the interior orientation (projective) parameters which are recovered simultaneously along with exterior orientation parameters and ground survey coordinates in self-calibration.

There are two applications of the banded-bordered system in Bundle Adjustment. The first concerns the concept of Simultaneous Adjustment of Photogrammetric and Geodetic Observations (SAPGO), Wong and Elphingstone [171]. Geodetic observations such as distances, azimuths, horizontal angles, latitude, longitudes etc may be used to generate additional observation equations of the type shown in eqns (19)

$$\overset{\theta}{V} + \overset{\theta}{G}\overset{\theta}{\Delta} + \overset{\theta}{E} = 0 \quad \text{(for horizontal angle } \theta) \qquad (19)$$

It was observed by Brown [147] and Wong, et.al [171] that the normal equations resulting from the simultaneous adjustment of eqns. (10), (13), (14) and (19), (that is SAPGO) do not conform to the banded diagonal structure in eqn. (15), the "offending" parameters being the geodetic observed parameters introduced in eqn. (19). The banded structure may be retained however by imposition of restrictions on the location of the geodetic observations in the block - a solution which in practice may not be feasible. Brown's [147] solution to this problem is that the "offending" parameter may be relegated to the border of the normal coefficient matrix (without causing ill-conditioning) by the method of "augmented bordering" with recursive partitioning, in which the band width of the photogrammetric system is retained and the border width is equal to the number of geodetic observation equations.

Another application of "bordering" relates to the concept of "Additional Parameters", which are intended to accommodate unknown systematic image errors in the block. If these errors are common to the all photos they may be treated as "block-invariant" parameters and the border of a banded-bordered system of normal equations may be used to accommodate these parameters Bundle Adjustment with additional parameters is discussed in Schut [169], Ebner [155].

6.21 Solution of Normal Equations in Bundle Adjustments

It should be noted that there are certain special procedures such as "cross-strip ordering" for photonumbering, appropriate "reordering of unknowns" in the normal equations and the concept of "collapsing", (see Brown [147] for details) important in generating a normal coefficient matrix which is diagonal dominance, of smallest possible dimension, with automatic minimum band width. It is also important to note that none of the normal equations discussed in section 6.2 is solved without deriving the reduced normal equations. The procedure for this may be illustrated by using eqn. (11) which may be solved by eliminating Δ to obtain the reduced normal equation (20)

$$(\dot{N} - \bar{N}\ddot{N}^{-1}\bar{N}')\overset{e}{\Delta} = \dot{u} - \bar{N}\ddot{N}^{-1}\ddot{u}. \quad (20)$$

In order to perform rigorous adjustment of large photogrammetric blocks with bundle method, the problems of finding a solution for large system of normal equations is a formidable task. The conventional solution of normal equations usually takes one of two forms; direct method and iterative methods.

6.211 Direct Methods

Three of the best known methods in this group are the Gauss-Cholesky method, D'autume [152a], Gauss-Jordan, Elassal [270] and Gaussian elimination with recursive partitioning method,Wong and Elphingstone [307]. These methods adopt the "block elimination" procedure whereby the whole vector of unknowns Δ in eqn. (12) is partitioned into sub-vector Δ_1, Δ_2, Δ_3,....Δ_n and their associated coefficient submatrices which are used as units in the computation. The on-diagonal sub-matrix S associated with Δ_1 is used as a pivot in the elimination procedure. After the elimination of one group of parameters the normal coefficient matrix must retain a banded or banded-bordered structure. The Gauss-Cholesky block-elimination procedure, D'Autome [152a] involves only the decomposition of S into the product of a lower triangular matrix and its transpose. Whereas in Gauss-Jordan the inverse of pivotal matrix S is computed. A good example of an efficient program constructed according to the principle of Gaussian elimination is SAPGO, Wong and Elphingstone [171] in which the banded portion along the diagonal of the full inverse matrix is solved in the backward process. By adopting a recursive partitioning algorithm combined with direct access I/O techniques for storage and retrieval of data, a solution which is faster than Cholesky's square root method and Gauss' methods, is achieved, Wong and Elphingstone [307]. The major disadvantages of all direct solution method is that external storage requirements are high. Besides the procedure is very difficult to programme and cumbersome as well as time consuming to operate on account of the fact that the submatrices of varying orders in the normal equations are transferred very many times between core and external storage devices. Some direct methods are also known to collapse due to the excessive amount of round-off errors introduced in the solution.

6.212 Iterative Methods

Amongst the Iterative Methods for the solution of normal equations in a large photogrammetric block which can be found in the literature, perhaps the best known include the Gauss-Seidel, method of successive Over Relaxation (SOR) and the conjugated gradient (C.G) method.

Gauss-Seidel method may be achieved by expressing the coefficient N in eqn. (12) in terms of three matrices as

$$N = C - E - F \tag{21}$$

where C = diagonal matrix of N; off-diagonals are zero.
E = lower triangular matrix of N, with zero diagonal.
F = upper triangular matrix with zero diagonal.

