Multi-scale block adjustment of aerial photogrammetric blocks

65615K Zhu, Lingli

Abstract: This paper mainly introduces the application of muti-scale bundle block adjustment in the Finnish Jabal Haroun Project(FJHP).The work flow of FJHP are listed firstly,such as digitizing,interior orientation and so on.Although these processes are based on the digital photogrammetry system, the work principle and mathematical model are also discussed.Then the method of bundle adjustment is described in detail—1:15000 and 1:30000 aerial photographs are combined into one block adjustment.In a bundle adjustment, the photograph is the elementary unit.Colinearity equations are set up according to the relationship between image coordinates and object coordinates.In the colinearity equations,we also consider the difference of the focuse length in different scales.There are more observations and redundancy in multi-scale block adjustment than in single-scale one,so higher precise is present.The technique of least squares—adjustment of indirect observation is used to solve the collinearity equations.The method of evaluation of adjustment solution is also introduced.The powerful calculation is required in performing the multi-scale block adjustment.

1. Introduction

Block adjustment procedures are one of the most important issues of research in photogrammetry.Without block triangulation,every stereomodel would need two horizontal and three vertical control points plus additional check points.The determination of control points is expensive and time consuming.Block adjustment greatly reduces the number of the control points required.The development of block adjustment is closely related to the computational power.Before the advent of computers,analytical methods were designed to use the output of existing stereoplotters and to minimize the amount of computation required by combining individual images into larger units.Then the block adjustment by independent models is developed to give much better results than previous methods..But the method of independent models introduced model coordinates as the intermedium to make the information lost.Recent research results and the technological developments during the last years in the navigation, positioning and orientation systems, result that the use of block adjustment procedures is rather widely.Bundle block adjustment presents the best accuracy than other methods.Nowadays nearly all block triangulation is done using the bundle method.

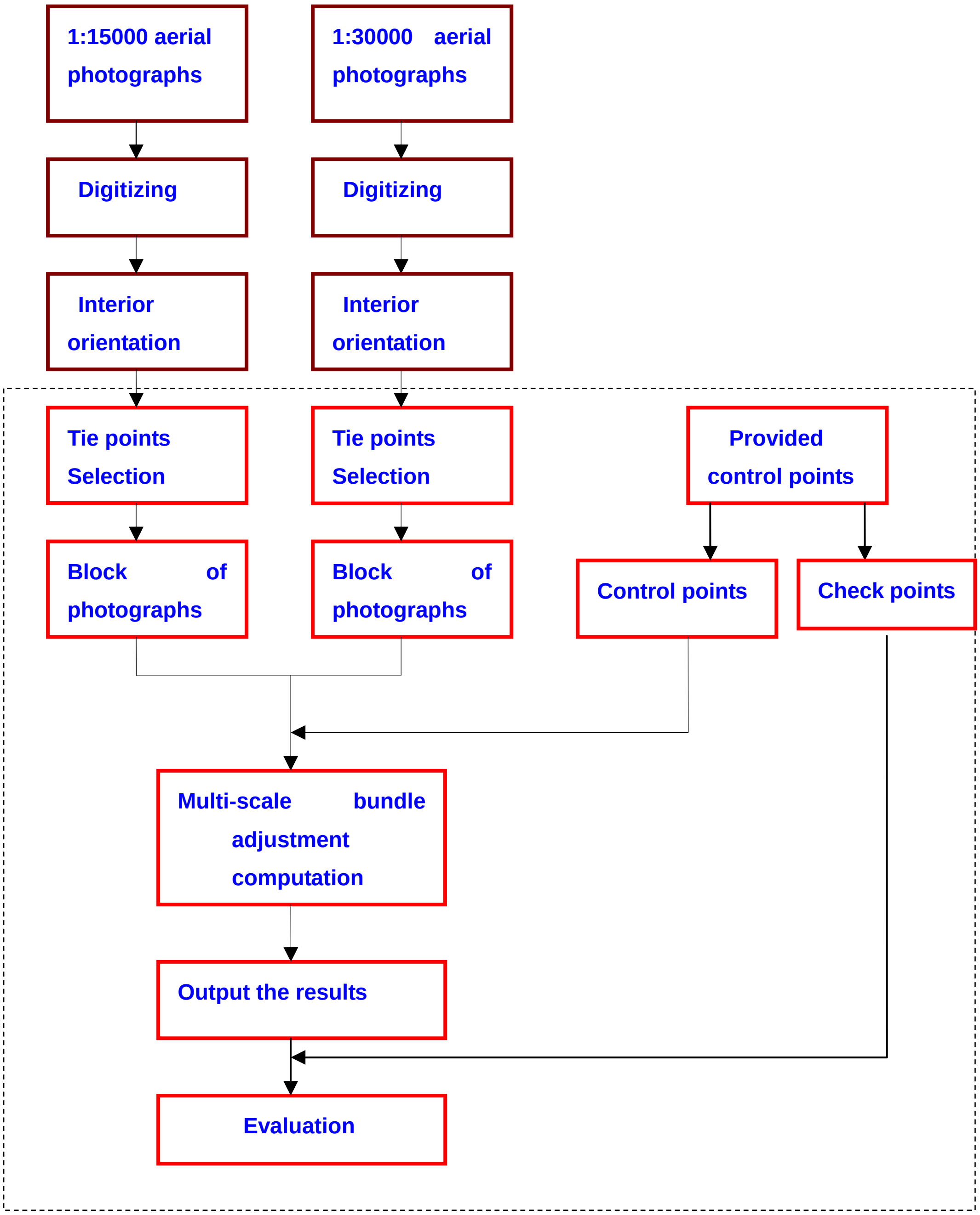
This paper presents the application of multi-scale bundle adjustment in the Finnish Jabal Haroun Project(FJHP).FJHP is Finnish Archaeological Project in Petra of Jordan. The survey and excavation data will be converted into the 3-D space for the visualization of the structures and the area.In this project,there are two sets of aerial photographs in different scales.One set is in 1:15000 and another is in 1:30000.Because there are no enough control points to cover the whole area,absolute orientation is a problematic.Block adjustment is a way which can not only get tie points coordinates for obsolute orientation,but also improve the project accuracy and consistent mapping across the entire region.Especially when different sets of aerial photographs are combined into one block,the accuracy of control points will be improved greatly because of the use of a great number of conditional equations in adjustment.

