Chapter 10
Principles of Photogrammetry

10-1. General

The purpose of this chapter is to review the principles of photogrammetry. The chapter contains background information and references that support the standards and guidelines found in the previous chapters. Section I reviews the basic elements of photogrammetry with an emphasis on obtaining quantitative information from aerial photographs. Section II discusses basic operational principles of stereoplotters. Section III summarizes the datums and reference coordinate systems commonly encountered in photogrammetric mapping. Section IV discusses the principles of aerotriangulation. Section V provides background information for mosaics and orthophotographs. A more generalized nontechnical overview of photogrammetry may be found in Appendix C.

Section I
Elements of Photogrammetry

10-2. General

The purpose of this section is to review the basic geometry of aerial photography and the elements of photogrammetry that form the foundation of photogrammetric solutions.

10-3. Definition

Photogrammetry can be defined as the science and art of determining qualitative and quantitative characteristics of objects from the images recorded on photographic emulsions. Objects are identified and qualitatively described by observing photographic image characteristics such as shape, pattern, tone, and texture. Identification of deciduous versus coniferous trees, delineation of geologic landforms, and inventories of existing land use are examples of qualitative observations obtained from photography. The quantitative characteristics of objects such as size, orientation, and position are determined from measured image positions in the image plane of the camera taking the photography. Tree heights, stockpile volumes, topographic maps, and horizontal and vertical coordinates of unknown points are examples of quantitative measurements obtained from photography.

10-4. Geometry of Aerial Photography

The geometry of a single vertical photograph is shown in Figure 10-1. The photographic negative is shown for completeness, but in practice it is typical to work with the photographic positive printed on paper, film, or glass. The front nodal point of the camera lens is defined as the exposure station of the photograph. The nodal points are those points in the camera lens system such that any light ray entering the lens and passing through the front nodal point will emerge from the rear nodal point travelling parallel to the incident light ray. Therefore, the positive photograph can be shown on the object side of the camera lens, positioned such that the object point, the image point, and the exposure station all lie on the same straight line. The line through the lens nodal points and perpendicular to the image plane intersects the image plane at the principal point. The distance measured from the rear nodal point to the negative principal point or from the front nodal point to the positive principal point is equal to the focal length f of the camera lens.
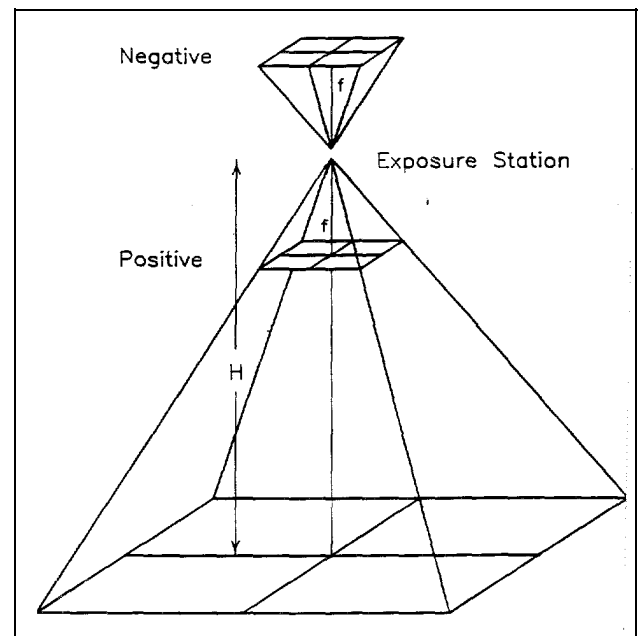

Figure 10-1. Single vertical photograph geometry

10-5. Single Vertical Aerial Photography

Vertical photographs, exposed with the optical axis vertical or as nearly vertical as possible, are the principal kind of photographs used for mapping. If the axis is

perfectly vertical, the resulting photograph is termed a "truly vertical" photograph. In spite of the precautions taken to maintain the vertical camera axis, small tilts are invariably present; but these tilts are usually less than 1 degree and they rarely exceed 3 degrees. Photographs containing these small, unintentional tilts are called "near vertical" or "tilted" photographs. Many of the equations developed in this chapter are for truly vertical photographs, but for certain work, they may be applied to near vertical photos without serious error. Photogrammetric principles and practices have been developed to account for tilted photographs, and no accuracy whatsoever need be lost in using tilted photographs.

a. Photographic scale. The scale of an aerial photograph can be defined as the ratio between an image distance on the photograph and the corresponding horizontal ground distance. Note that if a correct photographic scale ratio is to be computed using this definition, the image distance and the ground distance must be measured in parallel horizontal planes. This condition rarely occurs in practice since the photograph is likely to be tilted and the ground surface is seldom a flat horizontal plane. Therefore, scale will vary throughout the format of a photograph, and photographic scale can be defined only at a point.

(1) The scale at a point on a truly vertical photograph is given by

$$S = \frac{f}{H - h} \tag{10-1}$$

where

S = photographic scale at a point

f = camera focal length

H = flying height above datum

h = elevation above datum of the point

Equation 10-1 is exact for truly vertical photographs and is typically used to calculate scale on nearly vertical photographs.

(2) In some instances, such as flight planning calculations, approximate scaled distances are adequate. If all ground points are assumed to lie at an average elevation, an average photographic scale can be adopted for direct measurements of ground distances. Average scale is calculated by

$$S_{ave} = \frac{f}{(H - h_{ave})} \tag{10-2}$$

where h_{ave} is the average ground elevation in the photo. Then referring to the vertical photograph shown in Figure 10-2, the approximate horizontal length of the line AB is

$$D \cong \frac{d(H - h_{ave})}{f} \tag{10-3}$$

where

D = horizontal ground distance
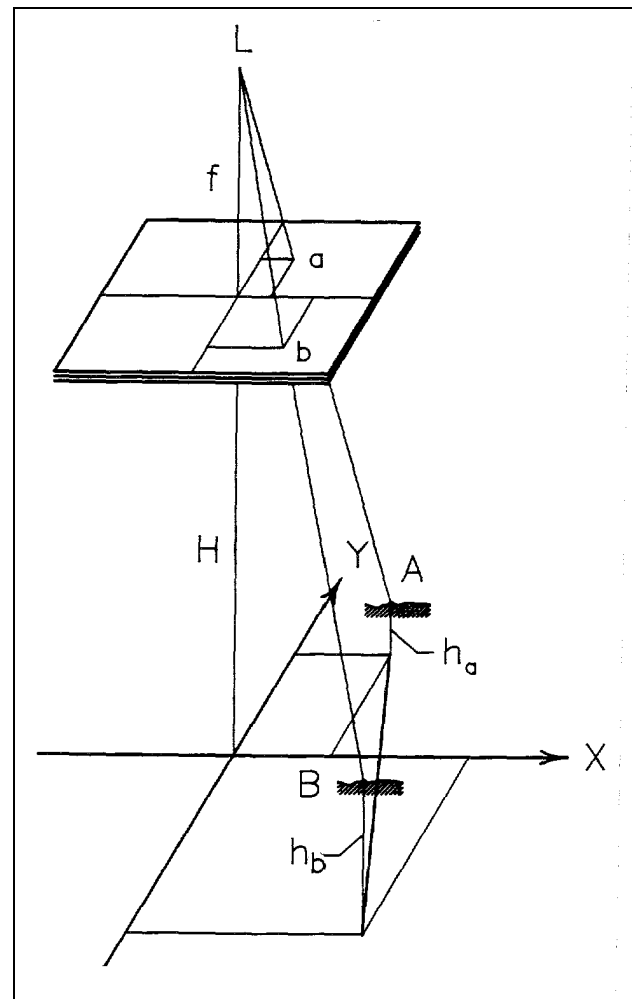
d = photograph image distance

Figure 10-2. Horizontal ground coordinates from single vertical photograph

The flat terrain assumption, however, introduces scale variation errors. For accurate determinations of horizontal distances and angles, the scale variation caused by elevation differences between points must be accounted for in the photogrammetric solution.

b. *Horizontal ground coordinates.* Horizontal ground distances and angles can be computed using coordinate geometry if the horizontal coordinates of the ground points are known. Figure 10-2 illustrates the photogrammetric solution to determine horizontal ground coordinates.

