CHAPTER 11

An Introduction to Machine Plotting

So far we have considered only simple methods of plotting from air photographs, in particular those based on the slotted templet method of increasing control, the simple mirror stereoscope and parallax bar for calculating heights, and the Sketchmaster for the final plotting of detail. In the past these methods have been used for making topographic maps, and there is no reason why they should not continue to be used for map revision and for making maps of scales between 1 in 100,000 and 1 in 25,000. Even at such small scales it would be economic to employ these simple methods only for relatively small projects or where the work is of a periodic nature. Most organizations dealing with map-making from air photographs would nowadays employ machine plotters of some sort.

The simple reflecting plotters make no attempt to correct lens distortions, and it is only possible to cope with height distortion by local adjustments. On the other hand, the simple mirror stereoscope does not correct for either lens or tilt distortion. We have seen in Chapter 7 how the radial-line plotter makes it possible to plot a map from the model formed in an ordinary mirror stereoscope, but this solution is only accurate within the limits of the radial line assumption.

SIMPLE CONCEPT OF PLOTTING INSTRUMENTS

In order to simplify the subject as much as possible we might consider all plotting instruments as derived from—

1. the simple mirror stereoscope,
2. the simple reflecting plotter,
3. the optical rectifier.

1. The basic instrument of this group is the simple mirror stereoscope with parallel mechanism, parallax bar and plotting attachment. In all such instruments the model is imaginary and not theoretically correct. The warping of the model may be corrected—

   (*a*) approximately as in the radial-line plotter (see Fig. 7.13);
   (*b*) mathematically as in the Zeiss Stereotope;
   (*c*) mechanically as in the Santoni Stereomicrometer (see Fig. 11.11.)

2. In this type of instrument a theoretically correct imaginary

model is set up. The plotting pencil is attached to a floating mark which is moved across the model and in contact with the model surface.

If we consider viewing two Sketchmaster photo-images simultaneously, one with each eye, then the theory of this type of plotter becomes apparent. One of the simplest instruments of this type is the S.O.M. Stereoflex (see Fig. 11.12).

3. In this type of instrument a pair of photographs is projected from two optical rectifiers and viewed either

(*a*) Stereoscopically as in the Zeiss Stereoplanigraph (see Fig. 11.14), or

(*b*) anaglyphically as in the multiplex type of instrument (see Fig. 11.1.)

Although by no means the most accurate instrument, the multiplex is perhaps the simplest of the larger instruments, and is therefore treated in some detail below.

The foregoing is intended only as an introduction to instrumentation and not as a classification.

Aerotriangulation

In common with the simple methods of plotting, machine plotters require control points in order that the models may be correctly set up. Each overlap will require at least two ground control points and three height control points. This would entail a very large amount of ground work. For medium and smaller scales the slotted templet assembly could be used in order to increase the control, but this mechanical adjustment cannot help with height control. Some instruments, including the multiplex, are capable of breaking down major control to form minor control. The process involved is comparable with ground methods of triangulation, and is known as aerotriangulation.

THE MULTIPLEX

These instruments have been made by most firms whose activities include the manufacture of large photogrammetric instruments, and all are similar in principle and design. The one described here is produced by the Williamson Manufacturing Co. Ltd, of London.

The basic idea is that of the anaglyph, which from time to time has been a popular feature of picture magazines. Two slightly different views of the same object are illustrated, one depicted in green and the other in red. The two images are superimposed on the page but are so arranged that one is slightly displaced to left or right of the other, the whole forming a rather blurred image. This page is viewed through a pair of spectacles, of which one eye-piece is a green and the other a red filter, so that one image is seen with one eye and the other with the other eye; thus a three-dimensional impression is conveyed to the brain.

In the multiplex the image of one photograph is projected in red on to a plain white surface, and the image of its overlapping pair is projected in blue-green on to the same surface. These reflected images are viewed with red and blue-green spectacles and a three-dimensional anaglyphic model is seen (Fig. 11.2). Since it is a positive image which is projected, the reflected image of the left-hand photograph in Fig. 11.2 will consist of blue highlights on black shadow; thus no light will pass a red filter, so that no image would be received by the right eye.

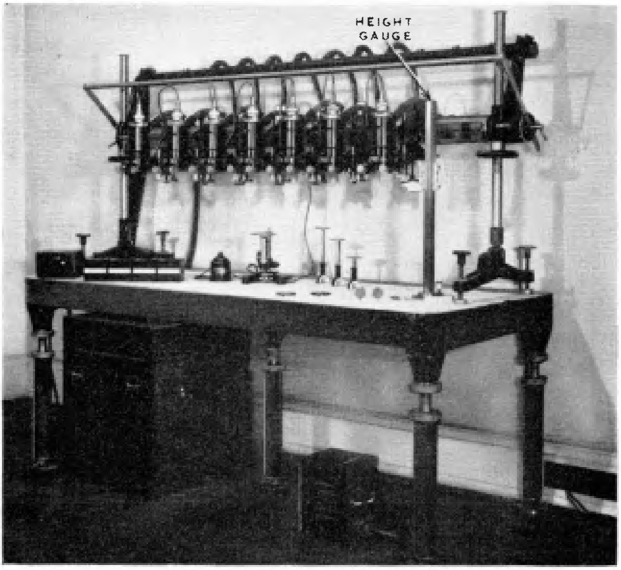

FIG. 11.1 (i) THE MULTIPLEX 7-PROJECTOR ASSEMBLY WITH ILLUMINATION CONTROL UNIT
(*Williamson Manufacturing Co. Ltd.*)

The general appearance of the instrument may be seen from Figs. 11.1(i) and (ii).

The apparatus consists essentially of the following parts—

1. A range of projectors, each of which is made to represent a particular camera station.

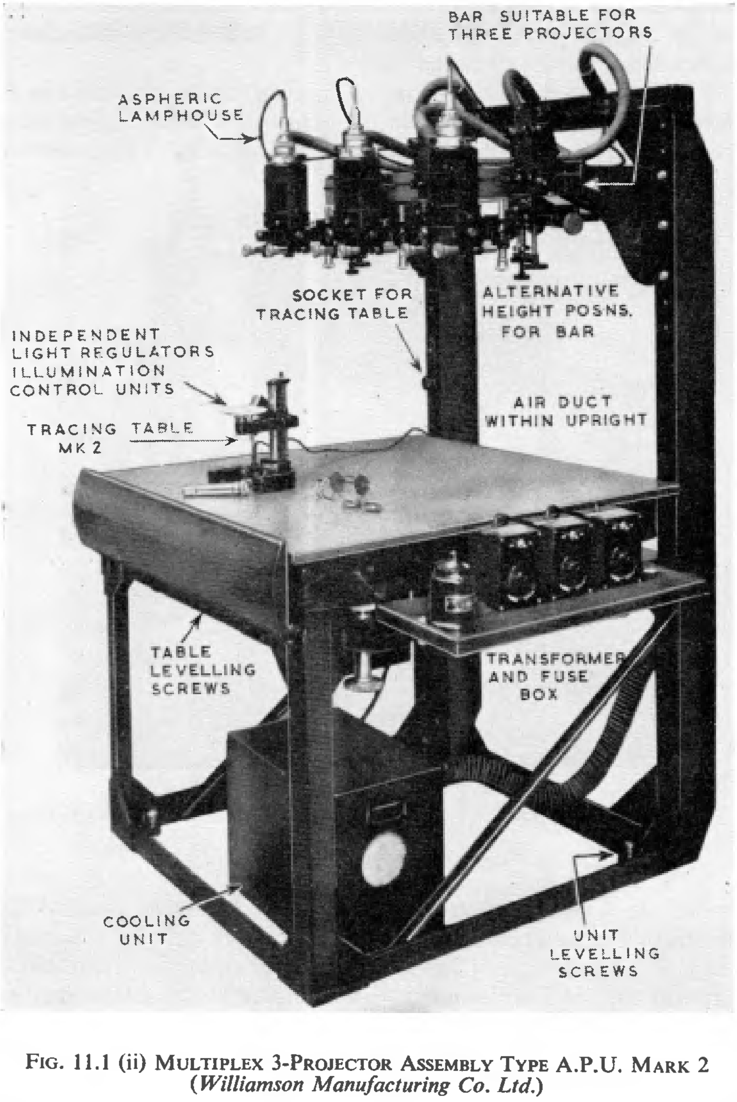

FIG. 11.1 (ii) MULTIPLEX 3-PROJECTOR ASSEMBLY TYPE A.P.U. MARK 2
(*Williamson Manufacturing Co. Ltd.*)

