AUTOMATIC MAP PLOTTING INSTRUMENTS—ANALYSIS AND CLASSIFICATION

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IN THE final analysis, the best map compiling procedure is the one that enables a mapping organization to produce a compilation of the necessary accuracy at the lowest cost in money and time. Usually, the most expensive single operation in compiling maps from aerial photographs is that of obtaining a complete network of control. Precise automatic plotting instruments promise considerable savings in compilation costs because they create most of their own horizontal and vertical control, in addition to providing an accurate method of obtaining topographic detail directly from the photographs.

The great advantages that appear to be offered by automatic plotting instruments captures the imagination of everyone. Many photogrammetrists of an inventive turn of mind try to develop some kind of a simple, accurate mapping device. The prospects of success seem very promising at first, but in most cases the inventor's efforts usually result only in a sadder and wiser photogrammetrist. This failure to develop a practical device is generally due to the unexpected complexity of the technical problems involved, and to a lack of knowledge of what has been accomplished by other workers in the field. The following material is presented in an effort to provide future inventors with an easily understood description of the theoretical problems involved in the designing of automatic plotting equipment. The general theory of plotting instruments will be outlined, various representative automatic plotting instruments will be classified according to their design, and certain new instruments will be described and analyzed in considerable detail.

An automatic plotting instrument is a device for drawing accurate topographic maps by the use of a visual system that provides for the stereoscopic observation of two overlapping photographs and a pointer. This pointer generally is a small dot called a "floating mark." The floating mark can be used to touch any desired detail point appearing in the stereoscopic model and can be moved along any desired topographic feature in one smooth continuous motion. The floating mark is connected mechanically to a pencil which may be used to trace on the map plane an orthographic projection of the movements of the floating mark. By causing the floating mark to touch any given detail point, the operator identifies and locates in space above the map plane the intersection of the corresponding pair of conjugate image rays.[1] These rays may be actual light rays or they may be only imaginary directions in space defined by the floating mark and the perspective centers, and represented by mechanical rods or levers. In either event, the photographs are oriented in the instrument so that these rays possess the same relationships to each other that were possessed by those light rays which exposed the original negatives. Each pair of intersecting rays forms a point in the stereoscopic model which represents a corresponding object-point on the original terrain. The total effect of the intersections thus established creates a true representation in space of that portion of the earth's surface which appears in the common area of a stereoscopic pair of photographs.

There are four possible ways in which relative motion can be induced between the floating mark and the stereoscopic model formed by the intersections

[1] A conjugate image ray must pass through the perspective center of the corresponding photograph or its image. Substitute perspective centers may be used under certain limited conditions.

of the various pairs of conjugate image rays. These methods are: (183)[2]

CASE A: Photographs (and their images) are fixed in space and the floating mark makes the required motions. [The floating mark usually is located at an appreciable distance from the plane of the photographs (or of their images). Where this condition occurs, special provision must be made either for the elimination of parallactic displacement, or for a great depth of focus for the optical system. Either alternative requires the use of very small apertures located at the perspective centers of the instrument.]

CASE B: The floating mark is fixed in space and the photographs (or their images) perform the required motions. [This type of plotting instrument always involves the use of projectors that are caused to rotate about the exterior nodal points of the corresponding objective lenses, by means of levers or rods connected to the floating mark. These exterior nodal points are fixed in space.] (186, 226, 228)

CASE C: The floating mark is fixed in space and the photographs perform the required motions. [In this type of plotting instrument the projectors are always fixed with respect to each other except for a horizontal component of motion and, as a single unit, perform all of the relative motions.] (208, 346)

CASE D: The photographs (or their images) and the floating mark both move with respect to the map plane. [The movement of the floating mark with respect to the photographs is accomplished by distributing the x, y, and z components of this motion between the floating mark and the projectors. To the operator, however, the floating mark usually appears fixed in space.]

The mechanical linkage which is used to create relative motion between the stereoscopic model and the floating mark must also cause the drafting pencil to trace on the map plane an orthographic projection of these relative movements. In addition, if necessary, this mechanical linkage must cause the observing telescope to follow the movements of the floating mark. The exact nature of this mechanical linkage depends upon the nature of the floating mark and the method by which the conjugate image rays are converted into map points of known position and elevation. In order to understand the general nature of these mechanical linkages, it will therefore be necessary to analyze the various possible kinds of floating marks and the methods which may be used to convert conjugate image rays into corresponding map points.