2.Preparation work

2.1 The original document and facilities

The standard sets of paper prints of 1:15000 and 1:30000 aerial photographs,23cm*23cm;
Some control points coordinates and also the explanation of its location in 1:15000 aerial photographs;
The implement specifications;
The data from camera calibrations;
Cannon Scanner and digital photogrammetry system.

2.2 The work flow



2.3 Digitizing aerial photographs

Digitizing aerial photograph is the first step of the work.Digitizing photograph is the process of converting an image into pixels,that are used on computers.There are all sorts of settings in the scanning software that determine the quality of the digitizing images.To ensure that no information in the photograph is lost,the digitizing interval must be adapted to the resolution of the photograph.The feature of interest on the scanner is the resolution for the various digitizing intervals that can be set.Scanning resolution refers to every inch across the image,the scanner reads the number of pixels.In theory,the higher the resolution,the better the quality of the image.But for too high resolution, longer time will be taken to digitize and a huge unmanageable file will be created.It not only takes up enormous amounts of disk space but also decreases the speed of compuer. Pixel dimension is the number of pixels in the image both horizontally and vertically. With a pixel dimension of 600 x 600, for example, an image has a total of 360,000 pixels. With a pixel dimension of 2400 x 2400 the image has sixteen times as many pixels (5,760,000) to play with. And clearly the more pixels, or specific points of information there are in a image, the more detail that can be represented.We can calculate the ground distance of one pixel in different resolution:Take 1:15000 aerial photograph as an example,for the resolution of 600 pixels/inch ,one pixel in its real ground distance can be calculated: 1/600 *15000 = 25 inch or 0.635 m.For the resolution of 2400 pixels/inch in the same scale photograph,the ground distance of one pixel is:1/2400 *15000 = 6.25 inch or 0.16m.From these numbers,it is obvious that 2400 pixels/inch will include more details.For this project,digitized images are mainly used on digital photogrammetric system for orientation.So the resolution of 600 pixels/inch is chosen.