2. A horizontal map table on to which the map is eventually plotted.

3. A bar which supports the projectors, and which on some models is capable of rotation about its axis (Fig. 11.1(i)) and of being " tipped " in the fore and aft direction.

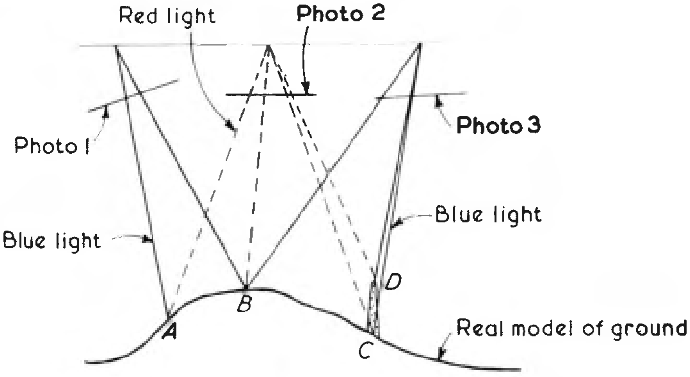

FIG. 11.2. FORMATION OF THE REAL MODEL IN THE MULTIPLEX

4. A tracing table (see Fig. 11.4) which forms the reflecting surface on which the coloured images of the two photographs are viewed. In the centre of the plane surface of the tracing table is the floating mark formed by a point source of light. The table itself is carried on a stand which can be moved over the surface of the map table. Vertically below the floating mark is a pencil which can be raised or lowered on to the map plane, and so can trace the plan route of the floating mark. The tracing table surface can be raised and lowered so that the floating mark can be kept in contact with the model surface. Variations in height of the floating mark can be read on the glass scale which will normally be graduated in millimetres, and therefore a graph will need to be constructed so that the readings can be converted to feet or metres at the model scale. A specially divided glass scale can be obtained to read directly in feet or metres if the amount of work to be done at any particular scale warrants such expenditure.

Each projector (see Fig. 11.3) consists of three main parts—body, condenser housing and lamphead, and is provided with an interchangeable red or blue-green filter and a projector bulb. The body is a small-scale reproduction of the taking camera, approximately

114 mm diameter and 62 mm high, mounted so that it may be rotated about, and translated along, three mutually perpendicular axes (see Fig. 11.5). Figure 11.3 is annotated to show the method of effecting these movements.

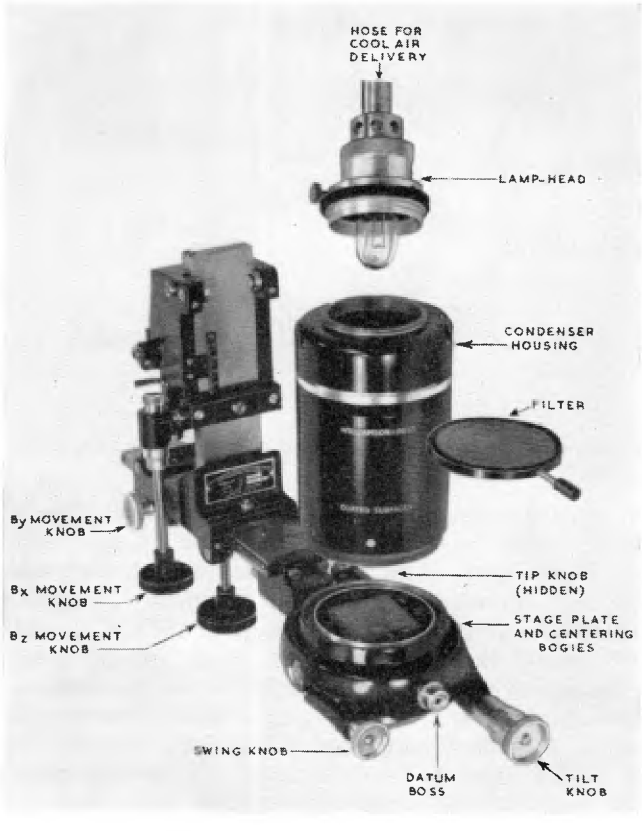

FIG. 11.3. MULTIPLEX PROJECTOR MARK 2
(*Williamson Manufacturing Co. Ltd.*)

Since the lamphead is small and the power of the bulb is high the projector must be cooled by pumping in air through ducts. This will prevent the emulsion on the diapositive from melting, and prolong the life of the bulb.

The diapositive is reduced in size to about 62·5 mm × 62·5 mm. It is obtained from the negative by projecting the original negative on to a sensitized glass plate in a reduction printer.

Although similar to an optical rectifier, the reduction printer makes no attempt to remove tilt distortion, but lens distortions are greatly reduced by matching the projector lens in the reduction printer against the camera and multiplex projector lenses.

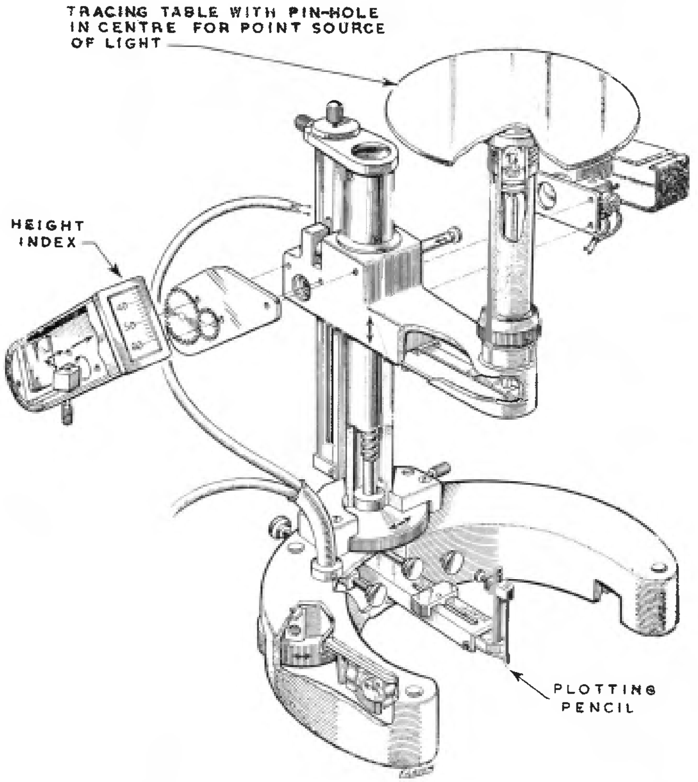

FIG. 11.4. MULTIPLEX TRACING TABLE MARK 2
(*Williamson Manufacturing Co. Ltd.*)

Once the instrument is properly set up, the plotting of detail and contours is a straightforward operation of the tracing table and pencil, but the process of setting up the instrument, usually known as orientation, is complex, and is carried out in the following stages—

1. *Inner orientation* which entails the re-establishment of the central perspective for each projector in turn. The projecting lamp must be centralized and focused, and the diapositive must be brought into its correct plane, i.e. that plane which simulates the focal plane in the taking camera. The diapositive must also be centralized by making the principal point lie on the axis of projection. In addition to making provision for the reduction of distortions, steps must be taken to satisfy the lens condition. The Scheimpflug condition does not apply as the lens plane and diapositive plane remain parallel as in the taking camera.

