LESSON 1
INTRODUCTION TO PHOTOGRAMMETRIC PRINCIPLES

What is photogrammetry?

Simply stated, photogrammetry is the art and science of making measurements from imagery. Historically, this meant using photographs, but today, digital images are becoming the medium of choice for many photogrammetric applications. In fact, the distinction between remote sensing and photogrammetry has gradually become blurred as conventional photogrammetrist employ "non-conventional" imagery for mapping purposes. One of the main advantages of photogrammetry is that the photograph/image forms a permanent record of the situation at that instant in time. This is ideal when change detection is important in a project.

Imagery is generally collected from an airplane. The advantage is that the camera can capture a very wide image from which the mapping can be performed. For example, most aerial photography uses a film size of 9" x 9" (23 cm x 23 cm). If the scale of the photograph was 1" = 500' then each photograph would image approximately 4,500' x 4,500' on the ground. Thus, with one click of the shutter, the image captures approximately 465 acres of land[1]. Another advantage of photogrammetry there is no line of sight problems that surveyors may encounter on the ground since we are looking at the land from above. There is, though, a need to have an unobstructed view from the camera.

Increasing the flying height, or distance from the camera to the object being mapped, has two effects. First, it can increase the area imaged on the photograph. In our example, if the scale was decreased to 1" = 1,000' then about 1,860 acres would be imaged on the photograph (a four times increase in coverage). This will save time in subsequent measurements on the photograph. But, the second effect of increasing the flying height results in a decrease in the resolution of the image. In other words, features that are too small may not be imaged on the photograph. Thus, the photogrammetrist is left with the task of determining the optimal flying height to match the requirements of the project.

Close-range photogrammetry (sometimes called non-topographic photogrammetry) is another area that has found widespread applications. Here, the photography is obtained from the ground, or near the ground level. It is used for a myriad of purposes such as medical photogrammetry, accident reconstruction, aircraft and ship construction, architectural studies and construction sites, just to mention a few. This form of mapping is ideal when the object to be measured is too hot, cold, unsafe, radioactive, inaccessible and delicate or when objects are moving so as to make direct measurement hazardous.

Satellite photogrammetry is a relatively new area of practice, especially among conventional photogrammetric companies. Historically, photogrammetry had been used to locate satellites in space in order to establish a more global network of control. With the advent of Global Positioning System (GPS) receivers, the use of photogrammetry with satellites has taken on a new role. Added to this is the emergence of very high-resolution imagery, on the order of one-meter or less. Thus, the future will see more utilization of this high-resolution

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[1] 1 acre = 43,560 square feet

imagery to both supplement and supplant conventional aerial imagery.

A concise history of photogrammetry can be found at the following web site, for those who are interested in the developments of this field:

http://www.ferris.edu/faculty/burtchr/sure340/notes/History.pdf

Metric and non-metric photography

Photogrammetry is a universal data collection tool since almost any kind of imagery can be now used for measurements and mapping. Cameras can be described as either metric or non-metric. A non-metric camera is characterized by the off-the-shelf cameras that are often used for conventional amateur photography. With these types of cameras, the elements of interior orientation are unknown, partially known or unstable. The elements of interior orientation include: the focal length, lens distortion and location of the center of the photograph. In a metric camera, these elements are known and routinely determined by calibration of the camera. These items are important in helping to understand the accuracy potential of photogrammetry. This is an important issue when one considers that the photograph is just a small-scaled rendition of the earth. The scale, as we will see soon, is a function of the focal length of the camera. Any small error in knowing the focal length will result in significantly larger errors on the earth.

The distinction between metric and non-metric cameras is not a statement on the quality of the camera. It just means that the elements of interior orientation are known and can be accurately applied to the mapping project when needed.

With the use of computer-aided lens manufacture, modern aerial cameras are sometimes called distortion-free. While this is not completely true, the amount of lens distortion at any point on the lens is often less than the uncertainty in the determination of the lens distortion values. For example, a camera calibration may find that the greatest lens distortion anywhere on the lens is 4-micrometers (1 micrometer = 0.001 millimeter). Yet, the uncertainty of the distortion value may be plus/minus 5 micrometers.

Since measurements made on the photographs are being used to determine comparable values on the ground, the relationship between the camera and the ground needs to be accurately determined. Therefore, most requests for proposals (RFPs) require that the aerial camera be calibrated within 2 years of undertaking a new project. The purpose of camera calibration is to accurately define in mathematical terms the camera. Therefore, the typical calibration report form will show the calibrated focal length, lens distortion characteristics, camera shutter efficiency, image resolution at various locations in the image plane, and the distances between and coordinates of the fiducial marks (index marks imaged on the photograph). To view the U.S. Geological Survey's (USGS) Arial Camera Specifications, see:

http://edclxs22.cr.usgs.gov/osl/acspecs.html

An example camera calibration report can be viewed at:

http://www.ferris.edu/faculty/burtchr/sure382/other_material/wyoming_DOT_camera_cal_rpt.pdf

One of the issues facing the industry today with the increased utilization of digital aerial cameras is how to perform the camera calibration. Camera calibration facilities used for analog or conventional aerial cameras cannot be used with the newer digital cameras. The industry is developing, testing and evaluating calibration techniques for this new breed of cameras.

Aerial camera

The aerial camera is a very specialized piece of equipment. Unlike conventional amateur cameras, photogrammetric cameras need to maintain a rigid distance between the focal plane (where the film lies during exposure) and the lens. This distance is called the focal length of the camera. In addition, the focal plane needs to be flat. If the film is not flat then parts of the resulting image can become displaced on the photograph. It will also lead to image blur at that location on the photograph making the interpretation of any images in that area difficult.

In an ideal world, the airplane would travel in a level straight line with its heading direction and actual direction of travel the same. Unfortunately, the aircraft is susceptible to variations within the flight line. Pitch and yaw of the aircraft introduce tilt into the photography. If there is a side wind, the aircraft must head into the wind in order to maintain the proper flight direction. The angle between the heading direction and the actual direction of the aircraft is called the crab angle. Crab is caused by drift of the aircraft. The effect of crab is a rotation of the aerial photo with respect to the flight direction thereby decreasing the amount of overlap within the photography (see figure 1). If left uncorrected, this would require acquisition of additional photography and additional processing.