A floating mark can be introduced into the stereoscopic model by any one of the following three ways:

METHOD 1: The floating mark consists of a single point which is placed on the surface of the stereoscopic model. [The Multiplex tracing stand illustrates the simplest and most practical application of Method 1. This type of mark has a wide angular field of illumination and usually does not require the use of a mechanical linkage connecting it to the perspective centers of the photographs, the viewing telescopes, or the frame of the instrument. This type of mark also makes it possible to use a very simple mounting for the tracing pencil. Since the floating mark usually is located at a considerable distance from the plane of the photographs (or of their images) Method 1 can be used successfully only when a great depth of

[2] The numbers in parenthesis, used throughout this article, refer to pages in O. Von Gruber's "Photogrammetry" American Photographic Publishing Co., Boston, 1942, where additional information may be found regarding the subject.

sharp focus is produced by the use of very small apertures located at the perspective centers of the instrument. The use of small apertures is not restricted to Method 1.]

METHOD 2: The floating mark consists of a pair of points, one point being placed on or near the surface of each photograph or its corresponding image. These two points fuse stereoscopically and form a floating mark that appears to rest on the surface of the stereoscopic model. [This type of floating mark is used in many of the European plotting instruments. A half-mark is mounted in a reticule located in front of each eyepiece. This condition requires that the image of each photograph be brought to a sharp focus in the plane of the half-mark.]

METHOD 3: The floating mark consists of two separate rays of collimated light. To the operator, the light rays appear to originate at the surface of the corresponding photograph. [This type of floating mark generally involves the use of a Zeiss Parallelogram.]

Intersections of conjugate image rays may be converted into corresponding map points of known elevation in either[3] one of two ways. The Multiplex illustrates the method which involves the use of polar coordinates. In this type of instrument the intersection of any given pair of conjugate image rays is projected upon one of an infinite number of planes that are parallel to the map plane. The second method of converting conjugate image rays is a mechanization of the radial line method of aerial triangulation and involves the use of rectangular coordinates. In this method, conjugate image rays, which are represented by mechanical levers, are orthographically projected upon two mutually perpendicular planes. The projection of these rays onto the horizontal map plane provides a plan view of that portion of the earth's surface which appears in the stereoscopic model. The simultaneous and automatic projection of the same rays onto a vertical plane gives an elevation of the relief. This projection onto the vertical plane constrains the movement of the floating mark in such a way that contour lines may be satisfactorily identified in the stereoscopic model and plotted in the horizontal mapping plane. The exact nature of these two types of instruments depends considerably upon the method that is used to represent the conjugate image rays. These rays can be represented either by light rays, by mechanical rods or levers, or by some combination of both. The various possible combinations are:

INDIRECT PROJECTION: The use of this system requires that diapositives be mounted within projectors that precisely reproduce the optical conditions that existed within the original camera. *The objective lenses are equivalent to the lens of the original camera* and are permanently fixed with respect to the plane of the diapositive. Within each projector body the conjugate image rays are represented by light rays. Outside the projector, however, the conjugate image rays may be represented either optically or mechanically. Those light rays from the photographs which pass through the projection lens form an image at an exceedingly great distance. In order to create an image of the photograph at a finite distance, an auxiliary system of lenses must be interposed between the projection lens and the plane of the desired image. This auxiliary system must be variable in focal length and rotatable in all directions. (289, 291, 294) The two possible applications of this system are:

[3] Where the possibility of a choice is offered by the use of the word "either" in this article, the author does not mean that both choices can be used interchangeably in any given instrument.

OPTICAL: The conjugate image rays are represented throughout their entire length by rays of light. The plotting accuracy of devices of this kind does not depend primarily upon rods, levers, or other mechanical linkages of any kind. The projected images of a pair of photographs may be observed directly by transmitted light or indirectly by light reflected from opaque or translucent screen(s). It is not possible to project an entire photograph all at one time by indirect optical methods except under very limited conditions. (289) Indirect optical projection therefore usually involves only the projection of conjugate image points because the theoretical restrictions are much less severe.

MECHANICAL: The conjugate image rays are represented outside the body of each projector by rods or mechanical linkages. The projected images of the pair of photographs may be observed directly by transmitted light or indirectly by light reflected from opaque or translucent screen(s). Indirect mechanical projection involves the observation of only a small portion of the stereoscopic pair of photographs at any one time.