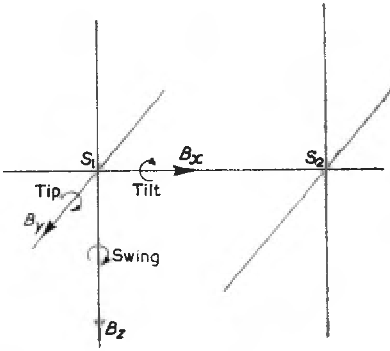

FIG. 11.5. THE MOVEMENTS OF A MULTIPLEX PROJECTOR

2. *Outer orientation* which replaces the four-point setting of the rectifier and comprises—

(*a*) *Relative orientation* of one projector with respect to another in order that a correct model may be reconstructed.

(*b*) *Absolute orientation* in which the model is oriented correctly in relation to the map plane by—

(i) *Scaling*, i.e. setting the horizontal scale of the model to agree with the compilation scale by increasing or decreasing the spacing of the projectors.

(ii) *Horizontalizing* the model. This might be done by altering the slope of the model as a whole by movements of the bar, or by tilting the map plane to agree with the general slope of the model. In some models (see Fig. 11.1(ii)) the bar is not adjustable, and horizontalizing is carried out by reciprocal movements of individual projectors.

Before beginning the drill for orientation of a particular strip of photography, the map plane should be horizontalized using the spirit level in accordance with the manufacturer's instructions. The map plane should then be covered with a flat sheet of white paper.

Inner Orientation

Figure 11.3 illustrates the various parts and movements of one projector. Turn on the air cooling system and then the lamp of the first projector. Move this projector so that the whole of the illuminated area falls on the map plane. Focus the lamp by moving the axial adjustment screw until the maximum intensity of light is obtained. Now move each of the two lamp centering screws in turn until there is a clear white square of light on the map plane. Sometimes it might be necessary to leave the corners of this square of light slightly rounded by a reddish-orange band. Turn off the lamp.

We are now ready to insert the diapositive. Remove the condenser housing and lightly but thoroughly dust the surfaces of the diapositive and the glass stage plate with a camel-hair brush. Hold the diapositive with the emulsion side down; orient so that the image appears as you wish it to be projected; now rotate the diapositive through 180° in swing and place it gently on the stage-plate. Release the two idling spring-loaded centering bogies which will hold the diapositive firmly in contact with the plate. Check that the diapositive moves linearly when the centering screws are rotated. Replace the condenser housing.

Turn on the lamp again. In the middle of the projected image on the map plane there should be a small black dot which is the projected image of a dot engraved at the centre of the stage plate. Nearby will be seen the projected image of the principal point cross which must now be made to coincide with the dot by movements of the two diapositive centering screws.

Each of the remaining projectors is similarly oriented. Inner orientation is now completed by zeroing the heighting scale on the tracing table in order to satisfy the lens condition approximately.

There is a limited range of focus for these projectors, and the optimum conditions are obtained when the vertical distance from the centre of projection to the tracing table is 360 mm. For the whole model to be sufficiently sharp this distance must be between 270 and 450 mm when viewing any point on the model. This projection distance Z represents the flying height in the model; thus—

$$Z = H \times \text{(scale of the model)}$$

If $H = 3{,}000\text{ m} = 3{,}000{,}000\text{ mm}$ then the scale of the model should approximate to $\frac{360}{3{,}000{,}000}$ or 1 in 8,333. Let us assume that we have decided to plot at a scale of 1 in 8,000, then

$$Z = 3{,}000{,}000 \times \frac{1}{8{,}000} = 375 \text{ mm}$$

Set the floating mark 381 mm below the projector datum boss, using the height gauge provided (see Fig. 11.1(i)). Release the glass scale clamp, and adjust the scale so that it reads exactly 50 mm. It is now in the centre of its run.

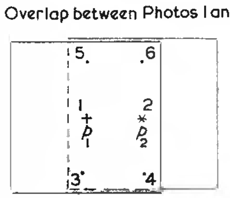

FIG. 11.6. LOCATION OF CONTROL FOR RELATIVE ORIENTATION

Outer Orientation

As shown in Fig. 11.5, each projector is capable of six movements—

1. Linear, horizontal, and parallel with the bar; known as B_x.
2. Linear, horizontal, and perpendicular to the bar; known as B_y.
3. Linear and vertical; known as B_z.
4. Rotation about the x-axis, or tilt; known as ω.
5. Rotation about the y-axis, or tip; known as ϕ.
6. Rotation about the z-axis, or swing; known as κ.

4 and 5 are sometimes also called *roll* and *pitch* respectively.

It will be noted that the x and y-axes correspond to those for the heighting drill at the end of Chapter 10.

Both of the first two projectors are set so that their distances in the y-direction from the bar are equal. Their heights above the map plane must also be equalized, and the B_y and B_z scales should be near the centres of their runs. The three rotational movements should be set so that the projectors are approximately horizontalized.

The separation of the projectors is now wholly in the x-direction and will govern the scale of the model.

If B is the horizontal distance between the two projectors, then when the scale is correct

$$B = b \times \frac{\text{model scale}}{\text{photo scale}}$$

where b is the mean length of the two photo base lines.

If we are using projectors 1 and 2 (numbering from left to right) of the three-projector instrument, then projector No. 2 is now brought to a central position on the bar, using the B_x-movement. Adjust projector 1 in the B_x-direction so that the distance between the two projectors is equal to the calculated value of B.

Put a red filter in projector 1 and a blue filter in projector 2, switch on the cooling system, and check that it is working properly. Now switch on both projectors.

If the photographs had both been truly vertical then a true to scale real model could now be seen by viewing through the spectacles provided. The presence of tilt, however, means that pairs of rays representing any particular ground point will probably not intersect at all (i.e. they will be skew lines). Thus, no matter how we alter the height of the floating mark, the two images of any point A cannot be made to coincide on the platen of the tracing table. Looking at the surface of the platen without using the spectacles we can see the red image and the blue image separately; raising and lowering the floating mark causes these two images to move towards or away from each other in the x-direction. If we view a particular point A, and by raising and lowering the floating mark we equate the x-coordinates of the red and blue images of this point, then the separation of the two image points is now wholly in the y-direction, and is known as want of correspondence or K. It is by systematically eliminating K at all points that relative orientation is achieved and the correct model becomes visible. In detecting small amounts of K it is usually considered better to use a small black cross drawn on the platen rather than the floating mark itself.

RELATIVE ORIENTATION. Choose six readily discernible image points approximately in the positions shown in Fig. 11.6 where 1 and 2 are near the principal points of projections 1 and 2 respectively.