2.4 Interior orientation

As the digitized image from aerial photograph,interior orientation is set up by measuring the fiducial mark.This process is made on the Z/I IMAGING digital photogrammetric system.Z/I IMAGING company is the combination of the two companies Intergraph and Carl Zeiss in the field of photogrammetry.This company is acting worldwide from two core locations—USA and Germany.This system offers the powerful software and hardware solutions.For this project,data from camera calibration is used to set up the camera file for interior orientation.Fiducial marks are measured manually.The purpose of interior orientation is to establish a relationship between pixel coordinate system and the image coordinate system.For digital cameras, the relationship between pixel and image coordinates is almost constant.This relationship is determined during calibration procedure. However, when aerial photographs are used, this relationship must be determined by measuring the fiducial marks. Different cameras have different fiducial marks.Fiducial marks are registered onto the film by projecting an image of the mark through a small lens. Each fiducial is designed and projected separately.In 1:15000 aerial photographs,fiducial marks are located on the edge frame of image.Differently,in 1:30000 aerial photographs,fiducial marks are placed on the corners of image (Figure1).

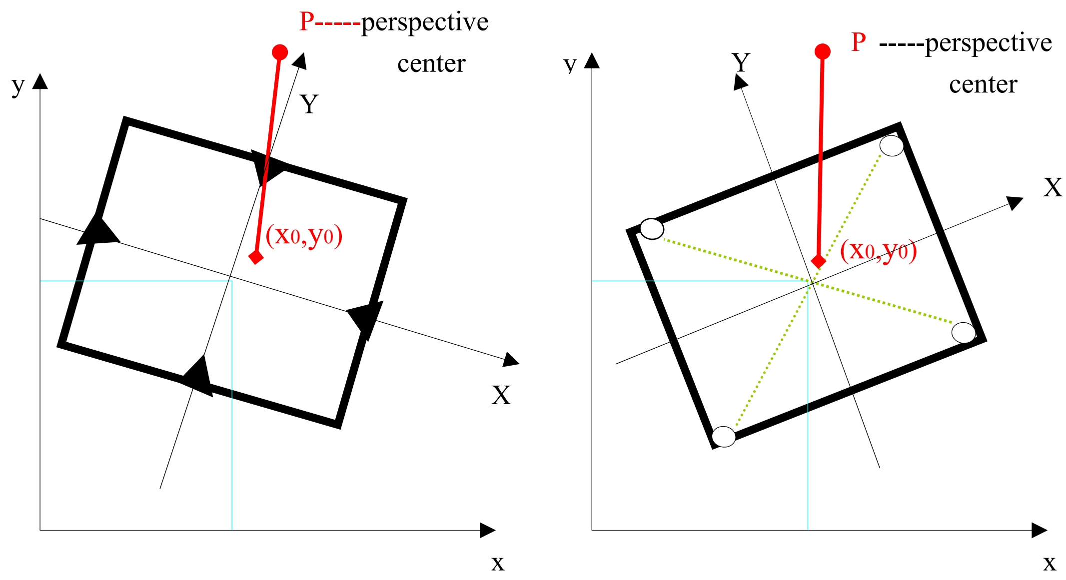


Figure 1. The relationship between pixel coordinate system and image coordinate system
X,Y-----image coordinate system x,y------ pixel coordinate system
(Left is 1:15000 image , Right is 1:30000 image)

The transformation from pixel coordinates to image coordinates is two dimension linear transformation.In photogrammetric job,coordinates system transformation is the most elementary operation.From interior orientation,relative orientation to absolute orientation,every step is based on the coordinate system transformation.For the linear transformation,there are six elementary transformations mathematically,each representing a single effect.They are translation,uniform scale,rotation,reflection,stretch(nonuniform scale factors), and skew. Photo coordinates are computed by 2D transformation, whose parameters are estimated using the measured and calibrated positions of the fiducial marks. Once you have performed interior orientation,you can determine the image coordinates of any point measured on the digital image by different transformation equations.For instance,six parameters affine transformation is commonly used:

$$X = a_{01} + a_{11}x + a_{21}y$$
$$Y = a_{02} + a_{12}x + a_{22}y$$

x,y------location of a point in pixel coordinate system
X,Y-----location of a point in image coordinate system
At least three fiducial marks are required for six unknown parameters.Since one usually works with more than three fiducial marks,the six unknowns are computed by least-squares adjustment.
For fiducial marks in the coners of the photograph,it is better to use a bilinear rather than the affine transformation.(K.Kraus 1993) The equation is:

$$X = a_{01} + a_{11}x + a_{21}y + a_{31}xy$$
$$Y = a_{02} + a_{12}x + a_{22}y + a_{32}xy$$

These equations have eight unknowns a_{ik}.At least four fiducial marks are required.
After the transformation of two coordinate systems,the image coordinate refinement is another important step in the interior orientation.This process refers to remove nonrandom

system components from the image coordinates.System errors include film and platen deformation,the principal point displacement,the distortion of lens,atmospheric refraction and the curvation of the earth.