Equation (12) becomes

$$(C-E-F)\Delta = +U \tag{22}$$

It can be shown that the final solution is given by

$$\Delta^{(k+1)} = C^{-1}(E+F)\Delta^{(k)} + C^{-1}U \tag{23}$$

Since C is a diagonal matrix, eqn. (23) may be written for ease of computation as

$$\Delta_i^{(k+1)} = \frac{1}{n_{ii}} \sum_{\substack{j=1 \\ j\neq i}}^{m} n_{ij}\Delta_j^{(k)} + \frac{1}{n_{ii}}(U_i);\ 1 \leqslant i \leqslant m \tag{24}$$

Eqn (24) is Jacobi's method for (k+1)th iteration. Expression for Gauss-Seidel may be obtained from eqn (23) as

$$\Delta^{(k+1)} = (C-E)^{-1}F\Delta^{(k)} + (C-E)^{-1}U \tag{25}$$

For (k+1)th approximation and

$$\Delta_i^{(k+1)} = \frac{-1}{n_{ii}} \sum_{j=i}^{i-1} n_{ij}\Delta_j^{(k+1)} + \sum_{j=i+1}^{m} n_{ij}\Delta_j^{(k)} - U_i,\ 1\leqslant i\leqslant m \tag{26}$$

which is Gauss-Seidel formula for (k+1) approximation.
Since equation (24) uses only Δ in computing $\Delta^{(k+1)}$ in contrast to equation (26) which uses $\Delta_j^{(k+1)}$, it can be deduced that Gauss-Seidel will converge faster than Jacobi's method.

Unfortunately, the rate of convergence of Jacobi and Gauss-Seidel methods for large systems of normal equations may still be slow. Amongst the various methods developed to accelerate Gauss-Seidel perhaps the most popular is the Block Successive Order Relaxation (BSOR) method. The concept of Successive Over Relaxation (SOR) may be illustrated by equation (27)

$$\bar{\Delta}^{(k+1)} = \Delta^{(k)} + w(\Delta^{(k+1)} - \Delta^{(k)}) \tag{27}$$

where $\bar{\Delta}^{(k+1)}$ = (k+1)th approximate solution vector by SOR.

$\Delta^{(k+1)}$ and $\Delta^{(k)}$ are the same as in equation (25) and w is a suitable constant acceleration parameter.

For BSOR the coefficient matrix N and corresponding vectors Δ and U in eqn (12) are partitioned into submatrices (blocks). Equations (26) and (27) may be combined to obtain the computational form of BSOR, eqn (28)

$$\Delta_i^{(k+1)} = \Delta_i^{(k)} + wN_{ii}^{-1}\left[-\sum_{j=1}^{i-1} N_{ij}\Delta_j^{(k+1)} - \sum_{j=i+1}^{m} N_{ij}\Delta_j^{(k)} + (U_i) - N_{ii}\Delta_i^{(k)}\right] \quad (28)$$

(See Brown et.al [263b] for details).
Carlson and Haljala [264] recommends that for a stable blocks with moderate geometric structure the value of w should be between 1.8 and 1.9; whereas in very weak blocks w should vary between 1.9 and 1.94. Note that if all the submatrices of N in equation (28) are of dimension 1 by 1 BSOR degenerates into SOR, method. It is also important to note that Gauss-Seidel is essentially a particular case of SOR when w=1.

Varga [306b] has proved that the optimum acceleration parameter w can be computed from the explicit formula

$$w = \frac{2}{1 + \sqrt{1+G}} \qquad o<w<2 \qquad (29)$$

where $G = (I-C^{-1}E)^{-1}C^{-1}F$.
Luisternik acceleration is obtained from eqn (29) as

$$\dot{\Delta}^{(k+1)} = \dot{\Delta}^{(k+1)} + (\frac{1}{1-G})(\Delta^{(k+1)} - \Delta^{(k)}) \qquad (30)$$

where $\dot{\Delta}^{(k+1)}$ = (k+1)th approximation from Luisternik and $\Delta^{(k+1)}$, $\Delta^{(k)}$ are from Gauss-Seidel.

From equation (28) it is not difficult to see how point iterative Gauss-Seidel process can be extended to Block iterative Gauss-Seidel (BGS) process. In a 2-photo simulated strip Brown et.al. [263b] found that the convergence rate of BSOR far exceeded that of BGS in the other of 40 to 50 times faster at 100 iterations.

Unlike the BSOR and Luisternik methods the conjugate gradient (C.G) method does not require a device for accelerating the iteration. It also allows the handling of observations and unknowns in any order and there is no need for a special preliminary determination of the approximate values for unknown parameters. The normal coefficient matrix is not computed and therefore not stored in core. These advantages make it possible to solve for large systems of equations in core, without using slow and expensive external storage devices. The mathematical development for this method may be found in Haljala [278]. In the experiment performed by Carlson and Haljala [264] involving 5000 unknown the conjugate gradients method converged faster than BSOR inspite of the fact that C-G system was built up without using external storage during iteration. This is in contrast to BSOR which was built up with large amount of external storage operations (disk and drum).