(1) Horizontal ground coordinates can be calculated by dividing each photocoordinate by the true photographic scale at the image point. In equation form, the horizontal ground coordinates of any point are given by

$$X_p = \frac{x_p(H - h_p)}{f}$$

$$Y_p = \frac{y_p(H - h_p)}{f}$$

(10-4)

where

X_p, Y_p = ground coordinates of point p

x_p, y_p = photocoordinates of point p

h_p = ground elevation of point p

Note that these equations use a coordinate system defined by the photocoordinate axes having an origin at the photo principal point and the x-axis typically through the midside fiducial in the direction of flight. Then the local ground coordinate axes are placed parallel to the photocoordinate axes with an origin at the ground principal point.

(2) The equations for horizontal ground coordinates are exact for truly vertical photographs and typically used for near vertical photographs.

(3) After the horizontal ground coordinates of points A and B in Figure 10-2 are computed, the horizontal distance is given by

$$D_{AB} = \sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2}$$

(10-5)

This solution is not an approximation because the effect of scale variation caused by unequal elevations is included in the computation of the ground coordinates. It is important to note, however, that the elevations h_a and h_b must be known before the horizontal ground coordinates can be computed. The need to know elevation can be overcome if a stereo solution is used.

c. *Relief displacement.* Relief displacement is another characteristic of the perspective geometry recorded by an aerial photograph. The displacement of an image point caused by changes in ground elevation is closely related to photographic scale variation. Relief displacement is evaluated when analyzing or planning mosaic or orthophoto projects. Relief displacement is also a tool that can be used in photo interpretation to determine heights of vertical objects.

(1) The displacement of photographic images caused by differences in elevation is illustrated in Figure 10-3. The image displacement is always along radial lines from the principal point of a truly vertical photograph or the nadir of a tilted photograph. The magnitude of relief displacement is given by the formula

$$d = \frac{rh}{H}$$

(10-6)

where

d = image displacement

r = radial distance from the principal point to the image point

H = flying height above ground

(2) Since the image displacement of a vertical object can be measured on the photograph, Equation 10-6 can be solved for the height of the object to obtain

$$ht = \frac{d(H - h_{base})}{r_{top}}$$

(10-7)

where

ht = vertical height of the object

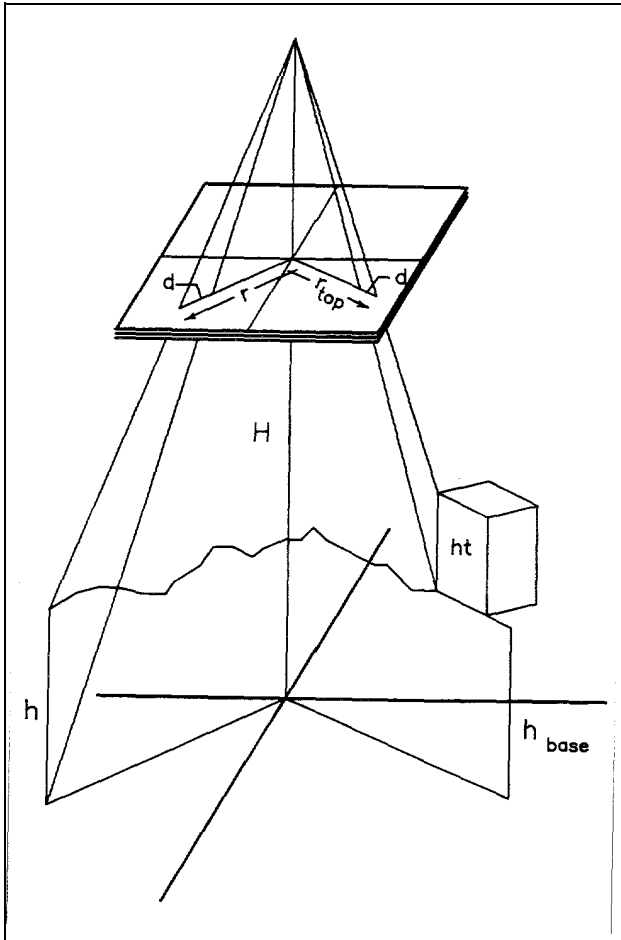h_{base} = elevation at the object base above datum

Figure 10-3. Relief displacement on a vertical photograph

Remember, heights of vertical objects can be determined on a single photograph, but elevation above datum cannot be determined.

10-6. Exterior Orientation of Tilted Photographs

Unavoidable aircraft tilts cause aerial photographs to be exposed with the camera axis tilted slightly from vertical, and the resulting pictures are called tilted photographs. The equations given above are exact for truly vertical photographs, and they are used with near vertical photography for planning, estimating, and photo interpretation. However, an accurate photogrammetric solution using aerial photographs must account for the camera position and tilt at the instant of exposure.

a. The exterior orientation of a photograph is its spatial position and angular orientation with respect to

the ground coordinate system. Six independent parameters are required to define exterior orientation. The space position is normally given by three-dimensional coordinates of the exposure station in a ground coordinate system. The vertical coordinate corresponds to the flying height above datum. Angular orientation is the amount and direction of tilt in the photo. Three angles are sufficient to define angular orientation, and two different systems are commonly used: the tilt-swing-azimuth system (t-s-α) and the omega-phi-kappa system (ω, ϕ, κ). The omega-phi-kappa system possesses certain computational advantages over the tilt-swing-azimuth system, but the tilt-swing-azimuth system is perhaps more easily understood. Figure 10-4 illustrates the parameters used to express exterior orientation of an aerial photograph.
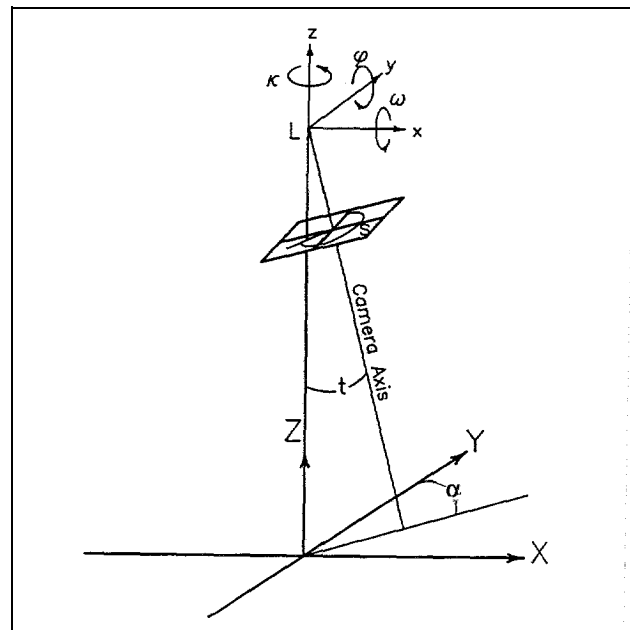

Figure 10-4. Exterior orientation of an aerial photograph

b. The tilt-swing-azimuth system is appropriate for hand calculations. An auxiliary photocoordinate system is defined with an origin at the photo nadir and y' axis along the direction of tilt. The expression for scale on a tilted photograph is

$$S = \frac{\dfrac{f}{\cos t} - (y' \sin t)}{H - h} \qquad (10\text{-}8)$$

where

y' = auxiliary photocoordinate

t = photo tilt angle

c. The tilt of aerial mapping photography is seldom large enough to require using tilted photograph equations for hand calculations when planning and estimating projects. However, Equation 10-8 does show that scale is a function of tilt, and scale variation occurs on a tilted photo even over flat terrain.

d. Since the swing angle *s* of a truly vertical photograph is undefined, the omega-phi-kappa angular orientation system is preferred when expressing exterior orientation of any photograph. In the omega-phi-kappa system, the angular orientation of a tilted photograph is given in terms of three *sequential* rotation angles, omega, phi, and kappa. These angles, shown also in Figure 10-4, uniquely define the angular relationships between the three image coordinate system axes of a tilted photo and the three axes of the ground coordinate system. Omega is a rotation about the x photographic axis, phi is about the y-axis, and kappa is about the z-axis.

e. The angular orientation of a truly vertical photograph taken with the flight line in the ground X or east direction is

$\omega = 0$

$\phi = 0$

$\kappa = 0$

The omega-phi-kappa angular orientation system is used in analogic and analytical solutions to express the exterior orientation of a photograph and produce accurate map information from aerial photographs.