In digital photogrammetric system,the transformation of coordinate systems and the image coordinates refinement are performed automatically according to the fiducial marks measured and the input data.

3. Implementation of multi-scale bundle adjustment

Without block triangulation,every stereomodel would need two horizontal and three vertical control points plus additional check points,requiring expensive ground surveys.In FJHP,there are no enough control points for absolute orientation.This is one of reasons to perform block adjustment.Another reason is to improve the project precise while the two sets of aerial photographs in different scales are used in one block adjustment.More observations and redundancies are used in least-squares adjustment of indirect observations.

3.1 Choice of the method of block adjustment

To design a block adjustment, the method of block adjustment should be firstly considered.Before the advent of computers,adjustment methods used analog devices or graphical techniques. With the development and availability of the computer,the unfavorable error propagation of analog photo strips was improved by simple strip adjustments, followed by polynomial strip adjustment and the block adjustment of independent models.The accuracy of polynomial adjustment is low and computationally economical,therefore it is well suited to the limited computational power available.Independent model block adjustment was the first really three-dimensional method.The model coordinates can be computed from photo coordinates, but the loss of information by the relative orientation and the changing combination of systematic image errors to systematic model errors is degrading the accuracy[5].At present,nearly all block adjustment is done using the bundle method.Only a small percentage of block adjustment is still done using independent models(Mikhail,2001).As far as multi-scale block adjustment is concerned,the method of bundle adjustment is only way to be chosen.In the method of independent model adjustment,the individual stereomodels are the basic units of aerial triangulation.Two sets of aerial photographs in different scale are impossible to establish the stereomodel each other.However,in a bundle adjustment of a block of photographs,the photograph is the elementary unit.Also,the coordinates transformation between image coordinate system and object coordinate system can be computed directly without introducing model coordinates as an intermediate step.Figure 2 shows the principle of bundle adjustment.An image ray connects an object space point,the perspective center of an image,and the projection of the point on the image,which are in one straight line.The image coordinates and the associated projection center of a photograph define a spatial bundle of rays.A photograph can be treated as a bundle of rays.The elements of outer orientation of all bundles in a block are computed simultaneously for all photographs(K.Kraus,1993).The known coordinates include the image coordinates of tie points,together with the image coordinates and object coordinates of the control points.

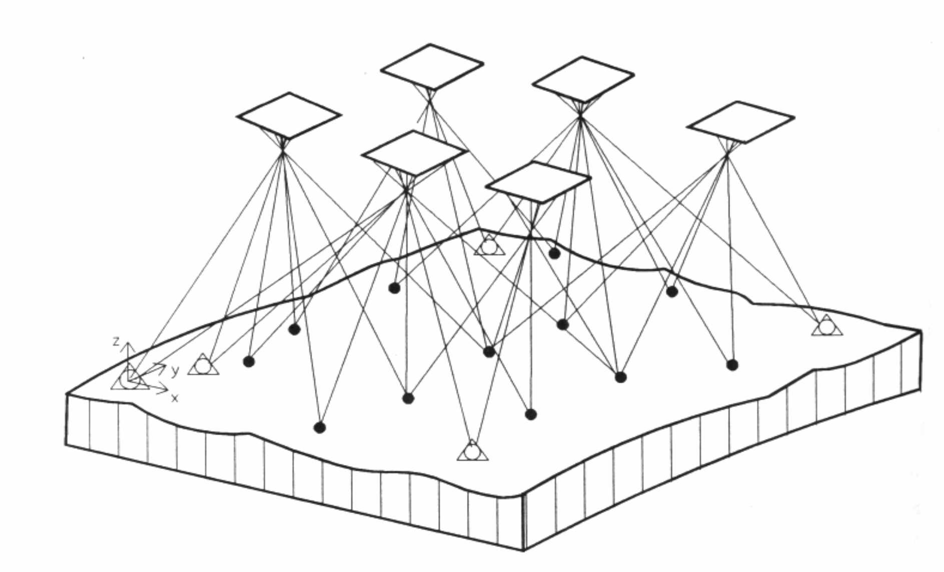


Figure 2: The principle of bundle adjustment(K.Kraus,1993)