Iterative methods in general tend to be easier to programme and require much less storage than direct methods. The only basic disadvantage in Iterative methods is that it is difficult to determine the convergence criteria, Schut [134]. Table 2 contains a brief description of some photo-trianqulation softwares which make use of iterative and direct methods.

Orthogonal Transformations in Bundle Adjustment

Yassa [310] has introduced yet another innovation to the solution of the problem of bundle adjustment in which the formation of normal equations is avoided by reducing very large system of observation equations to smaller systems through repeated partitioning of a vector space into subspace and its orthogonal complements. Two variants of this method were discussed by Yassa [310]; the Gram-Schmidt ortho normalisation process and the householder orthogonal transformation in which the estimates of parameters, their accuracies and covariance matrix can be evaluated without any matrix inversion associated with classical least squares approach via normal equations.

7. RELATIONSHIP BETWEEN BUNDLE ADJUSTMENT AND INDEPENDENT MODELS

Some elements of the projective equations in eqn (1) may be redefined as follows: x, y, z = image coordinates ith point in the image space. X, Y, Z = the corresponding ground coordinates in the object space. X_o, Y_o, Z_o = the object space coordinates of some discret point in the image space. If we linearize eqn (1), we have that

$$V = \overset{ee}{A\Delta} + \overset{ss}{A\Delta} + E = 0 \qquad (31)$$

Equation (31) is essentially the same as eqn (10). This can be similarly demonstrated by substituting the calibrated focal length (-f) for Z in eqn (1) to obtain eqn (32)

$$\begin{bmatrix} x \\ y \\ -f \end{bmatrix} = S_i \; m_i \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix} \qquad (32)$$

By multiplying the first and second equations of eqn (32) by -f we obtain the collinearity eqn (9) which is linearized to obtain eqn (10) or eqn (31).

Erio [188] has incorporated both the 3-D similarity transformation, for independent model adjustment and the bundle adjustment into one versatile computer program ALBANY (see Table 2). In a comparative experiment using ISP simulated test block Erio [188] obtained improved results with ALBANY compared to those obtained by bundle adjustment, independent models and sequential type of adjustment.

8. THE USE OF AUXILIARY DATA

Auxiliary data used in aerial triangulation may be defined as data, acquired at the instance of exposure, which provide useful information about the position, scale or orientation of the aerial photograph in space. Such data which are useful in controlling the strip or block may be acquired by means of auxiliary airborne "external sensors" such as APR (b_z, Z, scale), statoscope (bz), Horizon Camera (ϕ,ω), Solar Periscope (ϕ,ω), Gyro Systems (ϕ,ω), Inertial Guidance System (ϕ,ω,k,scale), Doppler Navigation (scale), Aerodist, Shiran, Hiran Autotape etc (scale, X,Y), and the versatile ANG-28 (ϕ,ω,k,bz,X,Y,Z,scale). Vertical auxiliary data may also be obtained from a lake which spreads across the photogrammetric block thus providing equal elevation constraints, or a "block-invariant" parameter.

There are four different ways of using auxiliary data to control a strip on block. The first is by analogue method e.g aerolevelling which is already discussed in section 3. Auxiliary data may also be introduced to the adjustment of a strip or block obtained through semi-analytical method of independent models; Auxiliary data for example the X, Y, Z of projection centre and the ϕ, ω, of each photo have been used in the adjustment of a block, Miles and Smith [34]. The fully analytical approach to Independent Models described in section 6.1 provides remarkable flexibility for incorporating additional observation equations related to auxiliary data. Auxiliary vertical controls from Lakes, Statoscope and APR have been incorporated with PAT-M-43 and tested in some aerotriangulation projects, Faig [31] and Ackermann et.al [27]. The fourth method of introducing auxiliary data is through bundle adjustment through the use of weight constraints on observed parameter e.g. orientation elements from ANQ-28 which yields eqn (13). The greatest merit of auxiliary data lies in the drastic reduction of control requirement both in terms of density and distribution. This relates to planning and economic consideration vis-a-vis accuracy requirements for phototriangulation projects. They are also useful in achieving a solution for Camera calibration in a relatively flat terrain, Brown [46], as an alternative to the method of "mixed ranges" proposed by Merchant [59].

