CHAPTER 11

Aerotriangulation

11.1 PHOTO CONTROL BRIDGING

A critical phase in photogrammetric mapping is rectifying the aerial images to the appropriate tract on the surface of the earth. This is accomplished by collecting horizontal and vertical data, as discussed in Chapter 10, to ascertain the spatial location of a number of features that are visible and measurable on the aerial images. The process is often called control bridging, which refers to passing horizontal and vertical information from one aerial image to the next.

Geometric stability requires that a minimum of four points with established horizontal and vertical location spaced in the corners of a full stereomodel be used to fully rectify the model as shown in Chapter 10, Figure 10.6. On a project involving a few stereomodels this may be a conventional ground surveying enterprise, but it can be a costly ground survey venture for most medium to large project areas. The expense and time required to collect the ground survey data in this manner may render the mapping project impractical.

Computer processing has played a major role in driving mapping scientists to develop rigorous and efficient mathematical protocols that allow for the densification of stereomodel control from a minimal number of strategically positioned ground survey points. This procedure is generally referred to as aerotriangulation. Analytical software available today, with its built-in quality checks, has made aerotriangulation the preferred method of image adjustment to the earth for photogrammetric mapping. This chapter will not discuss the theory of these processes, but rather it will provide necessary guidance and explanation of procedures to plan and estimate the efforts required to perform satisfactory aerotriangulation for a photogrammetric mapping project.

11.1.1 Control Point Selection

To georeference a spatial stereomodel to the ground, it is necessary to furnish at least a minimum amount of both horizontal and vertical field control points.

To illustrate a conventional control solution, Figure 10.8 (Chapter 10) denotes a mapping project covering three photo flight lines and the pattern of survey points required to fulfill the minimum of four points per stereomodel necessary to assure a reliable spatial solution. Due to terrain conditions, access restrictions, or lack of identifiable cultural features, it is not always feasible to conform to these control point patterns.

Early on there was analog methodology to accomplish photo control bridging, but the advent of computer technology changed photo control extension procedures forever. Software vendors have created protocols that allow for automation of data input, error checking, and easy-to-read data output. Software has also been developed to handle the peculiarities of ABGPS control.

An aerotriangulation solution simultaneously determines the spatial intersection of image rays of a finite point from its position on overlapping photos. It is the analytical procedure that allows a mapper to utilize a skeletal pattern of field survey control to analytically generate sufficient photo image points to map a project.

11.1.2 Bridging Spans

Aerotriangulation allows many models to contain no field survey information. In practice, there are certain maximum uncontrolled model spans. They should be limited to those noted in Table 11.1. Figure 11.1 presents a comparison of the relative

Table 11.1 Maximum Uncontrolled Models for Aerotriangulation

Map Accuracy	Uncontrolled Models	
	Vertical	Horizontal
ASPRS1	2.0	4.0
NMAS	2.5	4.5
ASPRS2	3.0	5.0
ASPRS3	3.0	6.0

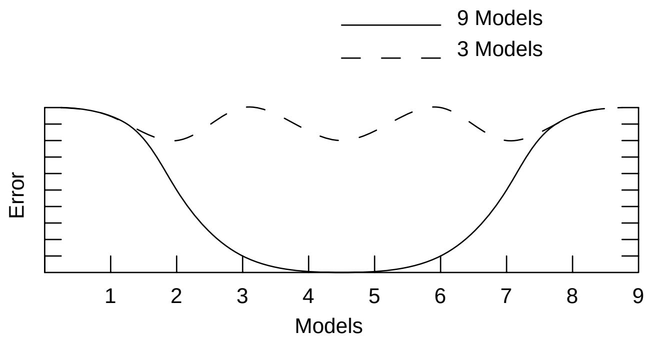

Figure 11.1 A comparison of the relative vertical errors propagated on a flight line spanning nine stereopairs.

vertical errors propagated on a flight line spanning nine stereopairs. The solid line represents a flight line spanning nine models, all of which are uncontrolled except for field control points at the extremities of the two end models. Compare this curve with the dashed line depicting the greatly reduced relative magnitude of errors if field control points were positioned at three-model intervals.