3.2 Tie points selection

For given photographs,there are 3 strips,each for 7 photographs in 1:15000 and 3 strips,each for 5 photographs in 1:30000.The overlap of all photographs within a strip is about 30%,the sidelap between strips is about 60%.Tie points selection is to connect model together within a strip and tie neighbouring strips together.For different sets of photographs, tie points are chosen dependently.For example (see Figure 3),when tie points No.12 and No.13 are selected on the aerial photographs of 1:30000, these points are also used in 1:15000 photographs as much as possible.It is the same situation in control points.Then according to the principle of arrangement of points,some new tie points in 1:15000 photographs are also needed.For given control points,the block adjustment requires at least 2 horizontal and 3 vertical control points at the edge of the area.The more control points are used,the better precision.Therefore,most of them are distributed in the blocks,the others are listed as check points.After block adjustment,these check points are used to evaluate the accuracy.

The arrangement of control points is very important so that it can affect the accuracy of the whole block adjustment.Control points are required at the periphery of the blocks with an interval of 4 to 6 base length. In the case of parallel flight lines with 60% side lap,control points are required with a distance in the flight direction of approximately 4 base length. If a smaller number of control points will be used, the accuracy of the block adjustment will be less than the accuracy within a model, individually oriented by control points. In addition small blunders of the control points cannot be determined. If vertical control points are missing totally in or close to the side lap of two neighbored strips, the normal equation system of the block cannot be computed. Figure3 shows the arrangement of points in a block of 1:30000 photographs.

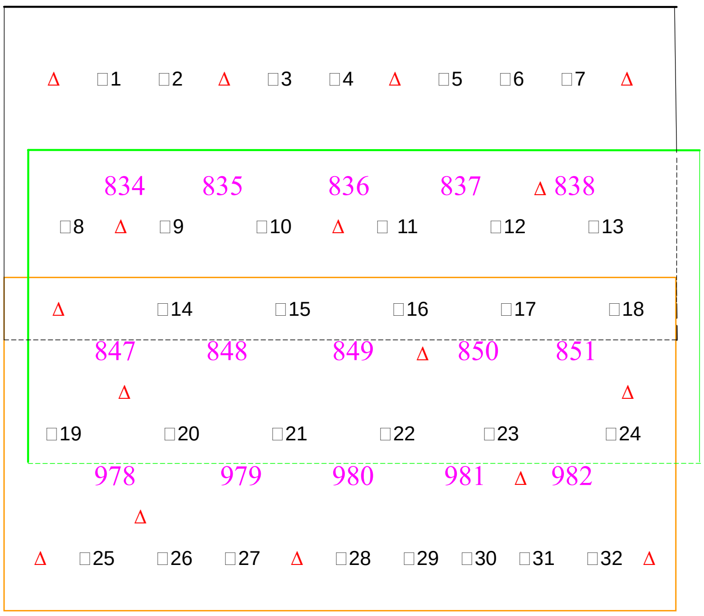


Figure 3: Set of 1:30000 photographs for a block adjustment

834,835---- aerial photograph number △ ----control point

□ ---- tie point 19,20---- tie point number

3.3 Block of photographs

After the tie points are chosen and marked on the aerial photographs.digital photogrammetric system as interface implements this process and brings these images into a block.Firstly,these points including control points and tie points are manually measured by interpreting the photographs.One tie point places at least two images,if it lies on the overlap of strips,it is possible to measure the same point on four or more images.The observations are done strip by strip.This process is similar to relative orientation-----successive images are rotated based on the first image,but,differently,it is multi-strip implemented and these strips are relevent each other by measuring the same tie point in neighbor strips.

For different sets images,the observations of points are done respectively to form different blocks.Two blocks are related by measurement of the same control points and tie points.

3.4 Multi-scale bundle adjustment computation

Bundle block adjustment is based on the collinearity equations, which describe the image geometry----- an object space point,the perspective center of an image,and the projection of the point on the image on a line in space.

Collinearity equations:

$$x - x_o = f \bullet \frac{a_{11}(X-X_o) + a_{21}(Y-Y_o) + a_{31}(Z-Z_o)}{a_{13}(X-X_o) + a_{23}(Y-Y_o) + a_{33}(Z-Z_o)}$$

$$y - y_o = f \bullet \frac{a_{12}(X-X_o) + a_{22}(Y-Y_o) + a_{32}(Z-Z_o)}{a_{13}(X-X_o) + a_{23}(Y-Y_o) + a_{33}(Z-Z_o)}$$

f = calibrated focal length; a = coefficient of rotation matrix;
(Xo,Yo,Zo) perspective center coordinates in object space ;
(X,Y,Z) point coordinates in object space;
(x,y)point coordinates in image plane;
(xo,yo)image principal point coordinates

For multi-scale bundle adjustment,collinearity equations are also used in different scale photographs.In single scale block,each image is different in the perspective center coordinates,rotation geometry and the position of image principal point. The difference between single scale block and multi-scale block only lies f-----the calibrated focal length,when collinearity equations are formed.For known interior orientation, parameter f is a constant.