9. ACCURACY CAPABILITY OF PHOTOTRIANGULATION

Many investigations notably Ackermann [1], [2], Kubik and Kure [19], Ebner [9], [10], have been made into the theoretical accuracy of photogrammetric triangulation. The merit of such studies lies in the predetermination of expected accuracy under certain specified influencing conditions (factors) relating to (i) density, distribution accuracy and type of controls, (ii) quality, type and scale of photograph, (iii) type and quality of camera lens, (iv) length of strip or size of block, (v) percentage forward and side overlaps, (vi) roughness and configuration of the terrain (vii) accuracy of photogrammetric instrument as well as observations and, (viii) the method of aerotriangulation. (All of these factors must be considered along with project specifications in planning phototriangulation projects, Jerie [76], Karara [78]). The results from such theoretical accuracy studies have been a guide to photogrammetrists in detecting the presence of uncompensated systematic errors in the practical block adjustments whose accuracies did not conform with theoretical expectations. The outcome of the application of theoretical accuracies has led recently to an intensive investigation of additional parameters (see Table 1) to account for uncompensated systematic image errors in the block, as exemplified by work done by Ebner and Schneider [187], Schut [168], [169], Brown [147], Bauer [142], Bauer and Muller [143] and Salmenpera Anderson and Savolainen [165] (see Table 3 for improved results obtained by the use of additional parameters). The alternative approach to additional parameters for improving the accuracy of block adjustment is the method of Least Squares Collocation first applied by Kraus and Mikhail [287] in which the signal is filtered from the residual errors resulting from practical block adjustment (see Table 1). Ackermann [311] and Rampal [163] have successfully improved the block adjustment accuracies by using Least Squares Collocation (see Table 3). Some representative accuracies displayed in Table 3 confirm the capability of aerotriangulation as a Geodetic tool (see results obtained by Ackermann [311] and Brown [320] in Table 3). No attempt is made to compare the relative accuracies of the methods shown in Table 3 since aerotriangulation methods were not performed under identical conditions. For comparison of relative accuracies of some of these methods, see Erio [188].

10. APPLICATIONS

For quite a long time the traditional application of phototriangulation has been in control extension for topographic mapping. However, the past few decades have witnessed new applications of phototriangulation (due to improved accuracy capability and economy) notably for densification of trig and geodetic networks (Ackermann [311], Brown [320], close range application for the calibration of engineering structures, Kenefick [334], Papo and Shmutter [345], lunar mapping, Kenefick et.al. [335], ship building, Haggren et.al. [327], and miscroscopic mapping, Maune [341] and Nagaraja [343]. Other applications of phototriangulation are listed in Table 4, with corresponding references.

CONCLUSION AND RECOMMENDATIONS

The optimum accuracy capability of aerotriangulation block adjustment has barely been reached for most adjustment procedures, the greatest obstacle being the third order systematic effects which so far have not been modelled by explicit theoretically derived formulas as could be done for second order systematic effects. Investigations on the use of "additional parameters" and self-calibration are therefore likely to continue. However, phototriangulation results obtained in some projects for densification of trig network, Ackermann [311] and urban geodetic as well as first and second order triangulation networks, Brown [320], have demonstrated beyond reasonable doubt, the capability of photogrammetric method of control extension in meeting geodetic accuracy standards.

Although there has been a remarkable development of highly sophisticated computer programs during the past two decades, the use of polynomial strip adjustment is by far still popular with some mapping organisations around the world. There is a great need to make these softwares available especially in developing countries. Also there is a need to increase research in the adaptability of these softwares for mini-computers particularly for organisations which have no access to or cannot afford to use, the high speed computers. In view of the conflicting statements made by researchers, there is also need for intensive comparative study of the efficiency of direct and iterative methods of solving large system of normal equations. Practical application is likely to be on the increase as aerotriangulation becomes more accurate and economically feasible. For example, the recent interest in the use of auxiliary data has shown a remarkable decrease in the density of control requirements in the block, particularly in elevation. Towards this end also the various computer programs, should be optimised for maximum efficiency and economy. Also in this connection, there is a need for developing a computer program which can be used for a systematic and scientific planning of phototriangulation projects with built-in efficiency-cost-and-accuracy-models.

There are today two philosophical as well as practical approaches to phototriangulation - Independent Models and Bundle Adjustment. It has been shown that the two approaches are not mutually exclusive. They should be regarded as being complementary in attaining the ultimate goal of phototriangulation.

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TABLE I: CLASSIFICATION OF PHOTOTRIANGULATION METHODS

CLASS	SUB. CLASS	METHOD	DESCRIPTION	REFERENCE
GRAPHICAL - MECHANICAL	Radial - line Triangulation	1 Radial Triangulation	A graphical method in which directions from radial centre (Principal pt., nadir or isocentre) of each overlapping photos are used for resection (to determine planimetric coords. of exposure station) and intersection (to determine planimetric coords of a new prints)	Wolf [1066]
		2 Slotted Templates	Method is similar to the graphical approach except that slotted templates are used. Such templates contain long narrow slots which represent directions radiating from the centre of photo. Positions of points are determined by resection and intersection.	Trorey [102]
		3 Mechanical Templates	Spider (mechanical) templates constructed kits such as Lazy Daisys which have dimensionally stable materials are used. The basic principle as in other radial line methods is that angles at the radial centre in a vertical photo are true horizontal angles on the ground.	McComas [96]
		4 ITC - Jerie	Jerie designed two Analogue computers for block adjustment of horizontal and vertical points. For horizontal block adjustment the computer consists of section stereo templates (for conformal transformation), Multiplets (for introducing relative discrepancies at the points) and elastically connected studs for introducing zero discrepancies. The vertical Analogue computer is designed to adjust a block of stereotriangulated strips by means of elastic rods which are also elastically connected to each other at the points.	Jerie [93] Moore [342]
		5 Stereo-Template	Employs stereotemplates - a composite slotted templates which represent a stereo model in plan-constructed from a model in the stereo plotter not designed for precise bridging.	Scher [100]
	Analogue	6 Multiple Projectors	Requires a bank of projectors for the formation of a strip consisting of relatively oriented models. Scale is transferred between successive models by imposing equal elevation constraints in the overlapping ground area. Misclosures which are determined on the last model by means of plotted ground controls are adjusted by prorating them back through the strip.	Williams [255]