Now eliminate K at each of these points in turn as follows, keeping the x-coordinates equal by appropriate z-movements of the floating mark—

(*a*) At point 1 by swing of projector 2.
(*b*) At point 2 by swing of projector 1.

Repeat (*a*) and (*b*) until positions 1 and 2 are free of K.

(*c*) At position 6 by tip of projector 1.

(*d*) At position 4 by tilt of projector 1; overtilt by imparting about three times the amount of tilt required to eliminate K.

Repeat above until points 1, 2, 4 and 6 are free of K.

(*e*) At position 5 by tip of projector 2. Check for K at position 3, and repeat all movements until K is eliminated from all six points.

At this stage the model is correctly set up but it still requires horizontalizing, i.e. it needs tilting as a whole relative to the map plane. In addition, the model will be only approximately true to scale.

ABSOLUTE ORIENTATION. This consists in setting the model to the correct scale and in making it horizontal. The former requires at least two ground control points and the latter at least three height control points. They need not be the same points, but it is desirable to have them so, as this provides a cross-check and simplifies identification.

Scaling. None of the above movements has involved a B_y- or a B_z-change in either projector so that the scale can still be adjusted by a B_x-movement of either projector, without reintroducing K.

Using the floating mark in the normal way, plot the positions of the two control points and measure the distance apart using a diagonal scale; let this be say 99·1 mm. If the correct distance should have been 98·3 mm, then by B_x-movement of projector 1, reduce the x-separation of the projectors in the proportion 98·3 to 99·1 (i.e. make the new distance $= 229 \times \frac{98{\cdot}3}{99{\cdot}1}$ where 229 mm was the originally calculated separation). Check again, and repeat until correct.

Horizontalizing. Where the bar is adjustable, by systematic tipping and tilting of the bar itself, the errors in the heights of the three height control points recorded on the glass scale of the tracing table can be equalized. The glass scale is adjusted to eliminate this error, and the tracing table index will now record correct elevations.

When horizontalizing by use of the projectors only, care must be taken to ensure that the relative orientation is not affected. Thus when one projector is tipped or tilted the other must be tipped or tilted by the same amount and in the same direction.

In Fig. 11.7, A, B and C are the positions of the three height control points as plotted from the scaled model on to the map plane. Their coordinates relative to p_1p_2 as the x-axis and O_y as the y-axis, where O is the mid-point of p_1p_2, are $(-53{\cdot}2, -5{\cdot}7)$, $(-9{\cdot}8, +49{\cdot}5)$ and $(+29{\cdot}7, -23{\cdot}2)$ respectively.

After taking height readings on the tracing table scale for each of these three points, determine the errors in height by comparing with the known height of each point. Let these height errors be

$$A - 5{\cdot}4 \text{ mm} \qquad B - 9{\cdot}8 \text{ mm} \qquad C + 6{\cdot}2 \text{ mm}$$

Note that these errors could have been converted to metres but it is usually more convenient to work in terms of units on the heighting scale—having first converted the known heights to these units at the scale of the model. Draw $AF = 2AG$ and parallel with p_1p_2.

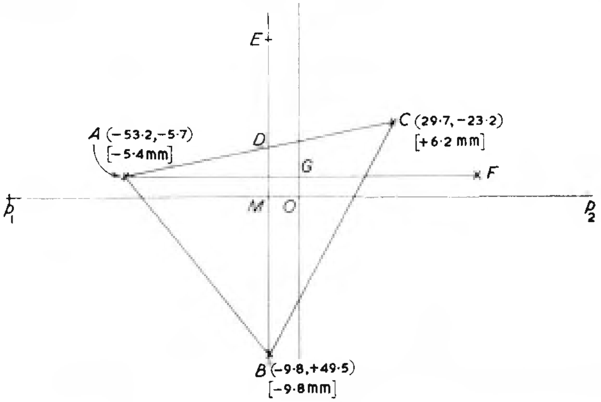

FIG. 11.7. ABSOLUTE ORIENTATION—HEIGHT CONTROL FOR HORIZONTALIZING MODEL

Draw BD perpendicular to p_1p_2, cutting AC in D and p_1p_2 in M.

Produce BD to E so that $EM = MB$.

Then coordinates of E are $(-9{\cdot}8, -49{\cdot}5)$ and the x-coordinate of D is $-9{\cdot}8$.

$$\therefore \quad y\text{-coordinate of } D \text{ is } -5{\cdot}7 - \left[(23{\cdot}2 - 5{\cdot}7) \times \frac{53{\cdot}2 - 9{\cdot}8}{53{\cdot}2 + 29{\cdot}7}\right]$$
$$= -14{\cdot}9$$

i.e. D is the point $(-9{\cdot}8, -14{\cdot}9)$

$\therefore$ by interpolation between errors at A and C, error at D will be approximately

$$-5{\cdot}4 + (5{\cdot}4 + 6{\cdot}2) \times \frac{53{\cdot}2 - 9{\cdot}8}{53{\cdot}2 + 29{\cdot}7} = -5{\cdot}4 + 11{\cdot}6 \times \frac{43{\cdot}4}{82{\cdot}9}$$

By extrapolation from B and D, the error at E is approximately

$$-9{\cdot}8 + \left(9{\cdot}8 - 5{\cdot}4 + 11{\cdot}6 \times \frac{43{\cdot}4}{82{\cdot}9}\right)\frac{49{\cdot}5 + 49{\cdot}5}{49{\cdot}5 + 14{\cdot}9}$$

Now the model must be tilted so that the errors at *B* and *E* are equal. This must be done by estimating the tilt required, then tilting one projector by that amount, removing *K* by tilting the other projector, and repeating this until the errors are equal. In practice experience will decide the amount of tilt to apply but

$$\tan\omega \simeq \frac{\tfrac{1}{2}(\text{difference between errors at } B \text{ and } E)}{y\text{-coordinate of } B}$$

The tip is corrected in a somewhat similar manner. The floating mark is set at ground level at *O*, and one projector is then tipped by an estimated amount. The other projector is then tipped in the same direction until the image of a point near *O* is at the same height as before the tipping took place. Again experience will normally decide the amount of tip and it may be necessary to repeat these tip movements after checking the heights at *A* and *C*.

The amount of tip can also be estimated by calculation—

$$\tan\phi \simeq \frac{\tfrac{1}{2}(\text{error at } A - \text{error at } F)}{x\text{-coordinate of } A}$$

A small amount of *K* will probably have been reintroduced at points off the base line, and this should be removed by B_z-movement of projector 1, which may make a slight B_y-movement also necessary.

It now remains to check the scale and adjust in B_x if necessary, then carry out the whole of the orientation again as a check, repeating until no errors remain. Finally the glass scale on the tracing table should again be zeroed, this time on one of the height control points.

Projectors 1 and 2 are now correctly oriented, and plotting may begin on to topographic base secured in the map plane. If the third projector is required, this can be oriented relative to projector 2, which will not be altered throughout the whole procedure. Projector 3 must be adjusted in inner orientation, and then oriented relative to projector 2 as follows; projector 3 will have a red filter, and no absolute orientation will be necessary—

The points numbered 1 to 6 are arranged now in the overlap between projectors 2 and 3, again in positions shown in Fig. 11.6. Eliminate *K* by movements of projector 3 as follows—

(*a*) At position 2 by B_y } repeat until free of *K*.
(*b*) At position 1 by swing }
(*c*) At position 6 by B_z.
(*d*) At position 4 by tilt, overtilting by tilting approximately 3 times amount required to remove *K*.