10-7. Stereoscopic Vision

Stereoscopic vision determines the distance to an object by intersecting two lines of sight. In the human vision system, the brain senses the parallactic angle between the converging lines of sight and unconsciously associates the angle with a distance. Overlapping aerial photographs can be viewed stereoscopically with the aid of a stereoscope. The stereoscope forces the left eye to view the left photograph and the right eye to view the right photograph. Since the right photograph images the same terrain as the left photograph, but from a different exposure station, the brain perceives a parallactic angle when the two images are fused into one. As the viewer scans the entire overlap area of the two photographs, a continuous stereomodel of the ground surface can be seen. The stereomodel can be measured in three dimensions, yielding the elevation and horizontal position of unknown points. The limitation that elevation cannot be determined in a single photograph solution is overcome by the use of stereophotography.

a. Lens stereoscope. A lens or pocket stereoscope is a low-cost instrument that is very useful in the field as well as the office. It offers a fixed magnification, typically 2.5X. The lens stereoscope is useful for photo interpretation, control point design, and verification of mapped planimetric and topographic features.

b. Mirror stereoscope. A mirror stereoscope can be used for the same functions as a lens, but is not appropriate for field use. The mirror stereoscope has a wider field of view at the nominal magnification ratio. Since photographs can be held fixed for stereo viewing under a mirror stereoscope, the instrument is useful for simple stereoscopic measurements. Mirror stereoscopes can be equipped with binocular eyepieces that yield 6X and 9X magnification. The high magnification helps to identify, interpret, and measure photographed features.

c. Floating mark. Stereoscopic measurements are possible if a floating mark is introduced in the viewing system. Identical halfmarks, such as a small filled circle or a small cross, are put in the field of view of each eye. As the stereomodel surface is viewed, the two halfmarks are viewed against the photographed scene by each eye. If the halfmark positions are properly adjusted, the brain will fuse their images into a single floating mark that appears in three-dimensional space relative to the stereomodel. By moving the halfmarks parallel to the viewer's eye base, the floating mark can be adjusted until it is perceived to lie on the stereomodel surface. At this point, the two halfmarks are on the identical or conjugate image points of two different photographs. The horizontal position and elevation of the mark can be determined and plotted on a map. The importance of the floating mark is that all points in a stereomodel can be measured and mapped. Thus, indistinct points, such as hilltops, centers of road intersections, and contours can be mapped in three dimensions from the stereomodel.

10-8. Geometry of Aerial Stereophotographs

The basic unit of photogrammetric mapping is the stereomodel formed in the overlapping ground coverage of successive photographs along a flight line. Figure 10-5 illustrates the ground coverage along three contiguous flight lines in a block of aerial photographs. ==Along each flight line, the overlap of photographs, termed end lap, is typically designed to be 60 percent.== End lap must be at least 55 percent to ensure continuous stereoscopic coverage and provide a minimum triple overlap area where stereomodels can be matched together. Between adjacent flight lines, the overlap of strips, termed side lap, is typically designed to be 30 percent. ==Side lap must be at least 20 percent to ensure continuous stereoscopic coverage.==
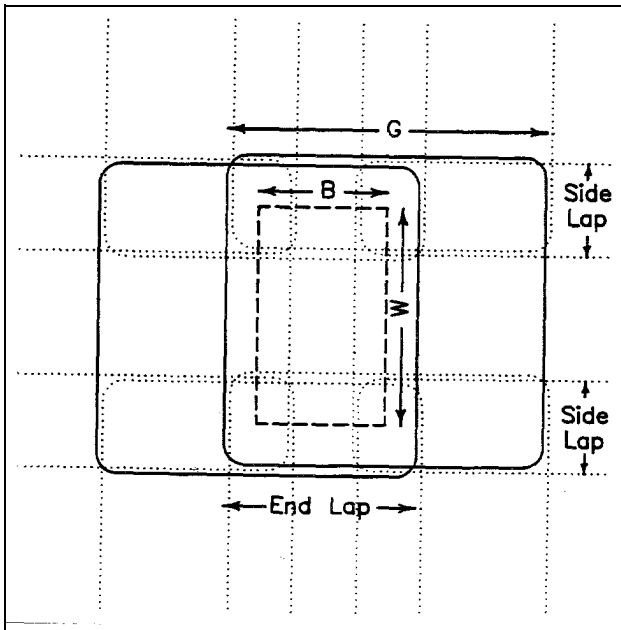

Figure 10-5. Aerial photography stereomodel and neat model

  a. Stereomodel dimensions. For project planning and estimating, photograph and stereomodel ground dimensions are computed by assuming truly vertical photography and flat terrain at average ground elevation.

  (1) Using average photographic scale, the ground coverage G of one side of a square format photograph is

$$G = \frac{d}{S_{ave}} \qquad (10\text{-}9)$$

where d is the negative format dimension. The flying height above datum is also found using average scale and average ground elevation.

$$H = h_{ave} + \frac{f}{S_{ave}} \qquad (10\text{-}10)$$

  (2) Let B represent the air base between exposures in the strip. Then from the required photo end lap E_{lap}

$$B = G \left(1 - \frac{E_{lap}}{100} \right) \qquad (10\text{-}11)$$

  (3) Let W represent the distance between adjacent flight lines. Then from the required side lap S_{lap}

$$W = G \left(1 - \frac{S_{lap}}{100} \right) \qquad (10\text{-}12)$$

  (4) Match lines between contiguous stereomodels pass through the center of the triple overlap area and the center of the side lap area. These match lines bound the neat model area, the net area to be mapped within each stereomodel. The neat model has width equal to B and length equal to W.

  b. Parallax equations. The parallax equations may be used for simple stereo analysis of vertical aerial photographs taken from equal flying heights—that is, the camera axes are parallel to one another and perpendicular to the air base. Conjugate image points in the overlap area of two truly vertical aerial photographs may be projected as shown in Figure 10-6. When the photographs are properly oriented with respect to one another, the conjugate image rays recorded by the camera will intersect at the true spatial location of the object point. Images of an object point A appear on the left and right photos at a and a', respectively. The planimetric position of point A on the ground is given in terms of ground coordinates X_A and Y_A. The XY ground axis system has its origin at the datum principal point O of the left photograph; the X-axis is in the same vertical plane as the photographic x and x′ flight axes; and the Y-axis passes through the datum principal point of the left photograph and is perpendicular to the X-axis.

(1) Photographic parallax is defined as the apparent movement of the image point across the image plane of the camera as the camera exposure station moves along the flight line. The parallax of the image point in Figure 10-6 is
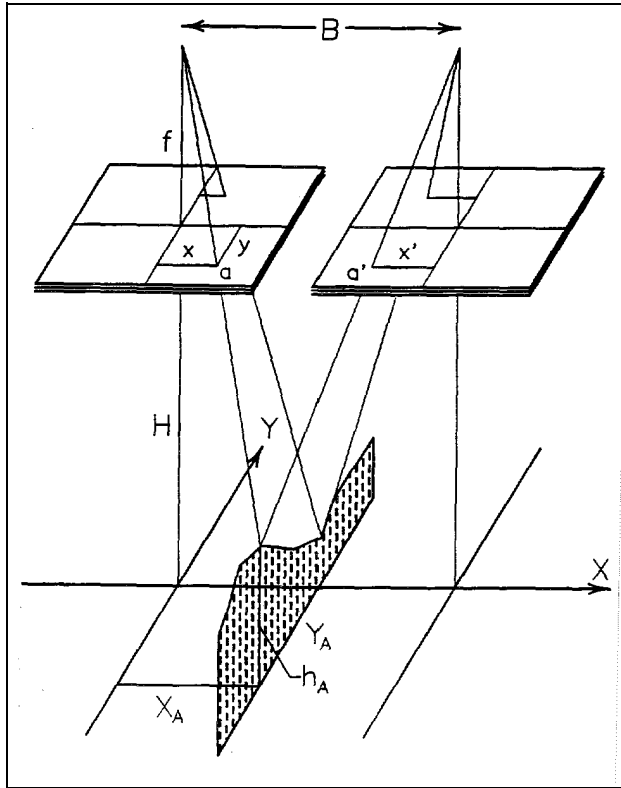

Figure 10-6. Stereopair of vertical aerial photographs

$$P_a = x_a - x_a'$$ (10-13)

where x_a and x_a' are coordinate distances on the left and right photographs, respectively. Since parallactic image motion is parallel to the movement of the camera, the parallax coordinate system must be parallel to the direction of flight. All parallax occurs along the x-axis in the axis of flight photocoordinate system. The y and y' coordinates are equal.