TABLE I CONTINUED

MECHANICAL	Analogue	7 Two Projectors	The first model is oriented relatively and absolutely. For other successive models the orientation elements (φ, w, k) of the right projector are transferred to the left projector; and w are measured with spirit level and k is transferred through dial reading or by special device otherwise it is set at zero. Scaling is done by analogue method as in (6).	Friedman [239] Holden [243]
		8 Aeropolygon	First order instrument is used for co-orientation of successive model with the aid of "base in", "base out" capabilities. Scale transfer is achieved by changing the base to attain equal elevation of points common to successive models as in (6). Only two projectors are required. Stripor block is adjusted by graphical or numerical methods.	Von Gruber [36] Adler [312]
		9 Aerolevelling	Exemplifies the use of auxilliary data (namely height obtained from statiscope data) for analogue aerotriangulation. The flying height of each exposure station is used to preset b_z values during co-orientation of successive models. This gives smaller closing errors compared to aeropolygon. Angular elements of orientation may also be preset in stereotriangulation by use of data from solar periscope, horizon photo and vertical gyros.	Strahle [252]
		10 Ind. Geodetic Control	Strip triangualtion is the same as aeropolygon or aerolevelling. Adjustment is by using independent base lines whose lengths and azimuths on the ground are known	Ghosh [189] Brandenberger [184]
SEMI-ANALYTICAL	Independent Models	11 Ind. Models (Polynomial)	Emperical relative orientation of models are performed independently with 1st or second order instrument. Strip on block formation is done by 3-D similarity transformation. Adjustment of strip or block is by polynormial transformation on the Computer	Ayeni [180] Derenyi [186]
		12 Ind. Models (3-D Transformation)	Relative orientation, strip or block formation are the same as in (11). Adjustment of strip or block is by 3-D transformation formula with 7 parameters which may be solved iteratively in groups of 4 and 3 i.e. plan-height iteration as in PATM-43.	Parsic [248] Ackermann [176]
		13 Ind. Models (An Block)	The procedure is the same as in (11): Strip on block adjustment is however accomplished by a two-dimensional transformation formula for planimetric adjustment as in PAT-M4.	Boniface [183] Ackermann [176]

TABLE I CONTINUED

SEMI-ANALYTICAL	Ind. Models	14 Ind. Models (Aux-Data)	Procedure for strip or block formation is the same as in (11) The X, Y, Z coordinates of projection centre, the φ and w elements of each photo determined from auxiliary airborne instruments are treated as controls in the adjustment of strips or blocks.	Miles et. al [34] Zarzycki [39]
SEMI-ANALYTICAL	Bundle	15 Semi-Analytical Bundle	Model Coordinates obtained from stereo plotter after relative orientation are transformed into photo coordinates which are corrected for systematic effects of flim, lens, refraction and earth's curvature. Classical bundle adjustment is performed as in (25)	Maarek [193] Derenyi [186]
FULLY ANALYTICAL	Radial Triangulation	16 Numerical Radial Triangulation	Radial triangulation performed numerically. Photo coordinates are measured. A mathematical model which imitates the graphical procedures of resection and intersection is implimented with the aid of the numerical computation	Wolf [106a] Hallert [91]
FULLY ANALYTICAL	INDEPENDENT MODELS	17 Independent Horizontal Control	This is analogous to (10) which is a semi-analytical approach. This method in contrast is a fully analytical approach in which ground distances and azimuths are used as controls in aerotriangulation.	Kenefick et. al. [192]
FULLY ANALYTICAL	INDEPENDENT MODELS	18 IMT Polynomial	Measured comparator coords are corrected for second under effects due to film, lens, refraction and earth's curvature. Numerical Rel. orientation is performed. Adjustment of strip, block or section is by Polynomials as in (11).	Ackermann [176]
FULLY ANALYTICAL	INDEPENDENT MODELS	19 IMT Direct Transformation	Procedures for coordinate measurement, refinement, Rel. Orientation, strip or block formation are the same as (15). Adjustment of strip, section or block is by 3-D transformation as described in (12).	Ackermann [311]
FULLY ANALYTICAL	INDEPENDENT MODELS	20 IMT with Collocation	This method is the same as in (18) or (19) except that after adjustment an advanced Least squares prediction method (Collocation) is used to filter out systematic deformations of a block thus reducing residual errors at control points. It is an alternative approach to the use of additional parameters in (23).	Ackermann [176]
FULLY ANALYTICAL	INDEPENDENT MODELS	21 IMT with Triplet	Comparator coords. are measured from separate photos and these are refined as (18). Separate units of 3 photos are relatively oriented with a forward overlap of one photo. The separate units (triplets) are assembled in strips or block. Strip or block adjustment is by polynomial (18) or by direct transformation (19).	Mikhail [219]