(*e*) At position 2 by B_y.

Repeat (*c*) (*d*) (*e*) as necessary.

(*f*) At position 1 by swing.

(*g*) At position 3 by tip.

Check for *K* at position 5 and repeat all steps until no *K* remains.

All three projectors are now oriented, and in an instrument having more projectors, each of these may be oriented in turn by orienting 4 on 3, then 5 on 4 and so on. This is called a cantilever, and errors will increase as further projectors are added. At least two ground control points and three height control points should appear in the last overlap, and the error should be spread evenly over the intervening overlaps; this is known as bridging. Normally some additional control is required near the middle of the bridge. This is aerotriangulation by which control for each overlap is built up from relatively sparse ground control.

The multiplex is a universal plotter as it is capable of aerial triangulation as well as plotting detail and contours. Although the model as seen is imaginary, plotting is from a real model formed by a purely optical process. The models are true perspective diagrams in so far as the camera lens distortions are balanced by the reduction printer lens and the final projection lens. Each instrument of this type is designed for use with a particular range of cameras: the Williamson models they designed for use with the Eagle IX which has a 152·4 mm focal length lens and a 230 × 230 mm format. The reason why the range of projection distances is limited is because the focal length of the projector is almost fixed and the sharpness of the image is relatively poor. Other drawbacks are low resolution due to the reduction in scale of the diapositive, and insufficient illumination. However, the multiplex is capable of a plan accuracy of about ± 0·5 mm and a heighting accuracy of about 1/1000 of the flying height. Its simplicity and the theoretical accuracy of its solution of the problem of re-forming the model of the ground, make it suitable for small- and medium-scale mapping.

The Kelsh type of instrument (see Fig. 11.8) is the result of an attempt to remedy the main defects of the multiplex. The diapositive is full-size, and a system of rods attaches the tracing table to each lamp. These rods direct the lamp towards that part of its diapositive which is being viewed. Such an instrument is not much more complicated than the multiplex itself, and is capable of greatly increased plotting accuracy. The Balplex (see Fig. 11.9) is a further variant of the multiplex principle, and is also available with a bank of eight projectors.

Viewing in colour accounts for some loss of illumination, and experiments have been made with polarized light, but a number of firms have produced instruments of both multiplex and Kelsh types incorporating " blink " viewing apparatus (see Fig. 11.10). Rotating shutters in each eye-piece are synchronized with similar shutters attached to the respective projectors. Thus when the left eye-piece shutter is open, so is the left-hand projector shutter, and the left eye obtains an uninterrupted view of the left-hand diapositive—at this moment the two right-hand shutters are closed. As the two left-hand shutters close so the two right-hand ones open. In this way first one image is seen and then the other in rapid

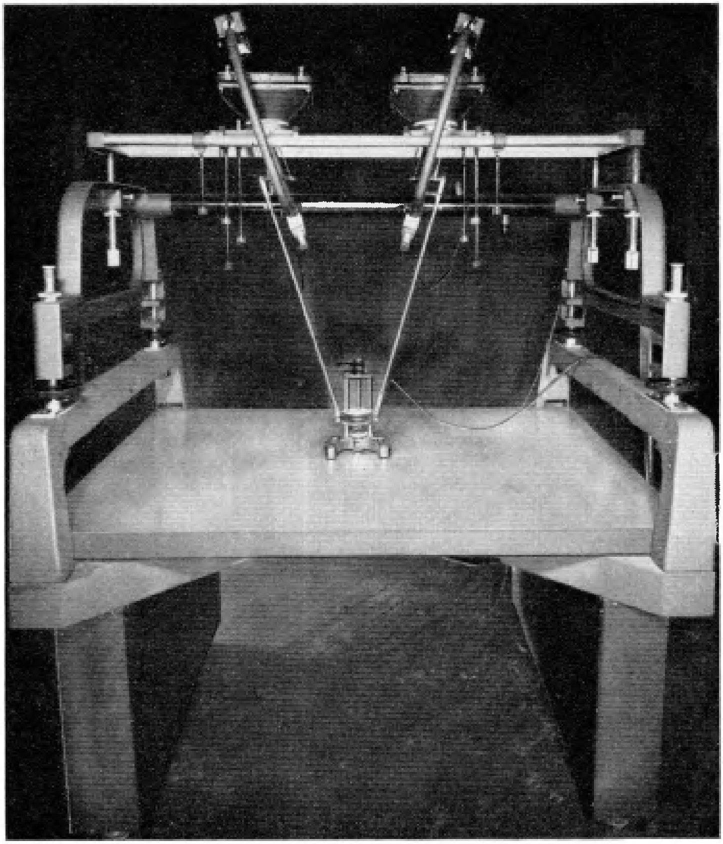

FIG. 11.8. THE KELSH PLOTTER
(*The Kelsh Instrument Co. Inc.*)

succession so enabling the brain to reconstruct a three-dimensional model.

When viewing the coloured images only a part of the spectrum is utilized; when using the blink apparatus illumination is wasted by discontinuity in time; even with polarized light only a proportion of the light vibrations can be used. There is then always some loss of illumination with these methods of viewing which is not shared when the viewing is stereoscopic.

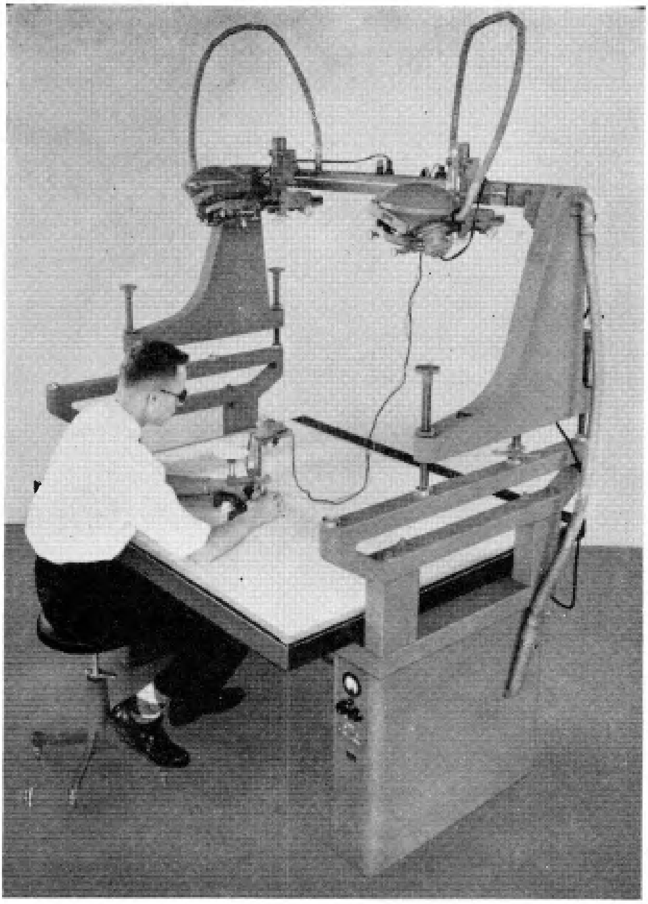

FIG. 11.9. THE BALPLEX PLOTTER
(Bausch and Lomb Optical Co.)

INSTRUMENTS BASED ON THE SIMPLE MIRROR STEREOSCOPE

Use of the mirror stereoscope involves no inner orientation; relative orientation is represented only by the swing correction carried out when making the base lines collinear, and some scale control is achieved by adjusting the *x*-separation of the prints for ease of fusion.