(2) Given truly vertical aerial photographs and photocoordinates measured in the axis of flight system, the following parallax equations can be derived:

$$X = \frac{xB}{p}$$

$$Y = \frac{yB}{p}$$ (10-14)

$$h = H - \frac{fB}{p}$$

where

X,Y = horizontal ground coordinates

x,y = photocoordinates on the left photograph

p = parallax

Note that the origin of the ground coordinate system is at the ground principal point of the left photograph, and the X-axis is parallel to the flight line.

c. Parallax difference equation. The parallax equations given in b above assume that the photographs are truly vertical and exposed from equal flying heights; thus, the camera axes are parallel to one another and perpendicular to the air base. Scale variation and relief displacement are not regarded as errors in the parallax method since these effects are measured as image parallax and used to compute elevations; however, tilted photographs, unequal flying heights, and image distortions seriously affect the accuracy of the parallax method. Absolute elevations are difficult to determine using the parallax equations given in b above because small errors in parallax will cause large errors in the vertical distance *H-h*. More precise results are obtained if differences in elevation are determined using the parallax difference formula

$$h_A = h_C + \frac{\Delta p(H - h_C)}{P_a}$$ (10-15)

where

h_A = elevation of point *A* above datum

h_C = elevation of point *C* above datum

P_a = parallax of image point a

P_c = parallax of image point c

Δp = difference in parallax (P_c - P_a)

The formula should be applied to points that are close to one another on the photo format. The differencing technique cancels out the systematic errors affecting the parallax of each point. If C is a vertical control point, the absolute elevation of A can be determined by this method.

10-9. Fundamental Photogrammetric Problems

The fundamental photogrammetric problems are resection and intersection. All photogrammetric procedures are composed of these two basic problems.

a. *Resection.* Resection is the process of recovering the exterior orientation of a single photograph from image measurements of ground control points. In a spatial resection, the image rays from total ground control points (horizontal position and elevation known) are made to resect through the lens nodal point (exposure station) to their image position on the photograph. The resection process forces the photograph to the same spatial position and angular orientation it had when the exposure was taken. The solution requires at least three total control points that do not lie in a straight line, and the interior orientation parameters, focal length, and principal point location. In aerial photogrammetric mapping, the exact camera position and orientation are generally unknown. The exterior orientation must be determined from known ground control points by the resection principle.

b. *Intersection.* Intersection is the process of photogrammetrically determining the spatial position of ground points by intersecting image rays from two or more photographs. If the interior and exterior orientation parameters of the photographs are known, then conjugate image rays can be projected from the photograph through the lens nodal point (exposure station) to the ground space. Two or more image rays intersecting at a common point will determine the horizontal position and elevation of the point. Map positions of points are determined by the intersection principle from correctly oriented photographs.

10-10. Photogrammetric Solution Methods

Correct and accurate photogrammetric solutions must include all interior and exterior orientation parameters. Each orientation parameter must be modeled if the recorded image ray is to be correctly projected and an accurate photogrammetric product obtained. Interior orientation parameters include the camera focal length and the position of the photo principal point. Typically the interior orientation is known from camera calibration. Exterior orientation parameters include the camera position coordinates and the three orientation angles. Typically, the exterior orientation is determined by resection principles as part of the photogrammetric solution. The remaining parameters are the ground coordinates of the point to be mapped. Planimetric and topographic details are mapped by intersecting conjugate image rays from two correctly oriented photographs. Methods of solving the fundamental photogrammetric problems may be classified as analog or analytical solutions.

a. *Analog solutions.* Analog photogrammetric solutions use optical or mechanical instruments to form a scale model of the image rays recorded by the camera. An optical analog instrument projects a transparency of the image through a lens such that the camera bundle of image rays is accurately reproduced and the projected image is brought to focus at some finite distance from the lens. A mechanical analog instrument uses a straight metal rod, a space rod, to represent the image ray from the image point, through the lens perspective center, to the modelled ground point. Analog instruments are limited in function (focal length, model scale enlargement, flight geometry) by the physical constraints of the analog mechanism. They are limited in accuracy by the calibration of the analog mechanism and by unmodelled systematic errors. Analog instruments cannot effectively compensate for differential or nonlinear image and film deformation errors.

b. *Analytical solutions.* An analytical photogrammetric solution uses a mathematical model to represent the image rays recorded by the camera. The image ray is assumed to be a straight line through the image point, the exposure station, and the ground point. The following collinearity equation expresses this condition:

$$x = x_o - f \frac{[m_{11}(X - X_L) + m_{12}(Y - Y_L) + m_{13}(Z - Z_L)]}{[m_{31}(X - X_L) + m_{32}(Y - Y_L) + m_{33}(Z - Z_L)]}$$

$$\text{(10-16)}$$

$$y = y_o - f \frac{[m_{21}(X - X_L) + m_{22}(Y - Y_L) + m_{32}(Z - Z_L)]}{[m_{31}(X - X_L) + m_{32}(Y - Y_L) + m_{33}(Z - Z_L)]}$$

where

x,y = measured photocoordinates

x_o,y_o = principal point photocoordinates

m_{ij} = nine direction cosines expressing the angular orientation

X,Y,Z = ground point coordinates

X_L,Y_L,Z_L = exposure station coordinates

The collinearity condition equations include all interior and exterior orientation parameters required to solve the resection and intersection problems accurately. Analytical solutions consist of systems of collinearity equations relating measured image photocoordinates to known and unknown parameters or the photogrammetric problem. The equations are solved simultaneously to determine the unknown parameters. However, since there are usually redundant measurements producing more equations than there are unknowns in the problem, a least squares adjustment is used to estimate the unknown parameters. The least squares adjustment algorithm includes residuals v_x and v_y on the measured photocoordinates that estimate random measurement error.

10-11. Terrestrial Photogrammetry

a. Definition. Terrestrial photogrammetry refers to applications where the camera is supported on the surface of the earth. Typically the camera is mounted on a tripod and the camera axis is oriented in or near the horizontal plane. When the distance to the object is less than approximately 300 m, the method is often referred to as close-range photogrammetry.

b. Applications. Terrestrial photogrammetry techniques can be applied to measuring and mapping large vertical surfaces. These applications include topographic mapping of rugged terrain and vertical cliffs, deformation measurement of structures, and architectural mapping of buildings. Close-range applications include measuring and calibrating irregular surfaces such as antenna reflectors and industrial assembly jigs, and three-dimensional mapping of industrial installations and construction sites.

c. Instrumentation

(1) Cameras. Cameras for engineering applications of terrestrial photogrammetry should be stable, calibrated metric cameras similar to aerial cameras. For highest accuracy, some cameras expose the image directly on glass planes to ensure image plane flatness. Film type cameras should have a film-flattening device. Terrestrial cameras are available in a range of focal lengths and format size. If the camera is combined with angle measuring capability for orienting the camera axis in a known direction, the instrument is referred to as a phototheodolite. Stereometric cameras are two cameras rigidly fixed to a base bar. Since the base is usually short, stereometric cameras fall into the close-range category.

(2) Stereoplotters. Some specialized stereoplotters have been developed specifically for terrestrial applications; however, these instruments are not typically available in the United States photogrammetric industry. Some analog stereoplotters can accommodate some terrestrial and close-range cameras; but often incompatible focal lengths, format sizes, and depth of field constraints make analog stereoplotters unusable for this work. Analytical stereoplotters can accommodate terrestrial and close-range cameras because no mechanical constraints are placed on the mathematical projection. Of course, monocomparators and analytical software work equally well for precise applications of point mapping.

d. Methods. The photogrammetric principles discussed in this chapter apply also to the terrestrial solutions. Terrestrial photogrammetry differs from aerial photogrammetry in the fact that the camera is accessible. Thus, the camera position and orientation can be measured. Theoretically this eliminates the need for control points and resection to orient the camera. When considering a terrestrial or close-range application, additional consideration must be given to optimum camera location geometry, focusing requirements of the camera, and depth of field requirements to capture the object to be measured.

Section II
Stereoscopic Plotting Instruments

10-12. General

A general overview of existing stereoplotter designs and general operating procedures is presented in this chapter. For the purposes of this chapter, only instruments that perform a complete restitution of the interior and exterior orientation of the photography taken will be considered. Although all types of stereoplotters are discussed, it is expected that analytical stereoplotters will become the industry standard because of accuracy, efficiency, and capability.