The acceptable feature types for field control points to be used in an aerotriangulation adjustment are the same as those described for conventional control. However, the number of field control points employed is substantially less and the spacing between them can be significantly larger. This procedure, when employed properly, should reduce field survey time and costs. To ensure this the aerotriangulation procedure involves a cost factor, but user-friendly software and high-speed computer processors have significantly lowered the time/cost element required to analytically adjust stereoimages to the earth. The cost of using aerotriangulation over less rigorous methods for most projects is also not a large percentage of the total cost of a mapping project today. Most major mapping contractors prefer to use this method because of the ease of use and the quality checks that the software can provide.

11.1.3 Skeletal Ground Control

Refer again to the conventional ground control point density in Chapter 10, Figure 10.10. The amount of skeletal horizontal ground control required to meet FGDC NSSDA, ASPRS, and NMAS skeletal field control requisites on the same site is diagrammed in Chapter 10, Figure 10.11. There are situations where breaking a large project into more than a single analytical run is advisable. In this event, ground points must be selected for each of the sectors as a separate entity.

It should be noted that photo image points, which fall outside the field control pattern, are subject to unusual errors. In this situation, the analytical bridge is actually extrapolating a solution whose accuracy tends to deteriorate rapidly. The further outside the control pattern the point falls, the greater the error. Therefore, it is desirable to have exterior photo control points located outside the mapping area.

11.1.4 Photo Control Extension Procedure

Photo control extension relies on utilizing differential parallax to analytically create coordinate sets on a number of selected photo image points. This process is designed to generate a sufficient pattern of photo image points based upon data collected on a minimal number of field survey stations. Several techniques accomplish photo control bridging. Analog procedures require a significant amount of manual manipulating in several stages, while bridging with softcopy instruments requires relatively little manual intrusion. So generally, the more manual bridging operation proceeds similarly to the procedure described herein.

11.1.4.1 Photo Image Point Location

A pattern of at least six photo image point locations per stereomodel, which equates to a minimum of nine points on most photos, is selected. Figure 11.2 suggests

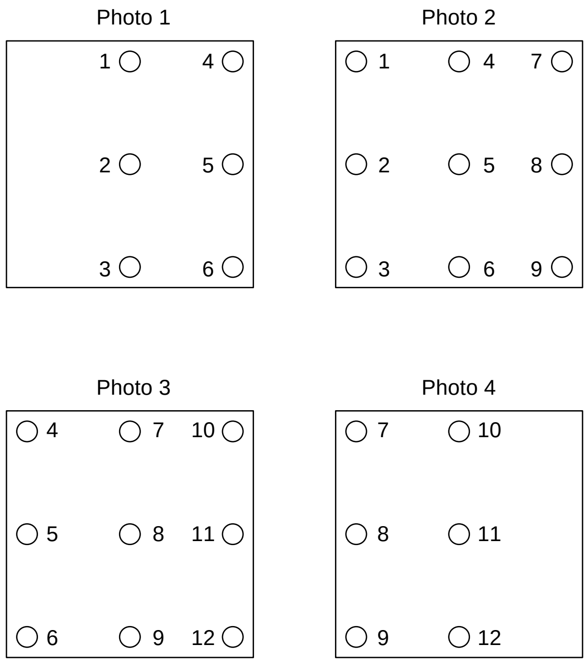

Figure 11.2 Basic patterns of at least six photo image point locations per stereomodel, which equates to a minimum of nine points on most photos.

the basic selection patterns of these arbitrary locations. Other pertinent points, such as field survey control points and strip connector pass points between adjacent flight lines, are also included.

11.1.4.2 Point Pugging

In the analog process an artificial target, called a pug point, is drilled into the emulsion of the diapositive at the location of each control point that appears on the image by employing a transfer device, as shown in Figure 11.3.

When utilizing a softcopy instrument, the control points are arbitrarily selected on the image which is displayed on the screen. Since the computer keeps these locations in its memory, there is no need for pugging.

11.1.4.3 Reading Diapositive Coordinates

Several pieces of information must be read from the pugged diapositives, utilizing a comparator device, into the aerotriangulation software prior to the processing. Once the point locations are selected on the image in the softcopy process, the computer keeps these locations in its memory, so there is no need for reading coordinates.