Take Figure 3 as example,there are 15 control points and 40 tie points involved.Each measured image point yields two observation equations.

Known coordinates:

Observed image coordinates 113*2 = 226;

Control point object coordinates(3* 15) = 45;

Total 271 knowns.

Unknowns:

3*15 = 45 projective center coordinates;

3*15 = 45 rotations;

3*32 = 96 tie point object coordinates;

Total 186 unknowns.

Redundancy: 226 – 186 = 40

Above shows 1:30000 images block.For 1:15000 images block, most of the points which are used in 1:30000 block are also arranged in this block,in addition,more tie points are distributed to connect the images.And then redundancy is also calculated----55.When the two blocks are conbined into one block,the redundancy is the sum of them.The total redundancy is 95.Abviously,more redundancy improves greatly the quality of the whole block adjustment.The method of adjustment of Indirect observation is used to calculate the collinearity equations.That is say,each equation contains only one observation and parameters.The collinearity equations are written in nonlinear form.However,least squares treatments are generally performed with linear functions,since it is rather difficult and often impractical to seek a least squares solution of nonlinear equations.Consequently,some means of linearization must be used to get linear equations.Series expansions and Taylor's series are often used for the purpose,where only the zero and first-order terms are used and all other higher-order terms are neglected.(Mikhail,1976).

The linearized collinearity equation is given by

$$v + B\vartriangle = f$$

v----image coordinate residuals;
B----the matrix of partial derivatives of collinearity equations with respect to each of the six exterior orientation elements and the three coordinates of the object point;

△----the vector of nine corrections to the approximations for the parameters;

$$f = \begin{bmatrix} -(x - xo) - f\ U/W \\ -(y - yo) - f\ V/W \end{bmatrix}。$$

where

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = M \begin{bmatrix} X - Xo \\ Y - Yo \\ Z - Zo \end{bmatrix}$$

After the linearity of collinearity equations,adjustment of indirect observations can be used.In the case of the indirect observations technique,each condition contains one observation.For n observations with a redundancy r and u parameters,the number of condition equations c is

$$c = r + u$$

In this project,the number of the condition equations can be calculated from the redundancy of the observations in 1:15000 and 1: 30000 image blocks and the number of the parameters in equations.

$$c = 40 + 55 + 9 = 104$$

Then the normal equations can be formed.One of the most important factors in the adoption of bundle adjustment has been the development of efficient algorithms for formation and solution of the normal equations.Detailed analysis of the structure of the parameter matrices greatly reduces the computational and storage requirements for the solution.The total normal equations are a large system of equations with a well-defined structure.From this structure,one set of variables----point coordinate corrections are eliminated to reduce the size of the matrices.After solving for the remaining image parameter corrections,the point coordinate corrections are obtained.

The reduced matrix form of the normal equations is

$$N\vartriangle = t$$

$$N = B'WB$$
$$t = B'Wf$$

N---- the normal equations coefficient matrix;
t---- the normal equations constant term vector;
W---the weight matrix of the observations;

From the above formula,△,the corrections of the parameters can be calculated.These parameters include six exterior orientation elements and three coordinates of tie points in object coordinate system.An adjustment yields corrections to the approximate values of these parameters.For initial approximations of the parameters,some assumptions can be made.For aerial photographs with approximately vertical axes,we can set approximations for the photo-tilts of $\omega o = \phi o = 0$.The approximation κo,which can be assumed to be constant for all photographs of parallel strips,can be taken from the flight-planning records or from the overview of all photographs.The approximate coordinates Xo,Yo,Zo of the projection centres and the approximate coordinates X,Y,Z of the tie points can be derived with the help of the rotation matrix.If the approximate\ions are very poor,the corrected values must be treated as new approximations for a new adjustment.When setting up an iterative adjustment program,criteria for terminating the iterations must be incorporated in the program.The criteria should be selected such as convergence of solutions and the choice of appropriate tolerance value.