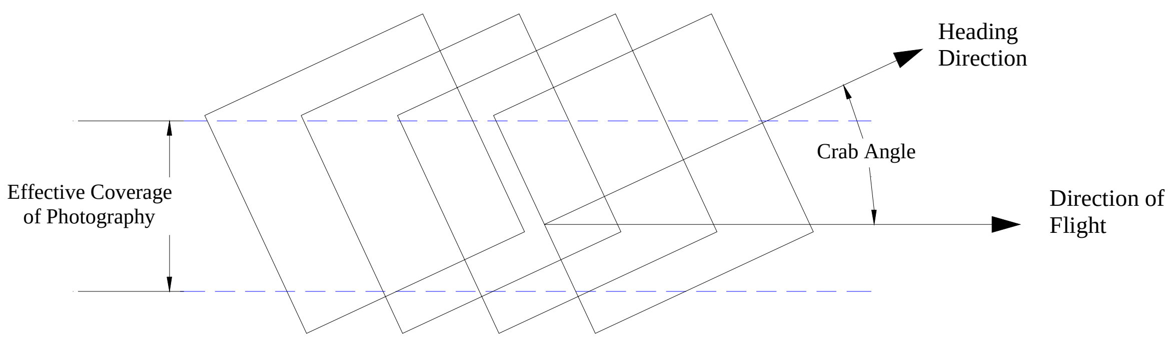

Figure 1. Effects of drift on aerial photography.

To correct for these natural effects, aerial cameras are usually fixed to the aircraft with a stabilized camera mount. The mount will allow for the correction of crab along with the neutralization of the pitch and yaw of the aircraft. This is done by rotating the camera about the vertical axis so that it follows the direction of flight. Additionally, the camera is leveled just before the exposure is made thus fixing it in the desired vertical direction. It should be emphasized that residual crab and tilt will still exist, but the amount is small and within the specifications for the aerial photography. Newer stabilizing platforms use advanced sensors to determine the amount of tilt and these values are recorded for subsequent processing of the photography. Camera mounts are also equipped with vibration isolators. The airframe of a plane experiences a lot of vibration. If this were not dampened then this vibration would be transferred to the camera thereby creating a blurred image.

Modern aerial cameras are also equipped with very special peripheral instrumentation. For example, almost all use a technique called forward motion compensation (FMC). In fact, most project specifications require photography acquired with FMC. Remember that the aerial camera is moving during the exposure. As we all know from experience with our hand-held cameras, when the camera moves during the exposure the image becomes blurred. Since the distance between the aircraft and the ground is relatively large, the amount of blur is pretty small. But, flying closer to the ground increases this blur. As an example, when we drive on a freeway we see that the features close to the road go by very fast, like a blur, while features in the background almost appear to stand still. This same phenomenon works with aerial photography. To eliminate this blur, FMC is used to advance the film a slight amount during the exposure. This will reduce the amount of blur in the image. Blur is not completely compensated for because the camera may be tilted slightly or the ground is uneven. Therefore, some minor blurriness may still be present in the image but its effects are generally negligible.

How much does the film have to advance during the exposure? The amount depends on the air speed, exposure time, focal length of the camera and flying height above the terrain. As an example, assume that an aircraft is traveling at 250 mph at a flying height above the ground of 5,000’. The focal length of the camera is 152.00 mm and the length of the exposure was 1/100 second. How much does the film need to be advanced during the exposure?

The air speed is first converted into other units, such as feet per second

$$\left(250\,{}^{\text{mi}}\!/\!{}_{\text{hr}}\right)\left({}^{1\text{ hr}}\!/\!{}_{3600\text{ sec}}\right)\left({}^{5280\,\text{ft}}\!/\!{}_{\text{mi}}\right) = 366.7\,{}^{\text{ft}}\!/\!{}_{\text{sec}}$$

Then, during the exposure, the plane has traveled

$$\left(366.7\frac{\text{ft}}{\text{sec}}\right)\left({}^{1}\!/\!{}_{100\,\text{sec}}\right) = 3.7\text{ ft}$$

As we will see later, the amount of movement in the plane of the photograph is a function of the photo scale. Rearranging that relationship, we can see that the amount of distance on the photograph is

$$\left(\frac{152\text{ mm}}{5{,}000\text{ ft}}\right)(3.7\text{ ft}) = 0.122\text{ mm}$$

Thus, the film needs to advance 0.112 mm, or 112 μm, during the exposure to negate the effects of image blur.

A second item that more photogrammetrists are employing is GPS (global positioning system). In the early days, GPS was used to provide the ground control necessary to perform the mapping. Today, it is being used in conjunction with the aerial camera to record the location of the exposure station at the instant the photograph was taken. The advantage in using airborne-GPS is that the ground control can be significantly reduced and, theoretically, totally eliminated, although this is not a good practice since there is no quality control on the photogrammetric solution. Again, more project specifications are beginning to require the use of airborne GPS. For a more thorough discussion of airborne GPS see the following web site:

http://www.ferris.edu/faculty/burtchr/sure440/pdf/Air_gps.pdf

One of the newer developments involving photogrammetry and auxiliary equipment is the integration of different tools into a measurement system. Photography is being integrated with GPS and inertial measurement unit (IMU) to create a system that provides for direct orientation of the photography – a process referred to as direct sensor orientation. Moreover, GPS and IMU are being used with other sensors, such as laser scanners and radar, to provide timely and accurate digital data on the terrain. These tools are being integrated into a new development in geographic information systems (GIS) called telegeoinformatics.

The camera takes a picture and the features are imaged on a negative. Then diapositives and prints are made from the negative. The diapositive is like a slide in that it consists of a translucent material upon which the images are fixed. It then forms a positive image from the negative. Diapositives are used because light is generally projected from the back of the film to the optics where the operator views the images. Paper prints, being opaque, do not allow light to pass through them.

Difference between maps and photographs

The main difference between maps and photographs lies in the method of projection (refer to figure 2). A map is called an orthographic projection where each point on the earth's surface is projected onto the map surface in a manner that is perpendicular to the map surface. Thus, the mapped position represents the true horizontal position of the point in question, just as if the observed was viewing the scene directly above the point/feature. This allows the user to accurately scale between points to obtain distance, as an example.