TABLE I CONTINUED

FULLY ANALYTICAL INDEPENDENT MODELS	22 IMT with Auxiliary Data	This method is analogous to (9) and (14). Auxilliary data obtained from APR, statiscope or Lake are all incorporated into the adjustment program as exemplified by PAT m - 43	Faig et al [31] Ackermann [256]
	23 IMT with Additional Parameters	The mathematical model for independent model in (19) is modified to incorporate additional parameters which will account for affine deformations, twisted models, perspective centre errors etc. Such parameters are treated as observations with appropriate weights.	Ebner et al [189]
	24 IMT by Simultaneous 3-D Transformation	A method analogous to bundle adjustment in which Independent Models in a block are simultaneously transformed by a 3-dimensional linear conformal transformation similar to collinearity equations.	Erio [188]
FULLY ANALYTICAL SIMULTANEOUS BUNDLE	25 Classical Bundle	Comparator coordinates are corrected for systematic effects as in (18). Collinearity equations are used in a least squares solution to obtain spatial coords. of unknown points on the ground. Calibration data are given.	Tegeler [348]
	26 Bundle with SAPGO	Simultaneous Adjustment of Photogrammetric and Geodetic observation is performed by extending the mathematical model for classical bundle Adjustment.	Wong et. al. [171]
	27 Bundle with L.S. Collocation	Advanced least squares interpolation is used to filter the signals from the residuals obtained from classical bundle adjustment. An a - posteriori full covariance matrix is then used in a new Maths Model for a second Bundle Adjustment.	Rampal [163]
	28 Bundle with additional Parameters	Analogous to (23). The mathematical model in (25) is expanded to include parameters which can take off third order systematic effects. These parameters although unknown are treated as observed quantities with weights attached to their approximate values.	Brown [147] Salmenpera et. al. [165]
	29 Bundle with Self-Calibration	The mathematical model from collinearity equations is employed in a least squares solution in which the camera constant, lens distortion constants, the principal point coordinates. The exterior orientation elements and the ground survey coords. are treated as observed (unknown) quantities. Their approximate values are given appropriate weights. The only true observations are the photo coordinates.	Brown [148] Davis [153]
	30 Bundle with Self-Calibration and Additional Parameters	The procedures involved are the same as in (29). The mathematical model is however expanded to incorporate parameters of third order systematic effects which may account for anomalous film deformation, atmospheric turbulence, etc. Additional parameters are also treated as observations with proper weights as in (28).	Brown [149] Brown [320]

TABLE 2: SOME COMPUTER PROGRAMS FOR PHOTOTRIANGULATION

NAME OR ACRONYM	DESCRIPTION	COMPUTER REQUIREMENT	AUTHOR (COUNTRY)
ALBANY	Adjustment of Large Blocks with ANY number of photos, points and images, using ANY photogrammetric measuring instrument and on ANY computer. Bundle adjustment and 3-D Independent Model adjustment incorporated in one computer program.	120K bytes on IBM 360 or 100k octal words on CDC6600 Fortran IV	Erio [188] (U.S.A.)
GIANT	General Integrated Analytical Triangulation program; performs a Least squares adjustment of arbitrarily arranged and Un constrained blocks of frame photographs. Can adjust max.of 460 photos, 400 ground controls and 9329 ground points.	IBM 360/370 with 340 bytes in Fortran IV	Elassal [270] USGS U.S.A.
I.M T	Independent Models Triangulation program which forms a strip or block from independently oriented (relative) photogrammetric models. Can handle 300 photos with 20 points per model.	Fortran on IBM 360/75, 252k bytes.	Ghosh and Morgan [273] (U.S.A.)
FORT BLOCK	Fortran program for BLOCK adjustment of photographys. Can handle 100 photos.	252k, bytes on IBM 360	Ohio State [298] (U.S.A.)
SAPGO - - mfl	Simultaneous Adjustment of photogrammetric and Geodetic observations - multiple Focal length - Geodetic observations includes horizontal angles, azimuth, elevation, etc. Computes min. band width solution of Normal eqn. by Gaussian elimination with recursive Partitioning.	Fortran 400k bytes on IBM 360/751, UNIVAC 1108 and CDC 6500	Wong and Elphingstone [171] (U.S.A.)
MUSAT	Multiple - Station Analytical Triangulation program for simultaneous block adjustment of up to 2000 photos. Features include, blunder elimination, data edit, control verification and statistical analysis.	Fortran, 32k memory on IBM 7094. UNIVAC 1108.	Matos [293] (U.S.A.)
URELO	Unit Relative Orientation. Performs rel. orientation with units of pair, triplets, etc. up to maximum of 8 photos each and assembles the units into one integral strip.	Xerox Sigma S Computer 24k Words.	[129] Purdue Univ. U.S.A.
COMBAT II	Commercial Block Analytical Triangulation program which executes Bundle adjustment with Self Calibration and error Model. Banded bordered form of recursive partitioning. Automatic minimum band width for normal equation which is solved by BSOR.	Xerox Sigma 5 Computer, 24k of memories, Four tape units and disk.	DBA [147] (U.S.A.)