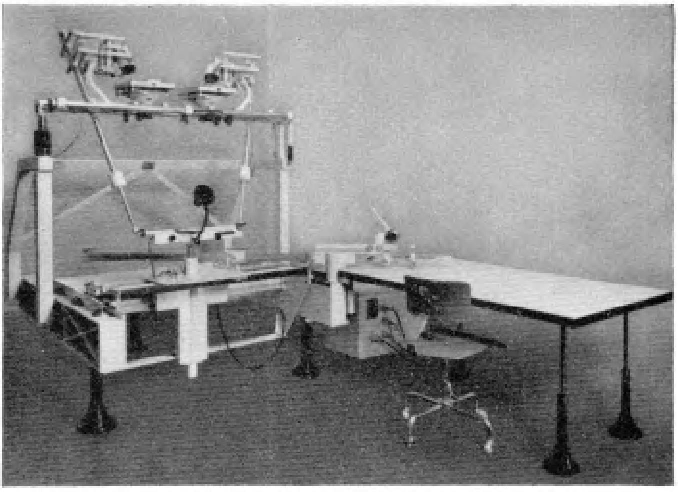

FIG. 11.10. PG1 STEREO RESTITUTION INSTRUMENT (BLINK TYPE)
(*Kern and Co. Ltd.*)

The radial-line plotter does require a measure of inner orientation, in that the principal point is automatically centralized. A measure of absolute orientation is also involved in setting the model to control before plotting begins. This instrument incorporates a linkage mechanism by which the movement of the plotting pencil is approximately corrected for the errors inherent in the model.

In other instruments under this heading, a theoretically exact correction is made to the movement of the pencil.

The Stereotope is a development of the Stereopret (see Fig. 7.15). The pencil movement is corrected mathematically by two computers incorporated in the instrument itself. This instrument is simple in operation and the makers claim results comparable with those of the multiplex.

In instruments which use an imaginary model, one floating mark is formed by fusing two similar marks, one in front of each eye; these are sometimes called half-marks.

In the Stereomicrometer (see Fig. 11.11) the half-marks are placed axially in each eye-piece, and might therefore be expected to remain fused in a floating mark which will appear to stay at a constant height.

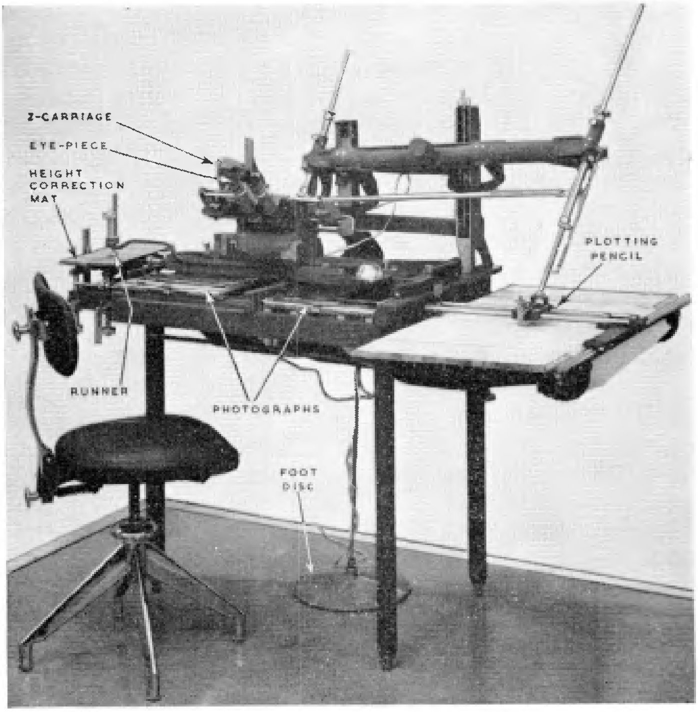

FIG. 11.11. THE STEREOMICROMETER
(*Officine Galileo*)

However, the floating mark is brought on to the " ground " surface by apparent x-movements of the two photographs, and since the model of the ground will seem more realistic to our brain, it will usually be the floating mark which seems to rise and fall rather than the model. In the Stereomicrometer the heighting knob operates the reading on the heighting scale, and at the same time varies the x-separation of the objectives of the viewing system, so that after the initial setting there is no further x-movement of the photographs themselves.

This instrument incorporates basic eye-piece and plotting pencil movements similar to those of many of the larger machines. A rigid horizontal frame is mounted over the photograph table, and is capable of movement only in the y-direction; it is therefore known as the y-carriage. The x-carriage is another rigid horizontal frame carrying the eye-pieces and capable of moving over the y-carriage in only the x-direction. The z-carriage is mounted on the x-carriage and capable of linear movement only in a direction perpendicular to that of the x- and y-carriages. A link mechanism, similar to a more or less vertical pantograph, conveys the apparent movement of the floating mark to the plotting pencil—it is actually the joint movements of the objectives which control the plotting arm.

Inner orientation is represented in the Stereomicrometer by a mechanical change in the link mechanism to accommodate the principal distance of the photographs, and by focusing the objectives and eye-pieces to obtain sharp images of the photographs and the half-marks respectively.

Relative orientation includes swing corrections similar to those of the multiplex; B_x movement of the left-hand photograph is used to make the height scale read zero when the right-hand principal point is being scanned; K is removed by B_y-movement of the left-hand photograph at the time each point is being heighted and plotted. (See Fig. 11.5.)

Scaling is carried out by setting to two control points as for the multiplex, but it is achieved by an alteration of the link mechanism and does not therefore affect the model.

When these stages of orientation have been carried out the instrument is capable of plotting a sketch map.

The model is warped due to lack of ϕ- and ω-rotations of the two photographs. Correction of the pencil movement is effected by systematic distortion of the surface of the mat on the height corrector. When this surface is set, movement of the viewing system causes the runner to move over the mat in such a way that its position on the mat represents the position on the overlap of the point being observed. As the mat is traversed, the rise and fall of the runner operates a system of levers which effect the necessary corrections to the height gauge and the plotting pencil.

The mat comprises a series of metal rods arranged parallel with the y-axis; thus corrections remain linear in the y-direction. The mat is capable of rotational movements in ϕ and ω and of up to three further warping movements. For complete setting of the mat, then, at least six height control points are required; the mat is systematically warped until the height gauge reads correctly for each of these points.

Oriented in this way the Stereomicrometer is considered to be of about the same accuracy as the multiplex.

INSTRUMENTS BASED ON THE SKETCHMASTER PRINCIPLE

Perhaps the simplest method of plotting from a theoretically correct stereoscopic model is that used in the Stereoflex (see Fig. 11.12). If we consider viewing two Sketchmaster photo images simultaneously then the theory of this plotter becomes apparent (see Fig. 11.13).

In the Stereoflex the model can be traced out point by point, using a floating mark and tracing table similar to those of the multiplex. With this instrument as with the Kelsh, a wider range of scale can be obtained by using the pantograph-type linkage for the plotting pencil.