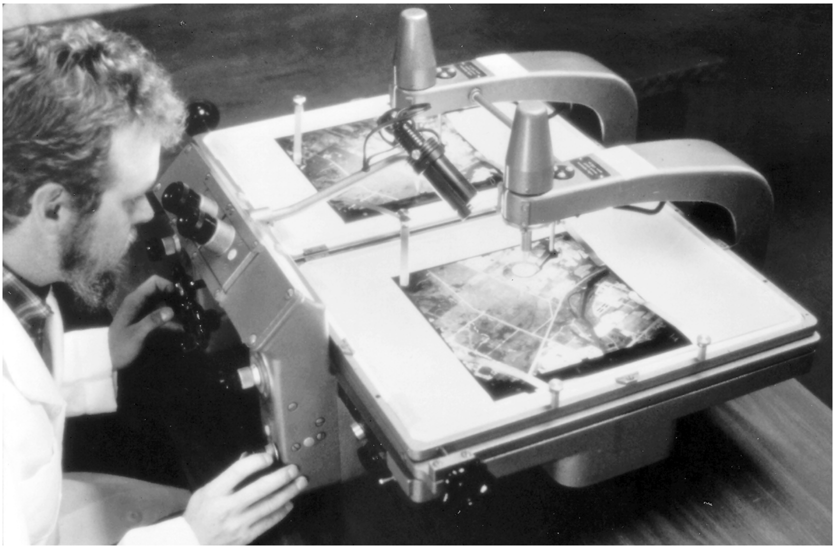

Figure 11.3 Point transfer device in use. (Courtesy of Surdex Corporation, Chesterfield, MO.)

11.1.4.4 Computer Processing

These raw plate coordinates, along with the field control point information, are imported into the computer and processed through an aerotriangulation package, of which there are a number available. A general procedure would include:

- In the sequential model assembly each stereomodel is processed through a relative orientation routine involving a least squares adjustment of colinearity equations. This solution produces individual model coordinates unrelated to any reference outside the matrix. Residuals of the model coordinates provide a test of the proficiency of the pugging and comparator readings.
- A strip formation procedure joins the independent stereomodels through a three-dimensional transformation. A series of equations links successive models by common pass points. The coordinates, at this stage, remain in an arbitrary reference scheme.
- Each strip undergoes a polynomial adjustment which produces preliminary ground coordinates for all of the photo control points.
- A simultaneous bundle adjustment provides a fully analytical aerotriangulation solution (as required for NMAS, ASPRS1, and ASPRS2), and the entire block of data passes through an iterative weighted least squares adjustment until a convergent "best fit" solution is attained. An RMSE error is noted so that the observer can judge how far the coordinates of each point were mathematically "stretched" out of position in order to resolve a solution.

11.1.5 Accuracy of Aerotriangulation

ASPRS map accuracy standards declare that the maximum horizontal and vertical RMSE of all the field control points should fall within that calculated by

Table 11.2 Accuracy Criteria for Aerotriangulation

Map Accuracy	Horizontal	Vertical
ASPRS1	10,000	9,000
NMAS	9,000	7,500
ASPRS2	8,000	6,000
ASPRS3	6,000	4,500

Equation 11.1. This equation can be used to calculate errors of X and Y coordinates and/or elevation.

$$E_{rms} = H/f_{xyz} \tag{11.1}$$

where:

E_{rms} = RMSE
H = flight height
f_{xyz} = factor specified in Table 11.2

There is a further, notable element to be considered. Since an RMSE may be roughly equated with an absolute average, be aware that there are errors at individual field points that will exceed the magnitude of the RMSE. Maximum error at any field control point, either horizontal or vertical, should not exceed triple the magnitude of the RMSE.

To pass judgment as to the validity of the RMSE, select the appropriate accuracy factor (dependent upon the desired accuracy goal) from Table 11.2. By entering this factor into Equation 11.1, the relevant maximum RMSE will become apparent.

11.1.6 Accuracy Check

There are a few items contained in the bridging printout that should be valuable in analyzing the relevance of the aerotriangulation:

- If the RMSE of the discrepancies at the field control points is significantly greater than that produced by Equation 11.1, there may be areas of intolerable inaccuracies.
- If the magnitude of the residual error at individual field control points is greater than triple the RMSE, there may be areas of intolerable inaccuracies.
- In the event that several field control points or points in critical locations are excluded from the final analytical solution, in order to gain a tolerable RMSE, there may be an adverse field control solution.
- If the analytical solution is the product of bare minimum control, the residuals may mask a faulty resolution.

11.1.7 Effects of Analytical Error

As noted by the fact that aerotriangulation networks generate an RMSE error, this analytical bridging procedure will introduce more error into individual photo control points than if data for these same points had been established by field surveys. This could have an effect on choosing a photo scale.