10-13. Types of Stereoplotters

The three main component systems in all stereoplotters are the projection system, the viewing system, and the measuring and tracing system. Stereoplotters are most often grouped according to the type of projection system used in the instrument.

a. *Direct-optical projection stereoplotters.* Direct-optical projection stereoplotters project a transparent positive of the original negative optically through a lens to recreate the bundle of image rays recorded by the cameras. This type of stereoplotter was the precursor of modern mechanical projection and analytical stereoplotters. Briefly, these stereoplotters use a fixed focal length lens for projection so that the principal distance and the projection distance of the instrument are fixed. Thus, the enlargement ratio from positive to stereomodel is also fixed. For a typical "Kelsh-type" instrument, the enlargement ratio of the stereomodel is five times the contact positive scale. The stereomodel is viewed directly on a reflecting platen in the model space. The floating mark is on the platen, and as the mark is moved through the model, its position is traced directly onto a map manuscript below the mark. The vertical movement of the platen is read out at model scale as the elevation of the floating mark. Direct-optical projection stereoplotters are classified as the least accurate instrument type. They have been replaced in practice by mechanical projection and analytical stereoplotters.

b. *Mechanical projection stereoplotters.* Mechanical projection stereoplotters are analog instruments that recreate the image ray using a metal space rod. The space rod pivots in a fixed gimbal joint representing the lens nodal point. Two space rods from adjacent diapositives intersect in the model space to define the terrain point. Since no lens is included in the projection

system, the principal distance and projection distance along the space rod can be varied. Usually a small range of camera focal lengths can be accommodated, and model scale can be varied within the mechanical limits of the instrument.

(1) The viewing system of a mechanical projection stereoplotter is an optical train system of lenses and prisms similar in principle to a mirror stereoscope. The operator perceives the stereomodel by looking directly at the positive image. Image magnification is included to increase the precision of the floating mark placement in the stereomodel.

(2) The floating mark is included in the optical train. Its position in the model space corresponds to the intersection of the space rods representing the two conjugate image rays. The model carriage where the space rods intersect may be free moving. The model carriage may include a pencil mount, and the carriage is hand-driven to trace out a map manuscript. The model carriage may be connected to a mechanical drive that can be digitally encoded. Thus, the movement of the floating mark is converted to digital x-y-z model coordinates in three dimensions.

(3) The accuracy of mechanical projection stereoplotters will typically be in the medium to high range. Plotters designed for map compilation are in the medium range. These plotters typically have free-moving model carriages that are hand-driven during map compilation. The Kern PG2, Galileo G6, and Wild B8 are some examples of medium-accuracy mechanical projection stereoplotters used for map compilation. Mechanical projection stereoplotters in the high-accuracy range warrant more precise measurement of the stereomodel space. In these instruments, the model carriage is mechanically driven and controlled by operator hand wheels and foot disk or similar control devices. These stereoplotters are also more massive and stable instruments than the medium-accuracy compilation instruments, and typically they are universal instruments capable of analog aerotriangulation. The Wild A8, Zeiss C8, and Jena Stereometrograph are some examples of these instrument types.

c. *Analytical stereoplotters.* Analytical stereoplotters use a mathematical image ray projection based on the collinearity equation model. The mechanical component of the instrument consists of a precise computer-controlled stereocomparator. Since the photo stages must move only in the x and y image directions, the measurement system can be built to produce a highly

accurate and precise image measurement. The x and y photocoordinates are encoded, and all interior and exterior orientation parameters are included in the mathematical projection model. Except for the positive format size that will fit on the photo stage, the analytical stereoplotter has no physical constraints on the camera focal length or model scale that can be accommodated.

(1) The viewing system is an optical train system typically equipped with zoom optics. The measuring mark included in the viewing system may be changeable in style, size, and color. The illumination system should have an adjustable intensity for each eye.

(2) The measuring system consists of an input device for the operator to move the model point in three dimensions. The input device is encoded, and the digital measure of the model point movement is sent to the computer. The software then drives the stages to the proper location accounting for interior and exterior orientation parameters. These operations occur in real time so that the operator, looking in the eyepieces, sees the fused image of the floating mark moving in three dimensions relative to the stereomodel surface. The operator's input device for model position may be a hand-driven free-moving digitizer cursor on instruments designed primarily for compilation, or it may be a hand wheel/foot disk control or similar device on instruments supporting fine pointing for aerotriangulation.

(3) Analytical stereoplotters are more accurate than analogic stereoplotters because the interior orientation parameters of the camera are included in the projection software. Therefore, any systematic error in the photography can be corrected in the photocoordinates before the photogrammetric projection is performed. Correcting for differential film deformations, lens distortions, and atmospheric refraction justifies measuring the photocoordinates to accuracies of 0.003 mm and smaller in analytical stereoplotters. To achieve this accuracy, the analytical stereoplotter must have the capability to perform a stage calibration using measurements of reference grid lines etched on the photo stage.

(4) Analytical stereoplotters capable of precise map compilation and aerotriangulation measurements include (but are not limited to) the Zeiss Planicomp P series, the Wild (now Leica) AC and BC series, the Kern (now Leica) DSR series, the Intergraph Intermap, and the Galileo Digicart (Figure 7-5).

d. Digital stereoplotters. The next generation of stereoplotters will be digital (or soft copy) stereoplotters.

These instruments will display a digital image on a workstation screen in place of a film or glass diapositive. The instrument will operate as an analytical stereoplotter except that the digital image will be viewed and measured. The accuracy of digital stereoplotters is governed by the pixel size of the digital image. The pixel size directly influences the resolution of the photocoordinate measurement. A digital stereoplotter can be classified according to the photocoordinate observation error at image scale. Then it should be comparable to an analog or analytical stereoplotter having the same observation error, and the standards and guidelines in this manual should be equally as applicable. See also paragraph 10-15.

10-14. Stereoplotter Operations

All stereoplotters, whether analog or analytical, must be set up for measuring or mapping in three consecutive steps: interior orientation, relative orientation, and absolute orientation.

a. Interior orientation. Interior orientation involves placing the photographs in proper relation to the perspective center of the stereoplotter by matching the fiducial marks to corresponding marks on the photography holders and by setting the principal distances of the stereoplotter to correspond to the focal length of the camera (adjusted for overall film shrinkage).

b. Relative orientation. Relative orientation involves reproducing in the stereoplotter the relative angular relationship that existed between the camera orientations in space when the photographs were taken. This is an iterative process and should result in a stereoscopic model easily viewed, in every part, without "y parallax"—the separation of the two images so they do not fuse into a stereoscopic model. When this step is complete, there exists in the stereoplotter a stereoscopic model for which three-dimensional coordinates may be measured at any point; but it may not be exactly the desired scale, and it may not be level—water surfaces may be tipped.

c. Absolute orientation. Absolute orientation uses the known ground coordinates of points identifiable in the stereoscopic model to scale and to level the model. When this step is completed, the X, Y, and Z ground coordinates of any point on the stereoscopic model may be measured and/or mapped.

10-15. Stereoplotter Accuracies

Stereoplotter accuracies are best expressed in terms of observation error at diapositive scale. In this way, instruments can be compared based on the fundamental measurement of image position on the positive. Measurement error on the positive can be projected to the model space so that expected horizontal and vertical error in the map compilation can be estimated. Stereoplotter accuracy affects the maximum allowable enlargement from photo scale to map scale and the minimum CI that can be plotted from given photo scale. The enlargement ratio and the empirical C-factor are discussed in Chapter 7, and maximum values for these two factors are specified in Chapter 2.

10-16. Stereoplotter Output Devices

Stereoplotters are connected to a variety of devices for plotting or recording line work and digital data. Although the direct tracing of map manuscripts on a stereoplotter is a form of output, it is expected that modern stereoplotters will be encoded and interfaced to a graphical or digital output device. Examples of these output devices are shown in Chapter 7.

a. Stereoplotters may be computer assisted. The movement of the measuring mark of these stereoplotters is digitally encoded. The digital signal is sent directly to a computer-controlled coordinatograph. The operator can include feature codes in the digital signal that the computer can interpret to connect points with the proper line weight and type, plot symbols at point locations, label features with text, etc. The final map product can be produced at the manuscript stage by an experienced operator.

b. A digitally encoded stereoplotter may also be interfaced to a digital compilation software system in which the compiled line work and annotations appear on a workstation screen. Similar to the computer-assisted stereoplotter and coordinatograph, the compilation on the workstation screen can be displayed with proper line weights (or colors and layers), line types, symbols, and feature labels. In addition, since the map exists in a digital computer file, basic map editing can be done as the manuscript progresses. Typically, the digital compilation file is converted (or translated) to a full CADD design file where it can be merged with adjacent compiled stereomodels and final map editing performed. The deliverable product from these systems is often in digital form on computer tape or disk.

Section III
Ground Control Datums and Coordinate
Reference Systems

10-17. General

Photogrammetric ground control consists of any points whose positions are known in a ground reference coordinate system, and whose images can be positively identified in the photographs. Ground control provides the means for orienting or relating aerial photographs and stereomodels to the ground. Almost every phase of photogrammetric work requires some ground control. Photogrammetric control is generally classified as either *horizontal control* (the position of the point is known with respect to a horizontal datum), or *vertical control* (the elevation of the point is known with respect to a vertical datum). Sometimes both horizontal and vertical object space positions of points are known so that these points serve a dual control purpose. Such points may be referred to as *total control*.