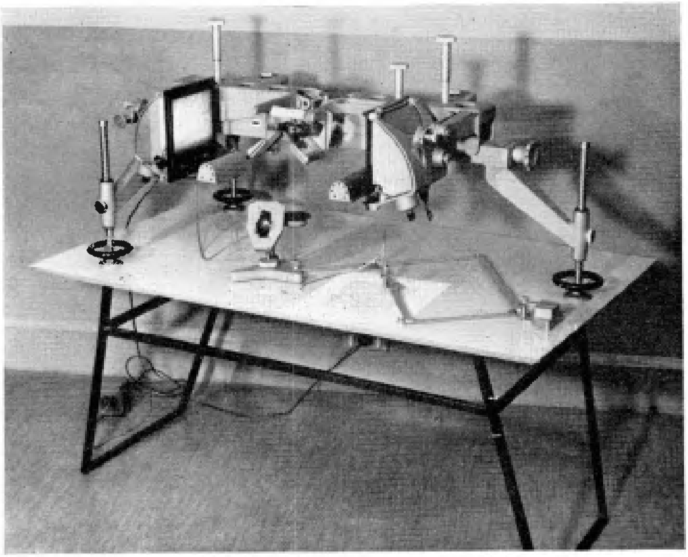

FIG. 11.12. THE STEREOFLEX
(*S.O.M., Paris*)

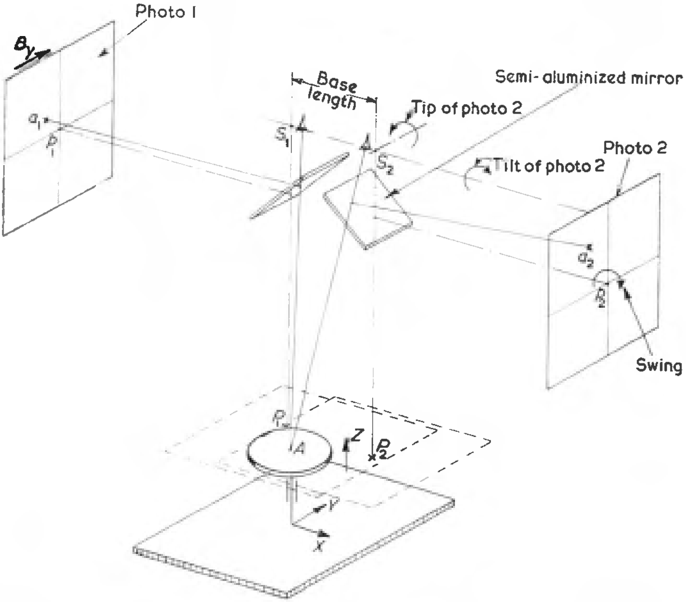

FIG. 11.13 LINE DIAGRAM SHOWING THE PRINCIPLES OF THE STEREOFLEX
The swing is by a movement of the photograph itself.
Tip and tilt are by movements of the relevant mirror system about two horizontal but mutually perpendicular axes through *S*.
(*S.O.M., Paris.*)

The photographs can themselves be rotated in swing. The scale adjustments, as with the Sketchmaster, are made by altering the eye-piece to photo and eye-piece to map distances. As these scale movements are carried out independently for each photo, they simulate the inclination of the air-base. Tip and tilt of each photo is dealt with by combined movements of eye-piece and photo-carrier.

The foregoing instruments are intended for map revision and for plotting detail at relatively small scales, and between previously plotted and fairly dense control. However some, notably the multiplex, can be used for aerotriangulation. Consideration of the more complex, rigorous solution instruments is deferred until the next chapter.

BRIDGING WITH THE MULTIPLEX

It has been seen that, given two ground control and three height control points for an overlapping pair of photographs, the appropriate diapositives can be mounted in two adjacent multiplex projectors and oriented so that a correct scale model is set up in space. Using the tracing table pencil, any point on the model surface can be projected orthogonally on to the base-grid lying on the plotting surface of the instrument, and a topographic map can be plotted. Similar kinds of procedure enable the other instruments mentioned in this chapter to plot maps from pairs of photographs. The amount of ground control required for plotting a complete block of photography in this way involves long and relatively costly field operations.

Using a multi-projector instrument similar to that shown in Fig. 11.1, a complete strip of photographs can be oriented in such a manner that the angular relationships between the individual projectors are exactly the same as were the angular relationships in space between the camera in its successive air station positions. Some instruments can be used to assemble up to 15 projectors.

When a strip is set up in this way, so that it starts from a fully controlled single model and finishes at another controlled model, the assembly is known as a multiplex bridge, and from it sufficient horizontal and vertical control can be obtained to enable each intervening stereo-model in the strip to be set up independently—e.g. on a two-projector instrument.

The usually accepted absolute minimum amount of ground control necessary for setting up a multiplex bridge is three height and two horizontal control points on the first overlap of the strip, two height and one horizontal control points on the last overlap, and two height control points on a central overlap of the strip. These control points should as far as possible be in the lateral overlaps, i.e. in positions similar to those of pass points or of points 3, 4, 5 and 6 in Fig. 11.6.

The bridging drill will begin with the construction of a base-grid on which the ground control is plotted. In Fig. 11.14 (i) *B* represents one of the horizontal control points in the first overlap, and *L* represents the ground control point in the last overlap. The control plot is laid on the plotting surface of the instrument, the diapositives are mounted in the appropriate projectors, and inner orientation is carried out. The next step involves setting up the first two projectors in relative and absolute orientation, there being full control for this overlap.

The second model of the strip is formed by setting the third projector in relative orientation with projector 2. In practice the scale may not be exactly the same for both models, and the second model may not occur at the same level as the first. This can be corrected as follows—

Choose a point *d* which occurs in both models 1 and 2; view the point as produced in model 1 and bring the tracing table height to ground level at this point; now turn off projector 1 and turn on projector 3; do not alter the height of the tracing table but bring the image point *d* back to ground level by an *x*- (i.e. scale) movement of projector 3. Check the relative orientation of model 2, and readjust if necessary using the same movements as before. To remove *K* completely it may also be necessary to carry out slight *y*- and *z*-translations of projector 3. This drill is often referred to as " passing through ".

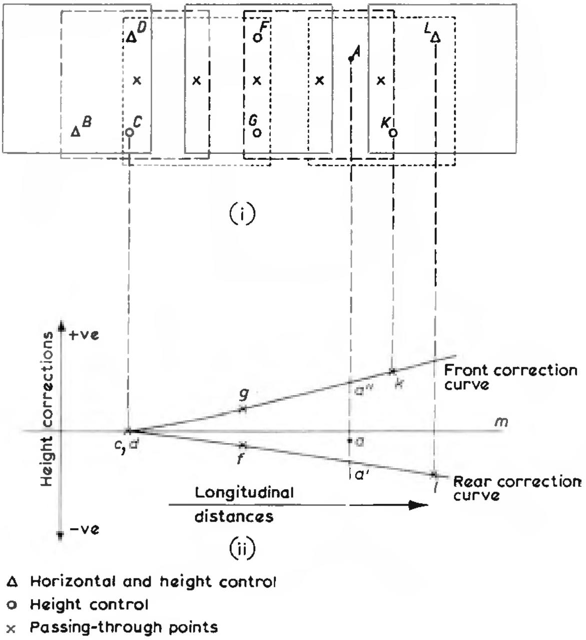

FIG. 11.14. GROUND CONTROL AND HEIGHT CORRECTION GRAPHS
B, *C*, *G* and *K* are in front lateral overlap. *D*, *F* and *L* are in rear lateral overlap.

The point *d* should be near the flight path, have an easily recognizable and precise image, and be located in an area in which the tracing table can be brought to ground level without ambiguity. Projector 4 is now oriented relative to projector 3, and the " passing through " drill is performed as above. In this way each successive model of the strip is set up.