TABLE 2 CONTINUED

SURBAT	Simultaneous Unlimited, Rigorous Block Analytical Triangulation. Can handle max. of 450 strips with automatic editing error propagational unlimited no. of photos per strip. Algorithm same as COMBAT.	GE 635	DBA [148] (U.S.A.)
LOSAT LOBAT	Lunar Orbiter strip Analytical Triangulation, Algorithm same Lunar Orbiter Block Analytical Triangulation as COMBAT.	GE 635	DBA [153] (U.S.A.)
(TPA)	Three photo Aerial triangulation for block adjustment consists of a set of programs, for coord. refinement, strip formation and resection which provide input for block adjustment. Normal equations solved by Gaussial Forward and backward elimination	IBM 360/370 in Fortram	NOS [156,] [191] (U.S.A.)
PAT-M4	Program Aerial Triangulation with independent models for panimetric adjustment An Block method of block adjustment. Normal equations solved by Hyper-Cholesky method uses Rodrigues - Caylary matrix.	minimum core capacity of 64k words on CDC 6600 on 256k on IBM 360/370 with additional external disc storage. Also on UNIVAC.	Stuttgart University Ackermann [109], [176] [256], [311] (W.Germany)
PAT-M43	Program Aerial Triangulation with independent Models with succession of 4 and 3 parameters Transformation, Plan-height iterative adjustment. Automatic minimization of band width and solution of normal equation by Hyper-Cholesky method.		
PAT-M43-APR STATOS-LAKE	Program Aerial Triangulation with Independent Models as M-43, With auxiliary data from APR, Statoscope and lakes.		
PAT-B	Program Aerial Triangulation with Bundle adjustment.		
BAP	Bundle adjustment with Additional Parameters and Self Calibration. Can handle 999 photos.	Fortram on IBM 370/158	Muller [348] (W.Germany)
ASP	Adjustment of Spatial Phototriangulation.	-	Mashimov [291] (U.S.S.R.)
HVB	Horizontal and Vertical Block adjustment of Independent Models using polynomial transformation. Can handle 200 or more models. Adjusts blocks consisting of strips or sections.	UNIVAC 1107 Algol	Holsen et al [280] (Norway)
SCHUT	Adjustment of strips and Blocks by Polynomial Transformation. Iterative Gauss-seidel solution of the complete set of normal equations.	Fortran on IBM 360/370 256k bytes of core storage.	Schut [305] (Canada)

TABLE 2 CONTINUED

SPACE - M	Spatial Photogrammetric Adjustment for Control Extension, using independent models and auxiliary data. Very few restrictions about position and density of controls. Can handle 1000 models. Normal equation solved by Choleskis square-root algorithm.	Fortran on CDC-- CYBER system or IBM with 300k octal words.	Blais [201] (Canada)
PABS	Polynomial Adjustment of Blocks of Strips formed from Independent models. Gauss-Jordan solution for normal equation. Can handle 120 models	Fortran on IBM 370/145 256k bytes of core storage -	Ayeni [180] (Nigeria)
BATT-SAP	Block Adjustment by Three-dimensional Transformations - similarity or Affine or Projective Transformation. Gaussi-Jordan solution of normal equation. Can handle independent models.		Ayeni [259] (Nigeria)
EMMBA	Extended Mathematical Model in Bundle Adjustment. Allows the handling of observations and unknown parameters in any order. Solution of normal equation by conjugate gradient method.	UNIVAC 1108	Haljala [278] (Finland)
BUEND	Adjustment by Bundle method. Program can also perform Calibration.	-	Schenk [164] (Australia)
STEREO	Swedish Block-Triangulation system with 7 parameters 3-D similarity Transformation. Iterative procedure for solving normal equation. Can handle up to 50 models.	CDC 6600 Fortran, 131k octal words.	Sigmark [203] (Sweden)
AN BLOCK	An Block method of calculating blocks of aerial triangulation with special techniques of data storage, data ordering and solution of normal equations.	-	Meulemester IGN [295] (France)
BUNDLE	Block adjustment by Bundle method; observations are reduced to quasi-observations. Normal equations solved by direct method - Gauss-Cholesky type		IGN [152a,b] (France)
IMT	Independent Model Triangulation by analytical Method. Corrections for systematic distortion, relative orientation; strip or block formation and adjustment by similarity transformation using Thompson's method.	-	Ord. Survey Proctor [195] G.Britain