The photograph uses a central perspective projection. Here, all of the light rays are brought to a bundle at the camera lens and are then projected onto the photograph. As one can see from figure 2, the datum position of a point is not represented accurately on the photograph. This will be discussed shortly. The effect of this type of projection is that the distances on the photograph do not represent the true horizontal positions on the ground, but instead represent the projected position.

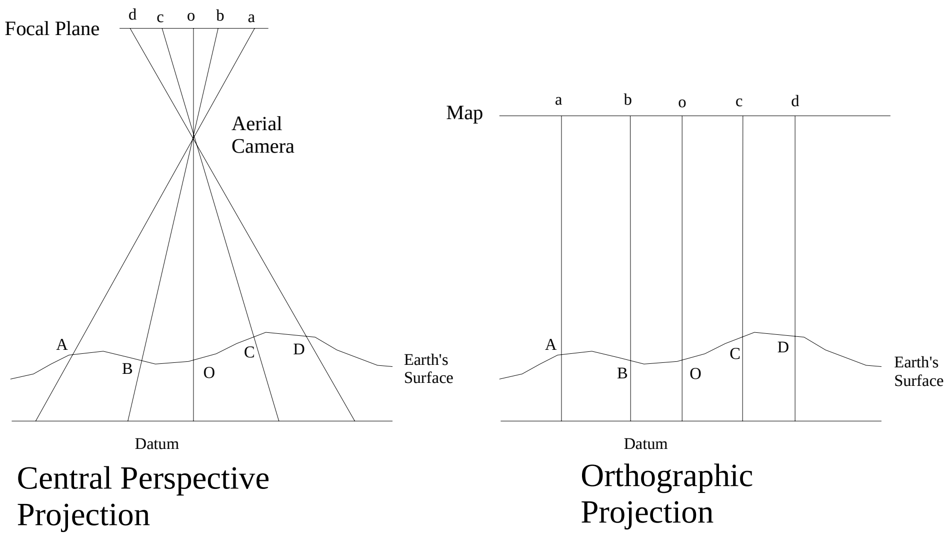

Figure 2. Difference between a central and orthographic projection.

As we will see later on, photogrammetrists do have the ability to orthographically project an image onto a map plane. This is called orthophotography. It requires additional processing of the image, either in an analog (map) form or digitally. This latter approach is the most common method used today.

Flying height and scale

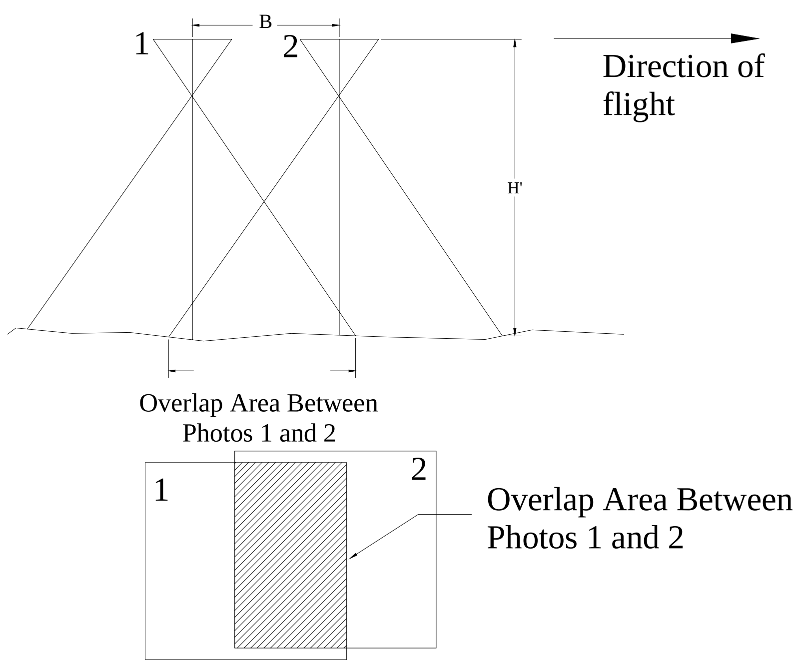

Figure 3. Geometry of aerial photography.

A fundamental operation of photogrammetry is the determination of scale. The scale relationship can be shown using figure 3. Scale can be simply stated as the ratio between a distance on the photograph to a corresponding distance on the ground. Using simple geometry and the fact that we have similar triangles, the scale can also be expressed in terms of the flying height. These relationships are shown by the following equation:

$$S = \frac{ab}{AB} = \frac{f}{H'}$$

where: H' is the flying height above the ground
f is the focal length of the camera
ab is the distance between two points on the photograph
AB is the corresponding ground distance between the two points, and
S is the scale of the photograph

Example: If the distance between two targets on the ground was surveyed and found to be 4,350 feet and the corresponding points imaged on the photo were measured as 2.34 inches, what is the scale of the photograph?

Solution: The scale of the photograph is found to be:

$$S = \frac{ab}{AB} = \frac{2.34''}{4{,}350'} = \frac{1''}{1{,}859'}$$

This would probably be rounded off to be 1" = 1,860'. Note that scale is always shown as a unit fraction, where 1 is the value in the numerator. As this example shows, the scale can be shown in fraction form or ratio form. It can also be depicted verbally such as 1 inch represents 1,860 feet. To change our scale into a representative fraction, simply multiply by 1'/12" (note that since 1' = 12", this ratio is equivalent to the number 1. The result is a unitless number. Any number can be multiplied by one without changing the value). In the example, the representative fraction is

$$S = \left(\frac{1''}{1{,}860'}\right)\left(\frac{1'}{12''}\right) = \frac{1}{22{,}320}$$

Example: If the scale of a photograph was found to be 1:20,500 and the focal length of the camera was 6.000", what is the flying height of the aircraft above the ground?

Solution: Rearranging the relationship for computing scale, we have

$$H = \frac{f}{S} = \frac{6.000''}{\left(1/20{,}500\right)} = 123{,}000'' = 10{,}250'$$

Unfortunately, the geometry depicted in figure 3 is not generally realistic since the ground is shown as being relatively flat. The normal depiction of scale is shown in figure 4 where the different points on the photo are at different elevations. This diagram introduces a new concept called the datum. Simply stated, a datum is a reference surface. Example datums include sea level, North American Datum of 1983 (NAD 83), and North American Vertical Datum of 1988 (NAVD 88). But, anything can be a datum. For example, a floor can be a datum for a window that has to be hung a certain distance above the floor. Datums that are not related to global systems, like NAD 83 and NAVD 88, are referred to as local datums.