If B' and L' are respectively the multiplex-plotted positions of the points B and L, then the bridge scale will be determined by measuring $B'L'$ and comparing this length with BL. The x-separation of each pair of projectors is then increased (or decreased) to a distance equal to $BL/B'L'$ multiplied by the original spacing. This adjustment is carried out by moving projector 2 first, followed in succession by projectors 3, 4, 5 and so on to the end of the strip. There is no easy way of measuring the x-separation accurately, so that this scale adjustment is usually done by calculating the correct tracing table height readings for each passing-through point in turn.

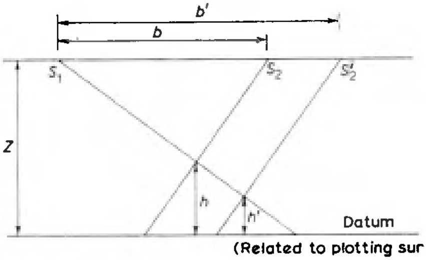

FIG. 11.15. CALCULATING TRACING TABLE HEIGHTS FOR SCALING BRIDGE

Actually it is the corrections which are calculated since these will be cumulative throughout the strip.

In Fig. 11.15—

h' = existing height of tracing table above datum
h = correct height of tracing table above datam
Z = distance of centres of projection above datum
b' = existing separation of projectors
b = correct separation of projectors

Scale ratio, $BL/B'L' = b/b'$

By similar triangles: $(Z - h)/b = (Z - h')/b'$

i.e. $Z - h = (Z - h') \times b/b' = (Z - h') \times BL/B'L'$

or $h = Z - (Z - h') \times BL/B'L'$

Thus, correction $= h - h' = Z - h' - (Z - h') \times BL/B'L'$

$= (Z - h')(B'L' - BL)/B'L'$

so that the corrected heights of tracing table are

Model 1 $h_1 = Z - (Z - h_1') \times BL/B'L'$
Model 2 $h_2 = h_1 - (Z - h_2') \times (B'L' - BL)/B'L'$
Model 3 $h_3 = h_2 - (Z - h_3') \times (B'L' - BL)/B'L'$

and so on.

When this procedure has been completed the length $B'L'$ should be the same as BL, so that the overall scale is now correct.

If the control plot is moved until B coincides with B', and L with L', then it might be expected that the bridge would be fully oriented and that plotting from each model could take place. However, even at this stage it is unlikely that the heights at the two final height control points or at the two centre height control points would be correct. The graphical adjustments which may be used are fairly intricate and only a simplified version is given.

Fig. 11.14 (ii) shows a graph in which *cm* is the *x*-axis. The height errors of the model at *G* and *K* would be determined and the required corrections plotted as ordinates on the graph (at *g* and *k* respectively); *C* and *D* were used in the orientation of model 1; they have no error, and are therefore represented by the point *c*, *d* on the *x*-axis. A ruler or straight-edge is made to stand on its edge, and bent until the edge passes through *c*, *g* and *k*; a curve is drawn by moving a pencil point along this edge—this is a spline curve, and represents the height correction at each point along the strip having similar *y*-co-ordinates to *C*, *G* and *K*. A similar curve *afl* is drawn through the plotted positions of *A*, *F* and *L*. Corrections for model heights may be read off the graph for any point within the bridge—e.g. the correction at *A*, midway between the flight line and the near lateral line of control, will be read off the graph as the ordinate of *a*, which is one-quarter of the distance from a' to a'' on the relevant correction curves.

Using a 3-projector Instrument

Bridging is possible with a 3-projector instrument. The first two models are set up in the usual way, then the first projector is removed and the second and third projectors are translated in *x* to the left. The second model is re-established by moving one of the two projectors in *x* until the height of the passing-through point is again correct. Scale errors may be detected by checking against points plotted during the initial setting. Projector 1 is remounted to the right of projector 3, and a diapositive of the fourth photograph of the strip is inserted. After inner orientation, projector 1 is adjusted relative to projector 3, and model 3 is scaled using a passing-through point whose height has been determined from model 2. By moving the projectors in rotation the bridge can be completed. The overall scale error is measured as before, and scale corrections are calculated in terms of tracing table heights for each model. Final height corrections and plotting can be carried out as before.

Using a 2-projector Instrument

In a 2-projector instrument exactly the same procedure is possible provided that the height of the right-hand projector above the plotting surface can be accurately re-established after it is translated to the left. A special height gauge (see Fig. 11.1) can be obtained which will enable this distance to be measured easily and accurately.

Bridging is carried out on other 2-camera instruments by comparable procedures; though those specially designed for bridging, such as the Wild A7, are constructed in such a way that the second model is set up with photo 2 still in the right-hand projector. In this case each alternate model is formed from the right-hand side of the right-hand photograph and the left-hand side of the left-hand photograph. This is the base-out position of the base-in, base-out procedure.

The Inclinometer

After the bridging operation has been completed, the requisite horizontal control plotted and the height control recorded, the plotting of detail will be carried out from the individual models. For this purpose it would normally be necessary to repeat the whole of the relative orientation drill for each model in turn. However, with the use of an inclinometer the angular settings of the projectors can be measured and recorded during the bridging, and then reset when the particular overlap is to be plotted. An inclinometer consists simply of a pair of spirit bubbles mounted at right angles to one another, and attached to the projector in such a way that two micrometer screws can be used to bring the bubbles to the centres of their runs, and so to determine the tilts of the projector.

Block Adjustment

These procedures would enable plotting to be carried out from successive overlaps of each strip in a block of photographs; but there may still be noticeable discrepancies between two adjacent strips. The slotted templet assembly is the simplest method of removing discrepancies in plan; but no height adjustment is involved, so that vertical discrepancies remain.

There are several ways in which improvements have been made to the simple slotted templet method—by using spring-loaded studs, and stereo-templet pairs; but the more mathematically based Jerie analogue computer can also be used in a slightly different form to perform a height adjustment. Some improvement in matching adjacent strips can also be made by running some cross-strips and carrying out bridging drill on these.

However, complete block adjustment can be carried out mathematically, by comparing three-dimensional coordinates established on the ground with similar coordinates of the same points as read from the plotting machines or from a stereocomparator. Equations can then be deduced which can be used to determine corrections to apply to three-dimensional machine coordinates of any other point.

FURTHER READING

There is an immense amount of literature dealing with this aspect of the subject, and an advanced student must read very widely; especially must he keep up to date with articles appearing in the periodical journals such as those listed in the bibliography (page 346).

STEREOSCOPIC PLOTTING

(i) Schwidefsky, pages 158–73, 196–205.
(ii) *Manual of Photogrammetry*, Vol, II, Chapter 13.
(iii) Hart, pages 275–326.
(iv) Moffitt, pages 305–60.
(v) Hallert, pages 119–76.
(vi) Lyon, Chapters 6 and 7.
(vii) Zeller, pages 62–79, 126–38.

AEROTRIANGULATION

(i) Schwidefsky, pages 248–76.
(ii) Hallert, pages 184–206.
(iii) *Manual of Photogrammetry*, Vol. I, Chapter 9.

ORIENTATION AND THE MATHEMATICS OF PLOTTING

(i) Hallert, pages 247–86 (theory of errors).
(ii) Lyon, Chapter 3, pages 38–43 and Chapter 5.
(iii) Zeller, pages 138–204.
(iv) Merritt, pages 133–53.

ANALYTICAL PHOTOGRAMMETRY

(i) *Manual of Photogrammetry*, Vol. I, Chapter 10.

INSTRUMENTS

(ii) Cimerman and Tomasegovic.

EXAMPLES

(i) Hallert, pages 287–330 (Appendix C).

(See Bibliography (page 346) for the full titles.)