10-18. Coordinate Datums and Reference Systems

A datum is a reference surface on which a coordinate system is defined. In surveying and mapping, many datums and many coordinate systems can be defined that will express the position of points on the earth's surface. It is of utmost importance to know the coordinate system used to reference any control survey or map. Control survey or map data sets referenced to different coordinate systems cannot be combined unless a transformation of one coordinate system into the other is performed. A detailed discussion of coordinate datums and transformations is given by Soler and Hothem (1988, 1989).

a. *Horizontal geodetic datum.* Datums are often separated into horizontal and vertical datums. A horizontal geodetic datum uses an ellipsoid as the reference surface. The size and shape of the ellipsoid are chosen to give the best fit to the earth on a global basis or on a regional or continental basis. Many different ellipsoids have been proposed. The datum definition is completed by orienting a specific ellipsoid to the earth and defining a coordinate system.

(1) Curvilinear coordinates. Geodetic longitude and latitude are curvilinear coordinates that define the position of a point on the curved ellipsoid surface. The coordinates are expressed in angular units. (Longitude

is the angle measured in the plane of the equator from the reference meridian through Greenwich, England, to the meridian through the point. Latitude is the angle in the plane of the meridian through the point from the equator to the normal through the point.) A geodetic height can also be defined as the distance along the normal from the surface of the ellipsoid to the point.

(2) Geocentric coordinates. Geocentric coordinates are defined for a given datum by placing the origin of a right-handed spatial rectangular coordinate system at the center of the reference ellipsoid. The z-axis coincides with the semiminor axis of the ellipsoid. The x- and y-axes are in the plane of the equator with the x-axis through 0-degree longitude. Simple Cartesian coordinate computations can be performed in the geocentric system. The ellipsoid parameters and curved reference surface are eliminated from the computations (Figure 10-7).
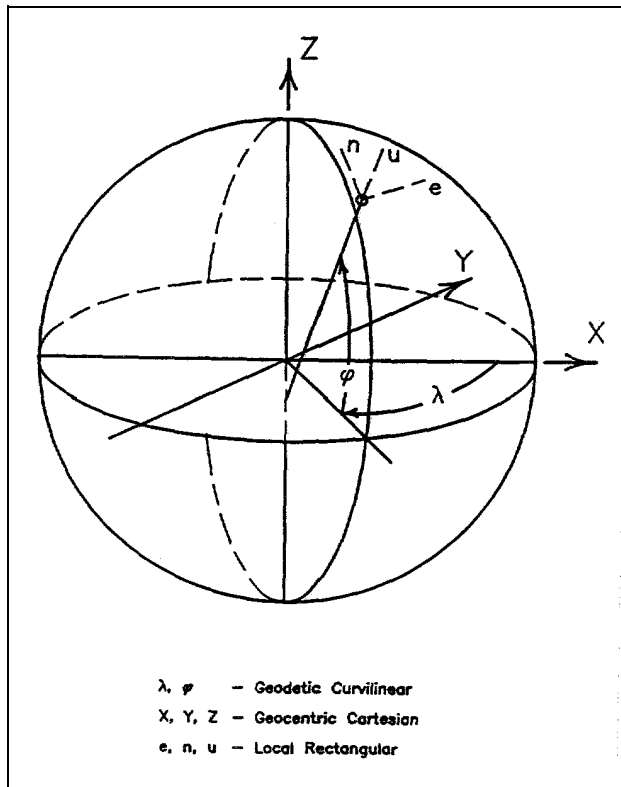

λ, φ   — Geodetic Curvilinear
X, Y, Z — Geocentric Cartesian
e, n, u — Local Rectangular

Figure 10-7. Coordinate reference systems

(3) Local rectangular coordinates. A local rectangular coordinate system can be defined for a given project area. The geocentric coordinate axes are translated to a convenient point in or near the project area. Then the x-y-z geocentric axes are rotated to align with local east, north, and up (along the normal), respectively, at the point. Local rectangular coordinates will appear more natural with respect to the terrain, and the coordinate magnitudes will be smaller for computations. Photogrammetric aerotriangulation should be computed in a local rectangular system (especially for large project areas) since earth curvature and map projection distortion are not present in Cartesian coordinates.

(4) North American Datum of 1927. In the United States, two horizontal datums are commonly encountered in engineering surveying and mapping: the North American Datum of 1927 (NAD 27) and the North American Datum of 1983 (NAD 83) (Table 10-3). NAD 27, a datum defined by an adjustment begun in 1927 of the national control point network, is a continental datum referenced to the Clarke 1866 ellipsoid. The ellipsoid is positioned and oriented to closely fit the geoid throughout the North American continent. Since the NAD 27 adjustment, new control surveys were added to the network by holding the original framework fixed and adjusting the new survey to fit the original. As the network grew without readjustment, distortions were found that demanded a readjustment of the network to meet modern surveying requirements.

(5) North American Datum of 1983. NAD 83 is a rigorous least squares adjustment of the entire national control network incorporating modern high-precision traverse and satellite measurements. NAD 83 is a global datum referenced to the Geodetic Reference System of 1980 ellipsoid. The ellipsoid is earth-centered and designed to be a best fit to the global geoid. Thus, the NAD 83 datum will have a larger geoid-to-ellipsoid separation than the NAD 27 datum in the United States. Since NAD 83 is a readjustment of the original observations in the control network, it is not possible to directly transform coordinates from one datum to the other. Interpolation methods using control points adjusted in both datums have been programmed by the NGS for the purpose of estimating the NAD 83 coordinates of points surveyed in the NAD 27 datum. Although the NAD 27 datum is still used, it should gradually be replaced by the NAD 83 datum.

b. Vertical geodetic datum. A vertical geodetic datum is a reference system for measuring vertical position or elevation. The reference surface is the geoid, which is an equipotential gravity surface that best approximates mean sea level. Elevation above mean sea level (the geoid) is measured along the direction of gravity, perpendicular to the equipotential surfaces. In the United States, the vertical geodetic datum is the

Table 10-3
Comparison of NAD 27 and NAD 83 Datum Elements

Datum Element	NAD 27	NAD 83
Reference Ellipse	Clarke 1866 a = 6,378,206.4 m b = 6,356,583.8 m	GRS 80 a = 6,378,137 m f = 1/298.2572221
Datum Point	Meades Ranch Station	Earth's Mass Center
Best Fitting	North America	Global
Adjustment	Terrestrial data for 25,000 stations and piecewise fits	Terrestrial and satellite data for 250,000+ stations

Note:
1. a = length of semimajor axis of ellipsoid.
   b = length of semiminor axis of ellipsoid.
   f = flattening of ellipsoid.

National Geodetic Vertical Datum of 1929. The elevation of a point can be combined with the horizontal position on the ellipsoid to define a three-dimensional coordinate, latitude, longitude, and height (ϕ, λ, h), by the relationship

$$h = H + N \qquad (10\text{-}17)$$

where

h = height above the ellipsoid

H = elevation above the geoid

N = geoid separation above the ellipsoid

c. Map projections. A map projection is a mathematical function that defines a relationship of coordinates between the ellipsoid and a plane. The purpose of a map projection is to display the curved earth surface on a flat plane that can be printed on a sheet of paper. If field survey observations are reduced to the plane, the computation and adjustment of horizontal control positions can be carried out in two-dimensional Cartesian coordinates. The need for more involved geodetic survey computations can be eliminated.

(1)   The final map reference system is a plane developed from a regular mathematical surface. Developable surfaces that can be rolled out into a plane include a plane, a cone, and a cylinder. The ideal map projection would display all distances and directions correctly, all areas would retain their correct shape and relative size, meridians and parallels would intersect at right angles, and great circles and rhumb lines would be represented as straight lines. Obviously, the earth's surface, being spherical, cannot be developed upon a plane without distortion of some of these quantities.

(2)   In engineering surveying and mapping, correct depiction of shapes is important. Thus, the characteristic of conformality is enforced in projections used for large-scale mapping. This is accomplished by mathematically constraining the projection scale factor at a point, whatever it may be, such that it is the same in all directions from that point. This characteristic of a projection preserves angles between infinitesimal lines. That is, all lines on the grid cut each other at the same angles as do the corresponding lines on the ellipsoid for very short lines. Hence, for a small area, there is no local distortion of shape. But since the scale must change from point to point, distortion of shape can exist over large areas. Remember that the distortion present in any map projection is not an "error" since it is a mathematically defined function. The distortion must simply be accounted for in transforming data from map to ground.