The line LO in figure 4 represents the vertical line or sometimes called the plumb line. Then, using the similar triangles L-B-O_B and L-b-o, the equation for the scale of point B is

$$S_B = \frac{ob}{O_B B} = \frac{f}{H - h_B}$$

In a similar fashion, the scale for point A can be written as

$$S_A = \frac{f}{H - h_A}$$

As one can see, scale is only valid for a point. This means that the scale changes through the photograph. This can be shown with the next example.

Example: A photograph was taken with a 6.000" focal length camera at a flying height of 8,000' above the datum. Point A has an elevation of 150' and B has a corresponding elevation of 625'. What is the scale of these two points?

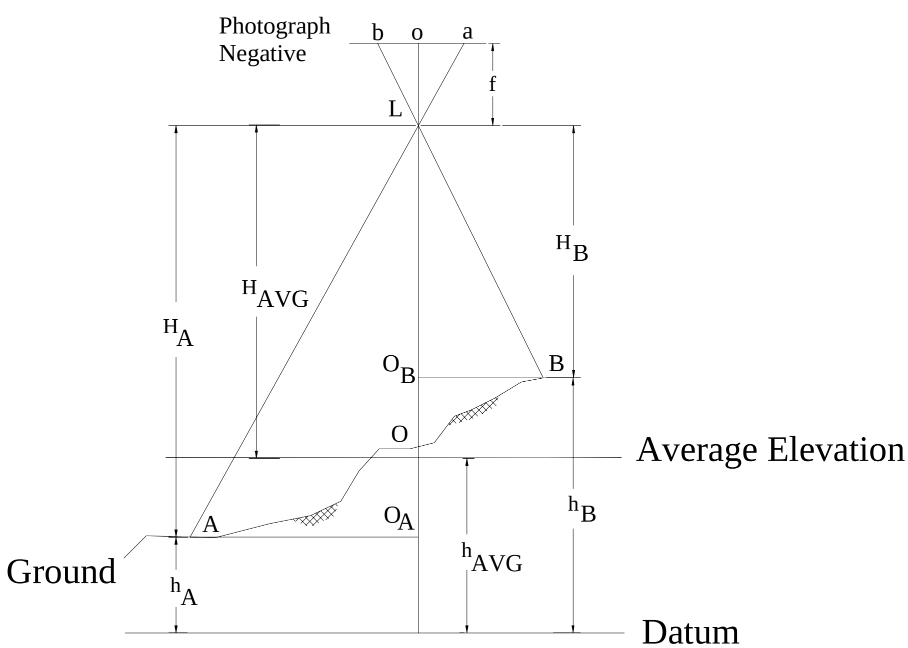

Figure 4. Geometry of aerial photography over variable terrain.

Solution: Using the formula presented above,

$$S_A = \frac{f}{H - h_A} = \frac{6.000''}{8{,}000' - 150'} = \frac{1''}{1{,}308'} \qquad \text{or} \qquad 1:15{,}700$$

For point B

$$S_B = \frac{f}{H - h_B} = \frac{6.000''}{8{,}000' - 625'} = \frac{1''}{1{,}229'} \qquad \text{or} \quad 1:14{,}750$$

We can see that the scale differs between the two points by a significant amount. Then, what is the scale of the photography? The photo scale can be represented as the average scale over the photo. It can be found by averaging the elevations (in this example, the average elevation is 387.5'). Then use the scale formula as follows:

$$S_{Avg} = \frac{f}{H - h_{Avg}} = \frac{6.000''}{8{,}000' - 387.5'} = \frac{1''}{1{,}269'} \qquad \text{or} \quad 1:15{,}225$$

So, what's the big deal? It depends on the level of accuracy you are trying to achieve. Lets assume that we measure a line that is 2'' on the photograph (ab). Then, the corresponding ground distance (AB) can be computed by simply rearranging our scale relationships. Thus,

$$AB_1 = \frac{ab}{S_A} = \frac{2''}{\left(1''/1{,}308'\right)} = 2{,}616'$$

$$AB_2 = \frac{ab}{S_B} = \frac{2''}{\left(1''/1{,}229'\right)} = 2{,}458'$$

$$AB_3 = \frac{ab}{S_{Avg}} = \frac{2''}{\left(1''/1{,}269'\right)} = 2{,}538'$$

The distance is about ½ mile. We can see that we have a variation of approximately 150' in the different values. The question to be answered is whether this level of uncertainty is acceptable. This will, understandably, be a function of the purpose of the photography.

One can see from this discussion that the scale becomes smaller[1] as the elevation decreases. On the other hand, scale will increase with increasing elevation or when using longer focal length cameras (assuming all other factors are the same).

Distortion in photography

There are a number of distortions associated with photography that need to be accounted for by the photogrammetrist. A large error is associated with the atmosphere. When light travels from one medium of refractive index to another it gets bent[2]. A good illustration is putting your arm in the water the next time you go to the beach. If the arm goes in at an angle, it will appear to change directions. This is due to the fact that water is denser than air and the light rays slow down and get bent. The same thing happens when light passes through glass. The atmosphere is made up of different layers with varying densities. Thus, light bends as it passes through these different layers. The result is that the image is displaced on the photograph. This distortion is impossible to remove completely but it can be reduced significantly by using an appropriate atmospheric model.

Lens distortion also changes the position of an image point. This distortion is caused by manufacturing problems. There may be small imperfections in the grinding of the lens' surfaces. An aerial camera is comprised of a number of individual lens elements. Each has to be properly manufactured and then aligned perfectly within the lens cone. Lens distortion is found from a camera calibration report and the results are used in mapping to correct for these values. When the lens distortion is due to faulty grinding of the lens, this is called radial lens distortion[3]. The distortion will occur on a radial line from the center of the photograph. Decentering lens distortion is caused from improper alignment of the individual lens elements. The effect of decentering distortion is the displacement of an object on a line perpendicular to the radial line from the center of the photograph.

Relief displacement also creates problems on the photograph. This is a displacement of an image due to the fact that it lies at an elevation above (or sometimes below) the datum surface. If you look at an aerial photography you will notice that structures with height are displaced outward from the center of the photo. For example, a smokestack will be shown with the base closer to the center of the photo than the top of the stack (figure 5). This effect is due to relief displacement. This displacement is always outward (for points above the datum). Increasing the flying height decreases the effects of relief displacement whereas the effects get larger for points farther away form the center of the photo. The photogrammetrist accounts for this distortion by placing the photography on a stereoplotter, which handles these changes in relief excellently. Thus, in stereophotogrammetry, this problem is alleviated.