11.1.7.1 C-Factor Adjustment

It is advisable to consider adjusting the C-factor, by utilizing Equation 11.2, on projects that employ analytical control bridging procedures.

$$c_{fx} = c_f * \left[1 - \left(0.05 * m_{uc}\right)\right] \qquad (11.2)$$

where:

c_{fx} = revised C-factor
c_f = original C-factor
m_{uc} = number of uncontrolled models spanned

11.1.7.2 Ground Targets

It would be good practice to consider ground targets for field control points. The use of preflight ground targets provides better definition to field control points and could help reduce aerotriangulation network residuals.

11.1.8 Example of Field Control Point Scheme for Aerotriangulation

Figure 11.4 shows a typical ground control plan. The plan shows the project boundary and flight lines as well as the approximate location or feature to be used as a ground control point most often established in the field by a surveyor. Spacing between control point locations in this example is approximately 2.5–3.0 models.

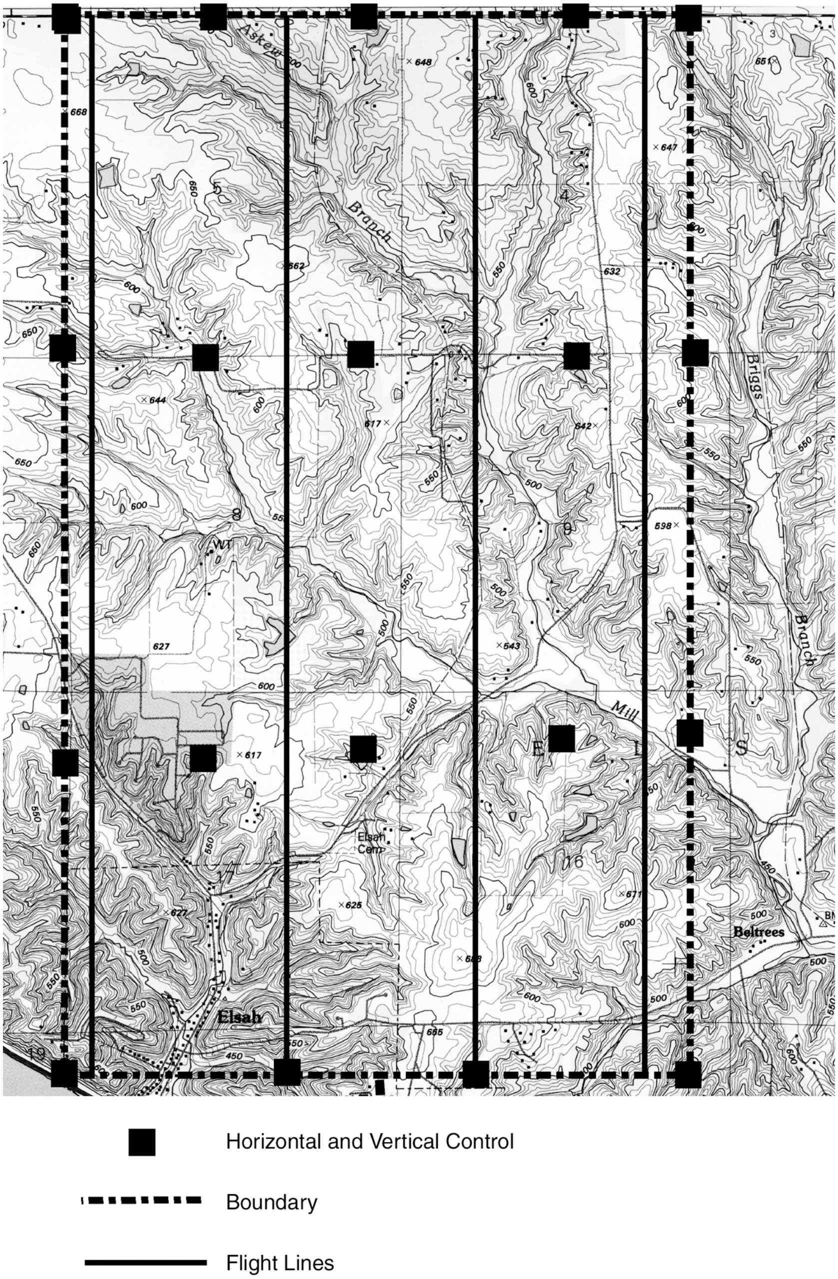

Figure 11.4 Map showing project boundary, flight line locations, and positions of suggested control point locations.