(3)   The most commonly encountered map projections in engineering surveying and mapping are the State Plane Coordinate Systems (SPCS). NGS has developed SPCS's for each state, and many states have formally adopted the systems by legislative action. The SPCS's are based on the Lambert Conformal Conic Projection or the transverse Mercator projection. For complete discussion of the SPCS's refer to Stem (1989).

(4) State Plane Coordinate Systems are defined for both the NAD 27 and NAD 83 datums. For the NAD 27 SPCS definition, the unit of length is the US Survey Foot. For the NAD 83 SPCS definition, the unit of length is variable among the states. Care must be exercised when using NAD 83 SPCS values in feet since either the US Survey Foot or the International Foot may be used in a specific state or locality. The conversion factors are given in paragraph 2-10a.

(5) Another commonly used plane coordinate projection system is the UTM projection. Since this is the standard military reference system, operational support mapping work may need to be compiled using this system. The UTM system uses a Mercator cylindrical projection with the axis of the cylinder oriented perpendicular to the earth's polar axis. The UTM coordinate zones are uniformly spaced around the equator at 6-degree intervals and extend north and south from the equator. A useful reference for the UTM system and other map projections is Snyder (1982).

Section IV
Principles of Aerotriangulation

10-19. General

The principles of aerotriangulation are reviewed in this section. The basic procedures for sequential and simultaneous aerotriangulation adjustment methods are discussed as background for Chapter 6. Emphasis is placed on fully analytical aerotriangulation procedures.

10-20. Aerotriangulation Principles

a. *Definition*. Aerotriangulation is the simultaneous space resection and space intersection of image rays recorded by an aerial mapping camera. The spatial direction of each image ray is determined by projecting the ray from the front nodal point of the camera lens through the image on the positive photograph. Conjugate image rays projected from two or more overlapping photographs intersect at the common ground points to define the three-dimensional space coordinates of each point. The entire assembly of image rays is fit to known ground control points in an adjustment process. Thus, when the adjustment is complete, ground coordinates of unknown ground points are determined by the intersection of adjusted image rays. Simultaneously with the ground point intersections, the exterior orientation of each photograph is determined by image ray resection through the camera.

b. *Purpose*. The purpose of aerotriangulation is to extend horizontal and vertical control from relatively few ground survey control points to each unknown ground point included in the solution. The supplemental control points are called pass points, and they are used to control subsequent photogrammetric mapping.

c. *Geometric principles*. The aerotriangulation geometry along a strip of photography is illustrated in Figure 10-8. Photogrammetric control extension requires that a group of photographs be oriented with respect to one another in a continuous strip or block configuration. The exterior orientation of any photograph that does not contain ground control is determined entirely by the orientation of the adjacent photographs. In a given aerotriangulation configuration, each photograph contributes to the exterior orientation of the adjacent photographs through the pass points located in the *triple overlap* areas. The term triple overlap refers to the ground area shared by two adjacent stereomodels along the strip. The triple overlap area is imaged on three consecutive photographs. Thus, when end lap is specified to be 60 percent, the alternate photographs will overlap each other by 20 percent at average terrain elevation.

d. *Pass points*. A pass point is an image point that is shared by three consecutive photographs (two consecutive stereomodels) along a strip. As the pass point is positioned by one stereomodel, it can be used as control to orient the adjacent stereomodel. Thus, the point "passes" control along the strip. Only three-ray points in the triple overlap area serve this pass point function. A two-ray point in the stereomodel is an intersection point only and does not contribute to the aerotriangulation function unless it is also a ground control point. A pass point that is shared between two adjacent strips is called a tie point.

10-21. Aerotriangulation Methods

Aerotriangulation methods can be characterized in several ways:

a. Photogrammetric projection method (analogic or analytical).

b. Strip or block formation and adjustment method (sequential or simultaneous).

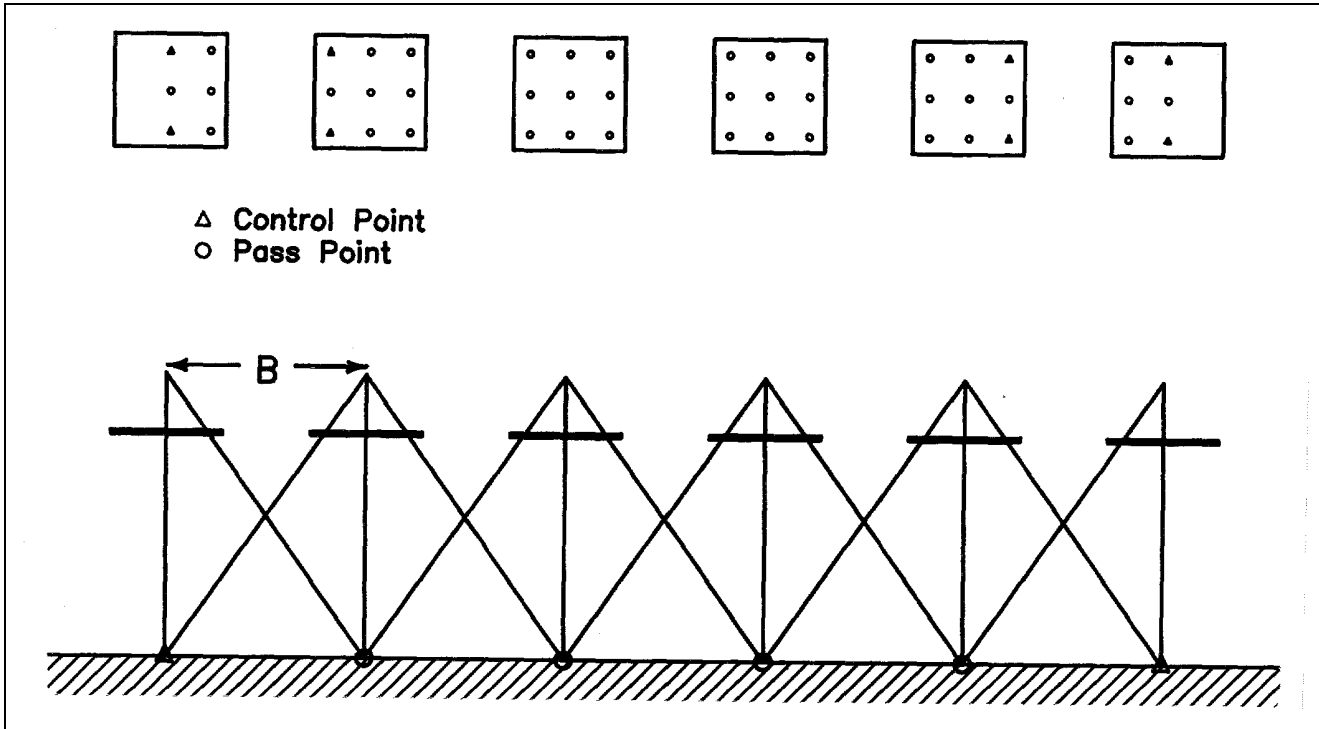c. Basic unit of adjustment (strip, stereomodel, or image rays).

Figure 10-8. Aerotriangulation geometry

Modern instruments and adjustment methods dictate that an analytical adjustment of stereomodels or image rays be emphasized.

a. Semianalytical aerotriangulation. Semianalytical methods use the stereomodel as the basic unit of the aerotriangulation process. Stereomodels may be formed by either analogical or analytical methods. After interior and relative orientation of each stereopair of photographs, stereomodel coordinates are measured in an arbitrary coordinate system defined in the model space. For aerotriangulation purposes, the spatial coordinates of the two exposure stations and each pass point in the stereomodel are required.

(1) Sequential strip formation. A strip unit is formed sequentially from the stereomodels by joining them at the exposure station and pass points shared by the new stereomodel and the previous stereomodel already in the strip coordinate system. Each stereo-model added to the strip provides the necessary points to bring the succeeding stereomodel into the strip unit. The sequential nature of the strip formation procedure allows systematic errors to accumulate as the strip unit is assembled from the individual stereomodels. Resid-ual systematic errors in the interior orientation, the rela-tive orientation, and the measurement system are propagated down the strip causing the horizontal and vertical strip coordinate datums to bow and twist. Al-though it is difficult to measure and completely remove individual systematic errors in each stereomodel, the total effect of all the errors acting on a strip unit is readily apparent after initially leveling and scaling the assembled strip unit. Discrepancies at the horizontal and vertical control coordinates are calculated by taking the coordinate differences between the known position of each control point and its position in the assembled strip unit.