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[1] A smaller scale is one whose denominator is larger than another scale value. For example, the scale 1:15,700 is smaller than the scale 1:14,750.

[2] This concept of refraction is related to what is called Snell's Law that mathematically describes the geometry of the light ray path as is gets bent.

[3] Faulty grinding of the lens elements results in both distortion and aberrations. Distortions affects the geometric relationship of the light rays – they do not intersect the film where they are supposed to intersect. Aberrations do not affect the geometry but do degrade the quality of the image making the feature appearance blurry or fuzzy. Again, with modern lenses, aberrations are also becoming smaller and smaller.

Figure 5. Aerial photograph showing the effects of relief displacement.

The principles that have been discussed up to this point have assumed that the photographs were perfectly vertical, a situation that is almost impossible to occur. When the optical axis of the camera is unintentionally tilted from the vertical by some small amount, usually less than 2°-3°, the photography is nearly vertical and is generally referred to as a vertical photograph[4]. When the photograph is intentionally tilted, it is referred to as an oblique photograph. There are two different types of oblique photos. If the photograph contains the horizon then it is referred to as a high oblique while a low oblique does not show the horizon.

Stereoscopic viewing

The power of photogrammetry lies in the fact that stereo photographs are taken of the

[4] For more information on the geometry of an aerial photograph, refer to one of the many textbooks on the subject.

same scene from two different locations, see figure 6. The distance between the two exposure stations is called the air base (B). H’ is the flying height above the ground. Then, when viewing each photo individually, with the left eye viewing the left photo and the right eye the right photo, the photogrammetrist can see the image in three dimensions. This is a requirement for measuring height of the desired point. The two photographs are referred to as a model or stereoscopic model.

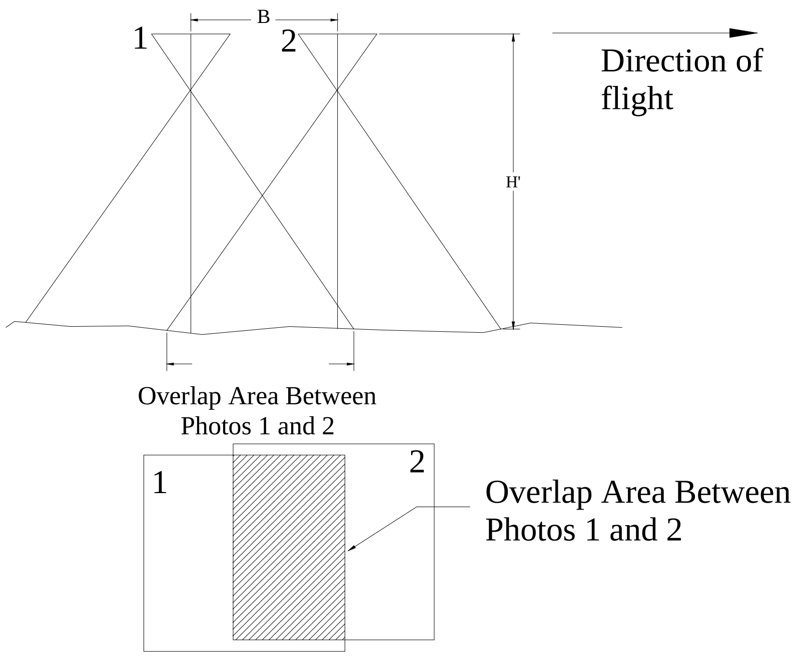


Figure 6. Overlapping aerial photography.

How far should the air base be? To be able to see stereo, all of the terrain needs to be viewed stereoscopically. Therefore, at least 50% of each photo needs to image the same terrain features. But 50% would mean that there is no room for error when flying. Thus, 60% overlap is usually the minimum requirement, but this amount of overlap may need to be modified. In figure 7, the effects of sloping terrain on stereoscopic imagery are shown assuming that the pilot it maintaining a constant flying height above the datum. Eventually stereoscopic viewing is lost. Moreover, the amount of detail imaged on the photo also decreases thereby requiring more flight lines closer together. While this situation is kind of unique and easily solved for by proper planning, it does show that variations in the terrain, along with fluctuations in the aircraft altitude, can affect stereoscopic coverage. Other situations may also result in a loss of stereoscopic coverage and they include excessive tilt of the camera axis at the instant of exposure and failure to maintain a constant flying height.

One of the unique and advantageous outcomes of stereophotogrammetry is that the vertical scale is exaggerated when viewed by the observer. This allows for accurate determination of height by the photogrammetrist. While increasing the flying height is advantageous for economical mapping, it will decrease the amount of vertical exaggeration. Again, if we look at our snapshots taken during our last vacation, far away objects appear flat on the image. By increasing the air base, vertical exaggeration is increased. But, there is a physical limitation here in that if the base increases too much, stereoscopic coverage is lost.

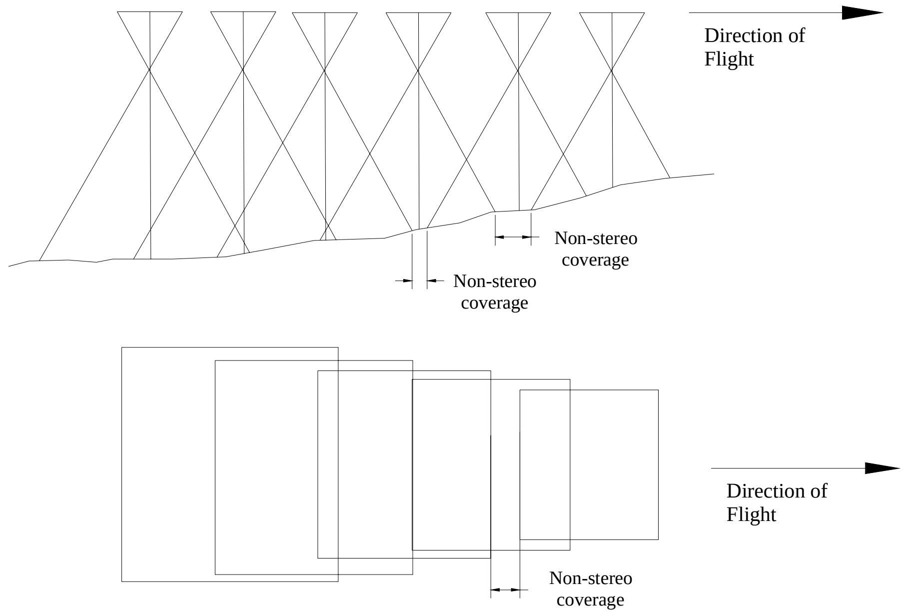


Figure 7. Effect of sloping terrain on aerial photography taken at a constant height above the datum.