DIRECT PROJECTION: The use of this system requires that diapositives be mounted within projectors which reproduce the optical conditions that existed within the original camera. *The objective lenses are not equivalent to the lens of the original camera* and may be either fixed or rotatable about the interior nodal point. Within the projector bodies the conjugate image rays are represented by rays of light. Outside the projectors, however, the conjugate image rays may be represented either optically or mechanically. Those light rays from the photographs which pass through the projector lenses form images at some desired finite distance. The two possible applications of this system are:

OPTICAL: The conjugate image rays are represented throughout their entire length by rays of light. The plotting accuracy of devices of this kind does not depend primarily upon rods, levers, or other mechanical linkages of any kind. The projected images of a pair of photographs may be observed directly by transmitted light or indirectly by light reflected from opaque or translucent screen(s). It is possible, at any one time, to project the entire surface of both photographs under certain fairly liberal conditions.

MECHANICAL: The conjugate image rays are represented outside the body of each projector by rods or mechanical linkages. The projected images of the pair of photographs may be observed directly by transmitted light or indirectly by light reflected from opaque or translucent screen(s). Indirect mechanical projection involves the projection of only a small portion of the stereoscopic pair of photographs at any one time.

MECHANICAL PROJECTION: A mechanical system of projection does not make use of projection lenses. The conjugate image rays are represented entirely by mechanical rods or levers. The floating mark must be brought by rods or levers into such a position relative to the photographs that it indicates the point which is being plotted on the map plane.

The simultaneous observation of the stereoscopic model and the floating mark involves the use of either constrained, semi-constrained, or unconstrained vision. Unconstrained vision requires the use of anaglyphic projection of the pair of photographs onto an opaque screen upon which a floating mark is mounted. It is not necessary for the operator to view the model through the fixed eyepieces of a stereoscope or other optical system. Plotting instruments similar to the Multiplex illustrate the application of this principal. All other types of plotting instruments involve the use of constrained or semi-constrained vision, and therefore require the operator to look through the fixed eyepieces of a stereoscopic viewing system. Constrained vision is identified by the fact that all light rays from the floating mark pass through a single small point in the center of the exit pupil of each eyepiece. Constrained vision always results from using Method 3. Semi-constrained vision requires that one-half of the floating mark appear exactly on the surface of each photograph or of its corresponding image. If these points do not appear to lie on the surface of the photographs, a movement of the operator's eyes will cause parallactic displacement between the floating mark and the corresponding image point on the model.

The photographs may be viewed directly by transmitted light or indirectly by light reflected from images of the photographs projected onto a translucent or opaque screen(s). The Multiplex illustrates the use of indirect observation and the K.E.K. Plotter illustrates the use of direct observation. The floating mark is generally observed by transmitted light in order to obtain good definition and adequate illumination.

The normal plotting scale of an automatic plotting instrument is directly proportional to its air base. (The air base is the distance between the perspective centers of the plotting field.) Changes in plotting scale can be made in one of these two ways:

1. The air base of the instrument is altered.
2. The air base of the instrument is permanently fixed; changes in plotting scale are made by the use of a pantograph mechanism connected to the floating mark, or by the use of a Zeiss Parallelogram.[4] (279, 287)

The author prefers to define an automatic plotting instrument as being a device for the continuous plotting of a series of conjugate image ray intersections which represent the correct relative position in space of topographic detail appearing on a given pair of aerial photographs. However, there are other ways of defining such instruments. For example, a plotting instrument may be regarded as a device for measuring differences of abscissae of conjugate image points. Experience has shown that these differences (differential parallax) can be measured with accuracies consistently approaching 0.01 mm. or ten minutes of arc.[5] (164) A plotting instrument also may be defined as being a device for the mechanical solution of a mathematical equation. Von Gruber refers to a number of such equations and describes the equivalent plotting instrument. He quite frequently refers to automatic plotting instruments as being devices for the simultaneous projection of a pair of photographs onto two or more sectional planes. (i.e., polar or rectangular coordinates are used.)

A systematic classification of the various plotting instruments helps one to understand the fundamental nature of these devices. Any method of classifying these instruments must be rather arbitrary. However, the following outline seems satisfactory because it presents in a concise, systematic fashion all the various combinations of elements that appear to be theoretically possible.

Even a casual consideration of the various devices listed in the above classification should make it clear that many difficult problems are encountered in designing a simple, practical plotting instrument. These problems result from

[4] "Stereophotogrammetry," Encyclopaedia Britannica.

[5] D. H. Jacobs, "Fundamentals of Optical Engineering," McGraw-Hill Book Co., Inc., New York, 1943, Pages 88, 253.