4.Evaluation of the block adjustment

After running a block adjustment,evaluation should be done in order to meet the project requirements and ensure that there are no bad measurements and assumptions.Two steps are processed----quantitive evaluation and statistical evaluation.

4.1 Quantitive evoluation

In a quantitive evaluation,the operator examines graphical representations of the adjustment's output in order to understand broad trends and to catch obviously bad inputs.Check points are present to evaluate the accuracy.These check points are known the coordinates in object space system but they are not be used as control in the solution.(See Figure 4)The direction of the error of check points should be random.If residuals all pointing in the same direction,it indicates the present of a systematic effect.These effects may indicate uncorrected errors,such as atmospheric refraction,or an image parameter that has been weighted too highly and not allowed to adjust.A residual that is larger than its neighbors or points in the opposite direction to those near it indicates a bad measurement. If there are enough check points available,a check point error plot can show the deformation of the block and indicate any problems with control point coordinates.In Figure 4,the check point on the LowRight shows the larger residuals,therefore the points around this check point should be adjusted or remeasured.In the multi-scale block adjustment,when the error occurs,cause should be checked in the observations of different sets images.

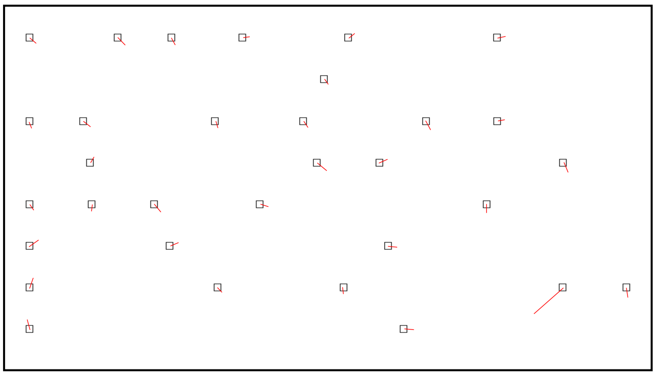


Figure 4 : plot of the check point error.

4.2 statistical evaluation

There are three aspects,precise,accuracy,reliability in statistical evaluation.

• The accuracy of the solution refers to how well the results agree with independent external measurements of the same quantities.The accuracy is assessed using check points.Calculation of mean squared error of check points yields a statistic that is an estimate for the average value of the coordinate covariance matrix,provided that the check point coordinates are consider perfect and that the solution is unbiased.If the check point root-mean-square-error is not close to the average coordinate standard deviation,then the solution should be examined closely for bad control points or systematic errors in the observations.

• The precision of the solution is evaluated by examining the covariances of the parameters ,which is the products of a least squares adjustment.The diagonal elements of the covariance matrix Σ are the parameter variances,and the off-diagonal elements are the covariances between the parameters.The value of each covariance reflects the degree of correlation between the corresponding observations.When all covariances are zero,the observations are said to be uncorrelated.

$$\Sigma = \begin{bmatrix} \sigma_{x2} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{y2} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{z2} \end{bmatrix}$$

In addition,another method can be used to evaluate the precision of the points.When variance and standard deviation are measures of precision of the one-dimentional case of a variable,error ellipses may be established around the point to designate precision regions of different probabilities in the case of two-dimentioal problem.In the three-dimensional case,where the elevation as well as the horizontal position of the point is involved,the precision region becomes an ellipsoid.An example of error epllises is given in Figure 5.It shows 13 strips and 13 photographs in each strip.Control points are distributed at the edge of the area.We can see that at the edges of the block,the precision of the point is poor.Therefore,in order to reduce the error of the point,the interest area should be away from the edges.

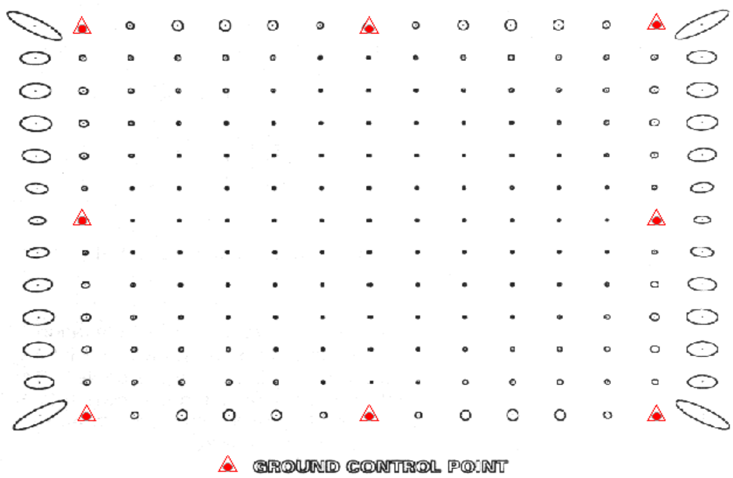


Figure 5: Error ellipses associated with ground points position

- Reliability of the solution is its resistance to gross errors,or blunders in the input data.If