Parallax is the phenomenon required for stereoscopic viewing. Parallax is basically the difference in the location of a point on two subsequent photographs. In other words, the object will not appear in the exact location on two photos. This makes a lot of sense when we consider that the aircraft has moved during the two exposures. There are two components. x-parallax is the difference in the position in the x-direction or direction of flight. This component is critical in the determination of height. In fact, there is a direct correlation between the amount of x-parallax in two images and the elevation of a point. The second component is y-parallax and this is in a direction perpendicular to the flight direction. If y-parallax exists, stereoscopic viewing is not possible. Tilt in the photography is the biggest culprit in introducing y-parallax. Therefore, a critical function of the photogrammetrist is to eliminate the y-parallax within the model.

The advantages of stereoscopy, or stereoscopic vision, include the obvious – the ability to view a scene in three dimensions. It also helps in the identification of features that may exist in the scene. A feature may appear flat when viewed monoscopically but when depth is added, features can stand out from their surroundings making them easier to identify. Stereoscopy is also critical when an individual desires to extract height or contours from imagery when creating a topographic map.

Stereoscopes

The simplest approach to viewing stereo is with a stereoscope (see figure 8). There are two common types of stereoscopes: mirror stereoscope and pocket stereoscope. The purpose of the stereoscope is to force the left eye to view the left image and the right eye to view the right image. The advantage of the mirror stereoscope is that the two photos can be laid out side by side for viewing. With the pocket stereoscope, the photographs have to be overlaid onto one another by a small amount for stereo viewing. This requires the user to flip the photographs to see the area that is hidden from view. The stereoscope is aligned such that the axis between the two eyes is parallel to the direction of flight.

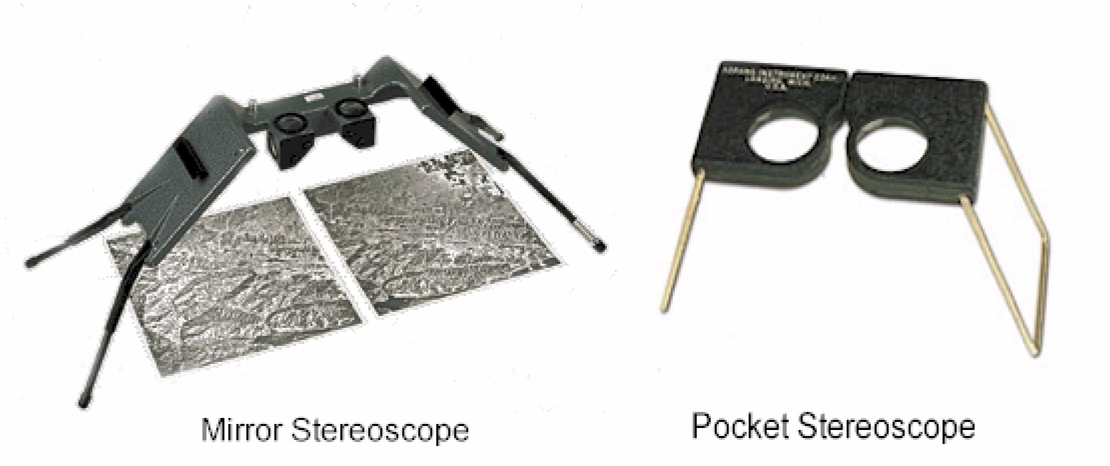


Figure 8. Example stereoscopes.

To illustrate this, let's look at a photograph taken from a metric camera. Located on the edges of the photography are a series of index marks, called fiducial marks (see figure 9). These fiducial marks can be located midway along each side (called midside fiducials), in the corners (called corner fiducials), or in both locations. Let's assume we have midside fiducials. Now, draw lines from opposite fiducials (figure 9). The point of intersection of these two lines is called the principal point.[5]

Each photograph has its own principal point. Since we have 60% overlap between successive photographs (as a minimum), this means that the principal point on the left photograph is imaged on the right photograph and the principal point on the right photograph is imaged on the left. These are commonly referred to as conjugate principal points. The photographs are properly aligned when the line through both principal points and both conjugate principal points is a straight line (figure 10). This is the line of flight. The axis of the stereoscope, which can be defined as the line between the centers of the two eyepieces, is parallel to the line of flight. If the two photographs are properly oriented then the line between all conjugate image points will be parallel to the line of flight.

Unfortunately, there is seldom a well-defined ground point located under the principal point. Therefore, the person using the stereoscope must continually move the photographs about until stereo is created. This is achieved once the y-parallax has been completely eliminated. Once the two photos are properly oriented, the principal points can then be transferred onto the respective conjugate imagery while viewing the two photos in stereo. The causes of y-parallax

[5] In photogrammetry there are a number of different principal points. The principal point found by the intersection of lines from opposite fiducials is called the indicated principal point. Other principal points include the principal point of photogrammetry, the principal point of autocollimation, and the calibrated principal point.

include tilt in the photography[6], residual effects of crab, and the photographs taken at different flying heights above the ground.