TABLE 3: REPRESENTATIVE ACCURACIES OF SOME AEROTRIANGULATION METHODS

METHOD	PHOTO SCALE	PHOTO TYPE	CAMERA TYPE	AREAL COVERAGE	F/S OVERLAP	INSTRUMENT	NO. OF PHOTO OR MODELS	NO. OF CONTROLS HOR.	NO. OF CONTROLS VERT.	NO. OF HOR. PER PHOTO OR MODEL	NO. OF VERT PER PHOTO OR MODEL	NO. OF CHECK PTS. HOR	NO. OF CHECK PTS. VER	R.M.S AT CHECK PTS. HOR CM	R.M.S AT CHECK PTS. VER CM	PROJECT TITLE	INVESTIGATOR
FULLY ANALYTICAL IMT (TYPE 19, 20)**	1/7800	Wide Angle	Zeiss RMKA 15/23	94.6 km^2		Zeiss PSK Comp	112	27	-	4.2	-	77++	-	5.3 (4.4)*	-	Appenweier Project, W.Germany	Ackermann [311]
FULLY ANALYTICAL IMT add Parameters (TYPE 23)**	1/28000	Wide Angle	Zeiss RMKA 15/23	1250 km^2		Zeiss PSK Comp.	100	32	-	3.1	-	226+	-	17.6 (28)·	-	Block Frankfurt, W.Germany	Ebner and Schnei [187]
SEMI-ANALYTICAL IMT (TYPE 12)**	1/28000	Wide Angle	Zeiss RMKA 15/23	1500 km^2	60/20	Wild A10	175	28	61	6.3	2.9	238+	240	42.2	46.7	Zurich Block, Switzerland	Parsic [248]

TABLE 3 CONTINUED

Bundle with L.S. Collocation (Type 27)**	1/4000	Wide Angle	Zeiss RMK 15/23	0.7 km^2	60/40	Zeiss PSK	8	6	6	1.3	1.3	7	7	2.2 (3.2)	1.6 (2.9)	Ph.D Thesis Casa Grande, U.S.A.	Rampal [163]
BUNDLE with add Parameters (Type 28)**	1/4000	Wide Angle	RMKA 15/23	4 km^2	60/60	Zeiss P.S.K.	47	8	16	5.9	2.9	100	100	2.3 (6.1)	3.0 (4.3)	Jamijarvi Test Field, Finland	Salmenpera Anderson and Salvolainen [165]
Classical Bundle (Type 25)**	1/8000	Wide Angle	RMKA 15/23	104 km^2	60/30	Zeiss P.S.K	84	-	-	-	-	72	-	5.0	-	Aalbong, Finland	Hvidegaard [333]
Self Calibration with Add Parameters (Type 30)**	1/17,500	Super Wide Angle	RMKA 8.5/23	32 km^2	60/60	B.B.A Comparator	27	6	6	4.5	4.5	18	19	7.0	3.0	Atlanta Project, (U.S.A.)	Brown [320]

* Result after Least squares Collocation for interpolation

** See Table

\+ Perimeter Control distribution at 26 (5km) interval

++ Perimeter (plus points inside) distribution

. Result obtained without Additional Parameters

.. Result without L.S. Collocation

TABLE 4: APPLICATIONS OF PHOTOTRIANGULATION

	APPLICATION	REFERENCE		APPLICATION	REFERENCE
1.	Rectification	[323]	11.	Ship Building	[327]
2.	Controlling Mosaic Construction and Planimetric Map revision	[106b]	12.	Engineering Structures (Close-range)	[334], [344], [345], [345]
3.	Control Extension For Topo Mapping — Small Scale	[343]	13.	3-Dimensional Microscopic Mapping	[341], [343]
	Medium Scale	[314			
	Large Scale	[324],[328], [329],[330]			
4.	Structural Geology (Estimation of Fractures, Slope Stability etc)	[313]	14.	Convergent Photo	[336], [95]
5.	Orthophoto Products	[315]	15.	Lunar Mapping	[335], [355], [322]
6.	Densification of Trigonometric or Triangulation or Urban Geodetic Net works	[311], [320], [329], [329], [333], [341], [348], [352]	16.	Side Looking Air-borne Radar (SLAR) Imagery	[339]
7.	Glacier Movement	[312]	17.	Missle Trajectory	[346]
8.	Land use Mapping	[316]	18.	Underwater Mapping	[349]
9.	Cadastral and large scale surveys	[176a], [318], [319], [338], [80], [81], [164]	19.	Traffic Accident and Police Work	[350]
10.	Highway Design and Construction	[321], [331], [332], [347]	20.	Relief Displacement and Miscellaneous	[337], [351], [354]

Fig. 1: IMAGE ERRORS - SOURCES AND EFFECTS