bad inputs are not detected,the solution results may be invalidated.Bad data can be detected only by having redundant observations,within a strong geometric configuration that allows them to serve as a check on each other.Blunders can be detected only by examining the residuals for each observation.If one point is measured only on two images,measurement error parallel to the epipolar line will have no effect on the calculated residuala and will only cause the depth of the point to be calculated incorrectly(Mikhail 2001).When this point is detected on the third image,error along the epipolar line can be found.Generally,The higher redundancy number for a observation,the more visible an error will be in the residuals and the better the probability of detecting an error in that observation.

The detection of blunders is based upon the examination of residuals,To use residuals to test for blunders,we must separate the effects of the geometry determining the residuals from the effects of a blunder in the corresponding observation.(Mikhail 2001)The geometry determining each individual residual is summarized in Q_{vv},the cofactor matrix of residuals.Standardized residual is often used as residual testing.That is,the residual divided by its standard deviation.The standard residual can be derived from the square root of the corresponding diagonal element of Q_{vv}.

5.Conclusion

The bundle adjustment is a flexible tool in photogrammetry.Especially nowadays,GPS,INS and self-calibration parameters are widely used in bundle adjustment.According to the principle of the bundle adjustment,each photograph can be as basic unit to perform the adjustment.Unlike in Independent model adjustment,each model is the basic unit,that is to say,the elementary condition is to form a stereo model between the neighbor photographs.Multi-scale block adjustment conforms the principle of bundle adjustment. Collinearity equations are formed based on each point.In multi-scale block adjustment.The number of redundancy of observations is the sum of the number of redundancy of different scale blocks.There are more number of redundancy than single scale block. The solution obtained using one subset is generally different from the solutions obtained using any other subset.The technique of adjustment of indirect observations is used to eliminate the inconsistent of the solutions in collinearity equations. The number of condition equations can be calculated from the number of the redundancy and parameters.These parameters includes the exterior orientation of each image and the object coordinates of tie point,totally nine parameters,which are the results of bundle adjustment.Normal equation system is formed to obtain the corrections of the parameters.A iteration program should be set up for the solution.The initial approximations of these parameters can be calculated based on some assumptions.The criteria for terminating the iterations must be incorporated in the program.The evaluation after block adjustment is also important.Quantitive evaluation and statistical evaluation are implemented based on some methods,such as the residuals of check points,covariance,standard deviation,standardized residuals,error elipses and so on.

6.Discussion

The paper presents the method of multi-scale bundle block adjustment.At present time,this project is in hand and there are further work processed.The solution and evaluation of the bundle adjustment have been described above theorically.Digital photogrammetry system limits the project in single scale image block.It is a problem to calculate the adjustment in different scales photographs based the digital photogrammetry system.Therefore,in order to implement this process,programming work is necessary.The implement will take some time.Later,more data and figures will be present.

References:

[1] K.Kraus. *Photogrammetry Fundamentals and Standard Processes* Volume I Edition 4th,Germany,1993

[2] K.Kraus. *Photogrammetry Advanced Methods and Applications* Volume II Edition 4th,Germany,1997

[3] Edward M.Mikhail,James S.Bethel,and J.Chris McGlone *Introduction to Mordern Photogrammetry*,John Wiley & Sons,Inc.U.S.A,2001

[4] Edward M.Mikhail *Observations and Least squares* Thomas Y.Crowell Company,Inc. University Press of America,Inc. 1976

[5] http://www.ipi.uni-hannover.de/html/publikationen/special/jacobsen/block_adjustment.pdf

[6] *ISPRS Journal of Photogrammetry and Remote,* 21 April 2006 http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6VF4-4JSFVBD-1-W&_cdi=6000&_user=952938&_orig=search&_coverDate=04%2F21%2F2006&_sk=999999999&view=c&wchp=dGLzVzz-zSkzS&md5=c03b74e3c8721d5d18e05fdcc99febfd&ie=/sdarticle.pdf