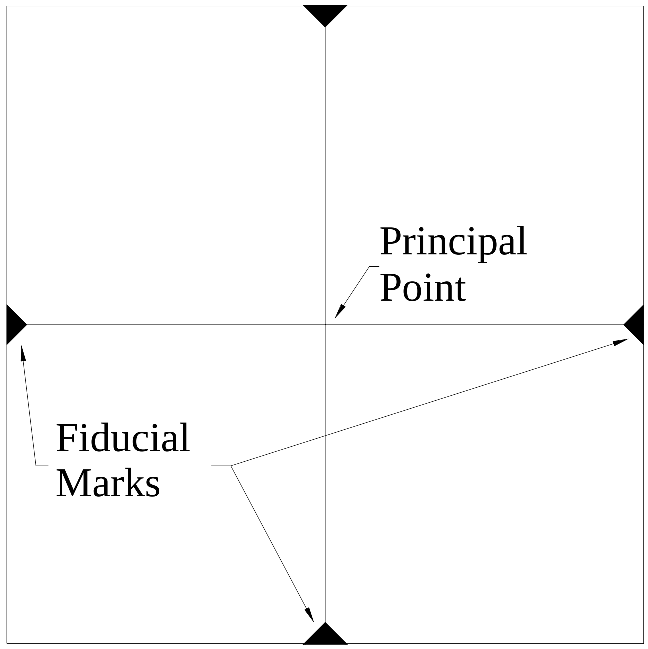


Figure 9. Aerial photograph with fiducial axes and principal point location.

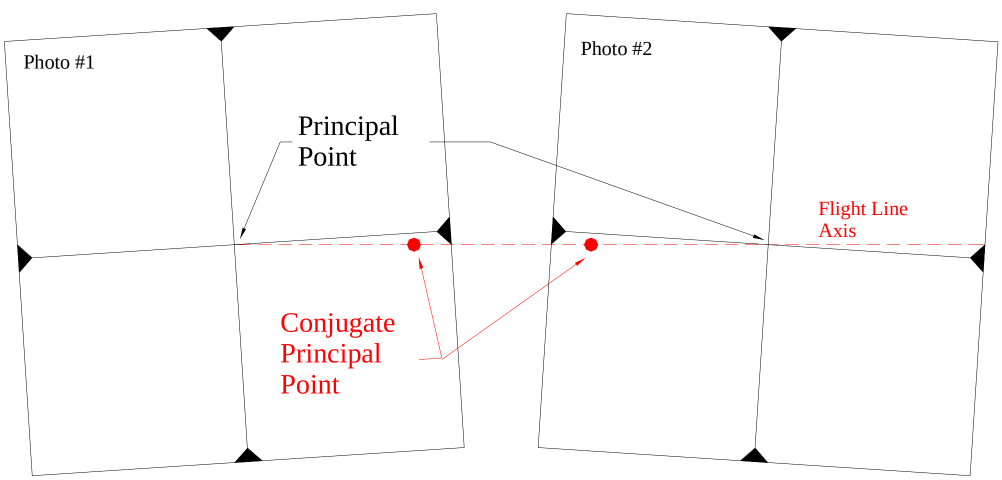


Figure 10. Flight line axis system.

Hence, when we talk about parallax we almost always refer to x-parallax. The power of parallax is the ability to derive height information from the stereo image. The parallax equation

[6] Tilt is caused by the pitch and yaw in the aircraft. Ideally, the optical axis of the camera should be in a truly vertical direction. In reality, it is close but not truly vertical. For most applications, the amount of tilt in the photograph does not affect the use of stereoscopes for stereoscopic viewing.

for determining height is generally given as

$$h = H - \frac{B\,f}{p}$$

where: h is the ground elevation,
H is the flying height above the datum (such as sea level)
B is the air base or ground distance measured between the two exposures
f is the focal length of the camera, and
p is the parallax.

Example: A pair of photographs were taken with a camera having a focal length of 152.3 mm at a height of 4,050' above sea level. The air base was found to be 1,280'. If the parallax at a point was measured as 3.61", what is the elevation of the point?

Solution: First, convert the focal length from millimeters to inches

$$153.3\,\text{mm}\left(\frac{1''}{25.4\,\text{mm}}\right) = 6.035''$$

Next, use the parallax equation to find the elevation of the point.

$$h = H - \frac{B\,f}{p} = 4{,}050' - \frac{1{,}280'\,(6.035'')}{3.61''}$$
$$= 1{,}910'$$

If a second point on the photograph was found to have a parallax measurement of 3.78", its elevation becomes

$$h = 4{,}050' - \frac{1{,}280'\,(6.035'')}{3.78''} = 2{,}006'$$

Thus we see that as the parallax increases, so does the elevation of the point on the ground.

There are other approaches to computing elevation.[7] For example, one can use the differences in parallax to determine the height of a point, provided that the elevation of one point is known. This equation is given as:

$$h_A = h_B + \frac{\Delta p\,(H - h_B)}{p_a}$$

where the subscript A indicates point A on the ground and subscript B is point B on the ground.

[7] For a more thorough discussion on parallax see, as an example, "Elements of Photogrammetry with Applications in GIS", 3rd edition, by P. Wolf and B. Dewitt, McGraw Hill, 2000.

The difference in parallax is designated as $\Delta p = p_a - p_b$. From the previous example, assume we know the elevation of the first point (h_B = 1,910'). Then, the elevation of the second point can be found as

$$\Delta p = 3.78'' - 3.61'' = 0.17''$$
$$h_A = 1{,}910' + \frac{0.17''\left(4{,}050' - 1{,}910'\right)}{3.78''} = 2{,}006'$$

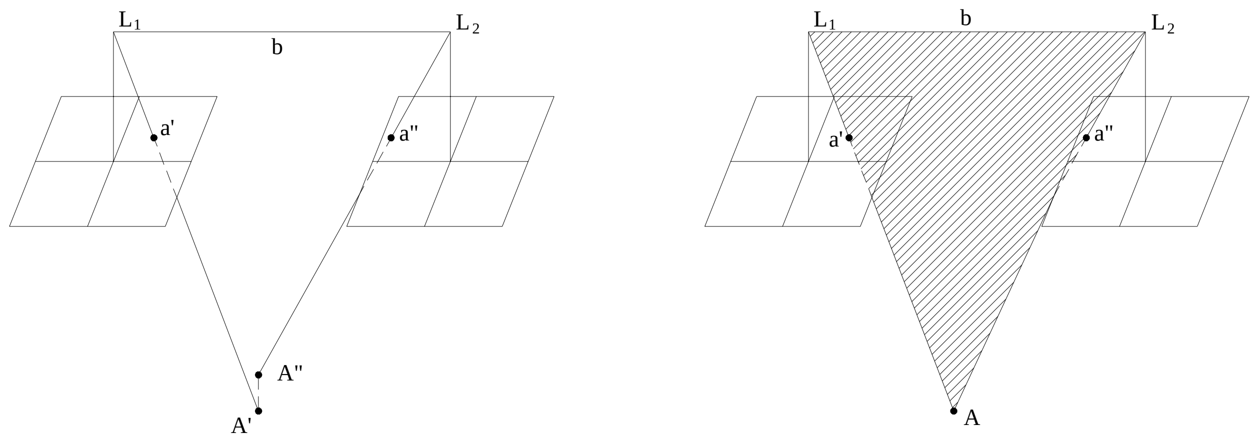
Stereoscopic plotters

The creation of a line map requires sophisticated, specialized instruments called stereo plotters. It is within these plotters that three-dimensional models are formed and then measurements made in that model. Throughout history, many different approaches have been used to accomplish this task, from optical projection of the film diapositives to mechanical reconstruction of the model to the numeric solution of the orientation task. This latter approach is the predominant form used today.