(2) Strip adjustment. The sequential strip formation causes the X, Y, and Z coordinate discrepancies at the control points to form smooth error curves. The error curves can be approximated by second- or third-order polynomial functions. Corrections to the strip pass point coordinates are derived by evaluating the polynomial functions at the strip location of each pass point. The corrections are applied to the original strip coordinates to complete the strip adjustment process.

(a) The polynomial functions model the error propa-gation in a single strip unit. Block configurations may be adjusted by using separate polynomials for each strip. The unique strip units in a block are joined together at tie points in the overlap area between strips. The

polynomial functions adjusting adjacent strips are constrained to yield the same adjusted coordinates at each tie point in the block.

(b) The polynomial adjustment of aerotriangulation is an approximate method that is less accurate than the simultaneous adjustment of stereomodels or photographs. The purpose of polynomial strip adjustment in modern aerotriangulation systems is to perform a preliminary adjustment of all the photogrammetric and ground survey measurements. The sequential strip formation and polynomial adjustment is an excellent way to detect blunders in the data and provide initial approximations for use in simultaneous adjustments.

b. Simultaneous adjustment of stereomodels. The adjustment of independent stereomodels as individual units is the logical extension of the strip unit adjustment discussed in the previous paragraph. Sequentially formed strip units are not used, but rather all stereomodels in an entire strip or block are simultaneously transformed into the ground coordinate system. Stereomodels without ground control points are carried into the ground coordinate system by the pass points and exposure stations shared with adjacent stereomodels. The simultaneous adjustment of stereomodels can rival the simultaneous adjustment of photographs if the individual stereomodels are corrected for all systematic deformations. However, the development of analytical stereoplotters that measure precise photocoordinates warrants that the more rigorous fully analytical aerotriangulation be required for all large-scale and high-accuracy mapping.

c. Fully analytical aerotriangulation. Fully analytical aerotriangulation is a simultaneous adjustment solution of collinearity equations representing all the image rays in a strip or block of photography. The adjustment is often referred to as the "bundle" method. Although the basic unit of adjustment is actually the individual image ray, the solution determines the exterior orientation parameters of the bundle of image rays recorded by each photograph, and the adjusted ground coordinates of each ground intersection point in the ground coordinate system.

Section V
Map Substitutes — Mosaics, Photo Maps, and Orthophotographs

10-22. General

Map substitute refers to those products where the compiled planimetric line map is replaced or augmented by the aerial photographic images. Since the photographic image will have scale variation caused by the perspective view of the camera, photo tilt, and unequal flying heights, each product must be evaluated according to how the scale variation problem is treated. Scale variation may be ignored, as in an index mosaic, and an approximate map substitute is obtained; or the scale variation can be compensated, as in an orthophoto process, and a nearly true map substitute can be obtained.

10-23. Aerial Mosaics

Aerial mosaics are constructed from sets of individual adjoining aerial photographs. Typically, the outer edge of the photo coverage of each print is trimmed back to a selected match line, and the photos assembled by carefully matching ground detail along the match line. A photo index mosaic is a rough composite of a number of individual photographs of a flight line or set of flight lines overlaid one on top of the other without trimming the photo prints. This composite may itself be photographed onto a single piece of film. Mosaic and index assemblies form a continuous representation of the terrain covered by the photography. Photo maps are maps using a photograph (or mosaic) as the base to which limited cartographic detail such as names, route numbers, etc., are added. Generally, a photo map is constructed from an orthophoto, or from several orthophotos mosaicked together.

10-24. Uses of Mosaics

The increased need for presenting a pictorial view of the earth's surface has led to the aerial mosaic as a means of showing a complete view of large areas. Because a single photo is limited in area, groups of photos are combined into mosaics to provide the aerial picture. Mosaics are of principal use for presenting synoptic views of a relatively large area, and as indexes of individual photographs. The features are usually labeled or "annotated" to facilitate the recognition of critical areas, or overlays may be prepared to show planning developments or contemplated changes in an area. For example, a mosaic can show the location of a proposed highway. Using this technique, laypersons, and particularly property owners adjacent to the proposed highway, can visualize its effect on their holdings. Photo indexes are used as a visual record of the photographs of a project and as a reference of availability of photographs over a particular area of terrain. Photo maps are particularly useful for land use, land cover delineation, land planning, zoning, tax maps, and preliminary engineering design.

10-25. Methods of Mosaic Construction

There are three principal construction methods for the making of mosaics:

    a. From paper prints. This is the simplest method. The paper prints that are to be joined are laid one on top of the other so that commonly imaged terrain is matched. Then the paper prints are cut, along a feature if possible, so that the edge joins will be as inconspicuous as possible. The photographs are matched and pasted to a base. As necessary, the photographs are stretched to assure a good match of features across the join line. The completed mosaic may be photographed if a reduced scale mosaic, such as an index mosaic, is desired.

    b. From negatives or diapositives. This method is called photomechanical mosaicking. The negatives to be used for the construction are overlaid and stud registered. After the join lines are selected, a mask is made that is opaque on one side of the join line and clear on the other. A negative of the mask is made for the other photo of the pair to be joined. These masks are also stud registered. After all negatives and masks have been stud registered, a piece of unexposed film is put down (in the darkroom) over the studs and the first photo negative and its corresponding mask are registered and an exposure made. The mask permits only that portion of the unexposed film under the negative to be exposed. Successive portions of the film are exposed as this process is repeated for each negative and mask until the whole film is exposed as a single mosaic.

    c. From digital imagery. Digital (or digitized) imagery can be used to create a mosaic. This method has been used most commonly with small-scale satellite photographs. The method is very computer intensive. Either by human or automated correlation, common points on the two images to be joined are selected. The computer can then match each pixel of the one image with the corresponding pixel of the second image. A join line is decided upon and the two images digitally "sheared" along the join line. The two sheared images are then brought together into a single file having a common pixel coordinate system.

10-26. Types of Mosaics and Air Photo Plan Maps

Mosaics or air photo plans may be uncontrolled, semi-uncontrolled, or controlled. They may be constructed from unrectified, rectified, or differentially rectified photographs. A controlled mosaic or air photo plan is prepared using photographs that have been rectified to an equal scale, while an uncontrolled mosaic is prepared by a "best fit" match of a series of individual photographs.

10-27. Orthophotographs

Orthophotographs are photographs constructed from vertical or near-vertical aerial photographs, such that the effects of central perspective, relief displacement, and tilt are (practically) removed. The resulting orthophotograph is an orthographic project.

    a. Orthophotomaps. Orthophoto maps are orthophotographs with overlaid line map data. The common line data overlays include grids, property lines, political boundaries, geographic names, and other selected cultural features.

    b. Limitation of orthophotographs. The original aerial negative from which the orthophotograph is made is a central projection and, as such, displays relief displacement and obscuration of features. For example, a building will obscure the terrain that lies behind it. This obscuration results in gaps of information that can be gotten only from other sources of information, such as field survey or separate photograph. Also, optical orthorectifying devices have a finite width and length slot width that can "rectify" only to an average elevation within that slot. Thus, small objects, such as trees, buildings, etc., are not rectified at all. Normally, only a "smoothed" approximation to the actual terrain is rectified. Digital rectifiers with spot diameters as small as 5 to 25 micrometers can, to a much greater degree, overcome this latter shortcoming.

10-28. Uses of Orthophotographs

Orthophotos and orthophoto maps are widely used for general planning purposes. The complete and accurate display of all features in a project area is an ideal medium for demonstrating terrain features to laypersons. Proposed designs of engineering projects can be superimposed on the orthophoto map for a vivid understanding of work to be accomplished. Many factors must be considered before deciding on a photomap product instead of a topographical map product. The intended use of the product needs to be classified exactly, together with the accuracy required and whether height information is required or not. For many USACE engineering, operations, and maintenance activities, rectified air

photo plan sheets may be used in lieu of fully rectified orthophotographs.

10-29. Methods of Orthophotograph Preparation

Orthophotographs are prepared from pairs of overlapping aerial photographs using specially designed ortho-plotting instruments. The photographs are oriented in the instrument in the conventional manner for standard stereo photogrammetric mapping. The requirements for ground control or control to be established by aerotriangulation are the same as for photogrammetric mapping. The instrument provides the means of scanning the stereomodel to effect corrections for the varying scales caused by topographic relief. The tilt and other distortions are corrected in the orientation of the stereomodel.