The Classification of Automatic Plotting Instruments According to the Method of Construction

Classification	Representative Instruments	Von Gruber
I Polar coordinates		
A. Optical solution		
1. Proj. lenses equivalent		322–24
a. Case A	Theoretically impractical	
1) Large apertures		
2) Small apertures		
b. Case B		
c. Case C	Hugershoff DRP 441879	208
	Zeiss Stereoplanigraph III	190–4, 346–52
d. Case D		
2. Proj. lenses not equiv.		316–20
a. Case A		
1) Large apertures	Bauersfeld Stereoplast	180–1
	Goerz Triangulator	217, 224
	Predhumeau Stereotopometer	181, 222
2) Small apertures	Lyon II	
	Miller I	
	Miller II	
	Multiplex Aeroprojector	
b. Case B		
c. Case C		
d. Case D		
3. Proj. lenses not used		
a. Case A		
1) Large apertures	Cook SCS Plotter	
	Deville	177
	K.E.K. Stereoscopic Plotter	
2) Small apertures	Lyon I	
b. Case B		
c. Case C		
d. Case D		
B. Mechanical solution		
1. Proj. lenses equivalent		324–30
a. Case A	Goerz II	213
	Goerz III	214
	Zeiss 1A	153, 182
	Zeiss 1B	183
	Zeiss 1C	184
	Zeiss 1D	186
	Zeiss 1E	186
b. Case B	Boucard III	228
	Hugershoff Aerocartograph	352, 365
	Wild Autograph	346, 356–9
	Wild Stereoautograph	226
	Zeiss 2A	153, 187
c. Case C		
d. Case D	Fourcade	230
	Goerz IV	215
	Poivilliers I	223
	Poivilliers II	225
	Zeiss 3A	189
	Zeiss 3B	190
2. Proj. Lenses not equiv.		320–22
a. Case A	Goerz I Aerogeodetic	212
b. Case B	Gasser Stereocomparator	200
c. Case C		
d. Case D		
3. Proj. lenses not used		221
a. Case A	Santoni Auto-reducer	221
b. Case B		
c. Case C	Zimmer	173
d. Case D		
II. Rectangular coordinates		
A. Optical solution	Theoretically impractical	
B. Mechanical solution		
1. Proj. lenses equivalent		324–30
a. Case A		
b. Case B		
c. Case C		
d. Case D	Hugershoff Autocartograph	206, 343
	Poivilliers II	223
2. Proj. lenses not equiv.		320–22
a. Case A		
b. Case B		
c. Case C		
d. Case D		
3. Proj. lenses not used		168–74, 340–5
a. Case A		
b. Case B		
c. Case C		
d. Case D	Zeiss Stereoautograph	168–74, 340–5

the need of creating an instrument that possesses certain essential characteristics. These essential characteristics are listed below, together with a number of others that are very desirable.

1. There must be no parallactic displacement between the floating mark and photographs (or their images). [Parallactic displacement is the apparent movement of the floating mark with respect to the photographs that is caused by the movement of the operator's eyes at the eyepiece of the instrument.]
2. The conjugate image rays must possess the same relationships to each other and to the map plane that existed between those light rays that exposed the original negatives. [In the case of vertical photographs, substitute perspective centers may be used as long as they are permanently fixed in the same place on the principal lines of both photographs.]
3. It must be possible for the observer to keep the stereoscopic model and the floating mark in sharp focus at all times.
4. The optical and mechanical systems must be practical, relatively simple, and theoretically precise.
5. Conjugate epipolar rays should appear in a plane of the observer's vision.
6. The directions of vision ought to be nearly parallel for the undistended eyes, and in no case should they converge more than that amount which occurs in unhampered and unconstrained vision in nature.
7. Provision must be made for change in plottings scale, and for change in the inter-ocular distance.
8. The device should be economical to build and easy to operate.
9. The images of the photographs should possess excellent definition and abundant illumination.
10. The image of the floating mark should be bright, sharp, and very small. It should not create difficult problems of construction.
11. The photographs should be presented to the eyes of the operator properly oriented and in correct sequence.
12. The device should be able to make satisfactory use of either vertical or oblique photographs.
13. The entire stereoscopic overlap should be visible to the operator at one time.
14. It should be possible to orient several consecutive photographs in the instrument at one time, in order to "bridge" geographic control.
15. The device should lend itself to easy collimation and calibration.

The practical value of any plotting instrument that does not possess the first eleven of the above characteristics will be severely limited.

ERRATA

LT. SHERMAN A. WENGERD, author of "Logarithmic Form for Rapid Computation of the Oblique Grid" in the September issue of PHOTOGRAMMETRIC ENGINEERING, calls attention to an error in computation in his paper.

In computational box No. 1, the log $\sqrt{A}$ should be 2.003020. This affects the remaining computations but does not cause the form to lose value.