The process of setting up a stereoplotter for mapping requires three stages. The first is called interior (or inner) orientation. The purpose of interior orientation is to recreate the geometry of the taking camera. Think of the process this way. Take two cameras out in the field and take a picture of the same area with both separated by a defined distance (air base). The axes of both cameras are parallel to one another. Lets further assume that a slide is taken much like a Polaroid picture (in other words, the film does not have to be removed for processing). Then, take the two cameras and mount them onto a stereoscopic viewing device. When the light hits the film and is projected through the lens, it would negate the distortion of the image that comes when the light travels from the terrain through the lens and onto the film. But it is impractical to have a bunch of cameras like this. Therefore, the projectors where we will place our film from the camera need to be adjusted so that they mimic the distortion of the taking camera. Interior orientation involves preparing the diapositives, accommodating for the lens distortion, centering the diapositives, and setting out the proper principal distance (focal length).

Once the interior orientation is performed, the stereoplotter operator needs to complete relative orientation. Here, the same relative angular relationship that existed between the two successive exposures are recreated within the stereoplotter. This is done by methodically eliminating the y-parallax that is present within the stereomodel. This can also be described as determining the differences in the pitch, yaw and crab between successive exposures and putting these differences in the stereoplotter. Once the relative orientation is completed, the operator is able to view the model in stereo. Recall that earlier it was pointed out that to view images stereoscopically that the y-parallax must be eliminated.

Relative orientation is best describes using the coplanarity concept as shown in figure 11. Points L_1 and L_2 represent the light sources for the left and right stereoplotter projector respectively. When the two photos are improperly oriented, the two vectors (lines) defined as L_1a'A' and L_2a"A" do not intersects, as depicted in figure 11(a). Once the model is relatively oriented then these two vectors will intersect as shown in figure 11(b). In fact, points L_1, L_2 and A will form a plane, a situation that can only occur when y-parallax is removed from the stereomodel.



(a) (b)

Figure 11. Coplanarity concept.

The stereoscopic model created after relative orientation is not referenced to any survey system. In other words, the model is created in space. Our map, on the other hand, requires fitting the orientation to the ground. In photogrammetry, this process is called absolute orientation because it brings the model datum parallel to the ground datum. This is also the place where scale is applied to the mapping process by assigning the proper coordinates to the control for the photogrammetric process. Figure 12 shows the model that needs to be fitted to the datum defined by the table surface of the stereoplotter. The table is where the map is made. Thus, absolute orientation involved rotating the model so that the model datum coincides with the map datum defined by the table surface.

There is a wide array of stereoplotters available to the photogrammetrist. A simple approach is by optical projection (this is shown in figure 12). This is similar to the situation when viewing a slide show. The diapositives are illuminated and the latent images are directed to a surface for viewing. The only difference, though, is that two images are projected instead of one in a slide show. To separate the images such that only one eye sees the appropriate image, some sort of viewer is required. A simple method is anaglyphic viewing that operates like some of the older 3-D movies where red and blue lenses are used in a pair of glasses. What happens is that one picture is passed through a red filter and the second passes through the blue filter. The operator wears glasses with the same colors. Since these colors are complementary, they block out the projection of the other image. This means that the left eye will be forced to view only the left image while the right eye will only see the right photo. An example of the anaglyphic display is shown in figure 13. As you can see, the image appears blurry since it represents two projected images. If you have anaglyphic glasses, you should be able to see the scene in 3-D.

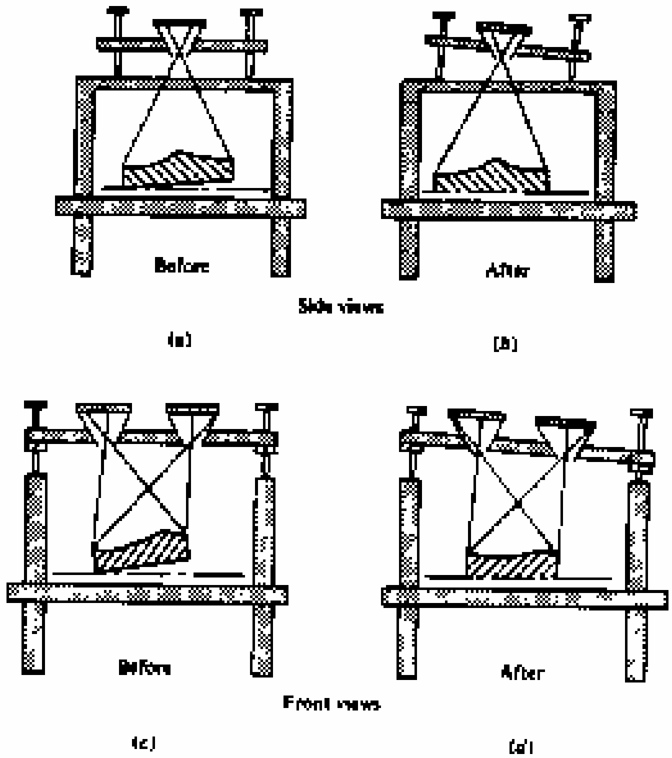


Figure 12. Schematic diagram showing the concept of leveling a model.

Other systems use Polaroid filters to achieve the same result. Here the filters are oriented out of phase therefore blocking the opposite image from passing to the eye. Again, the image is passed through the Polaroid filters and the operator wears like-oriented Polaroid glasses. A third approach is to use shutters that alternate the picture display. Like the anaglyphic and Polaroid filters, the operator must wear glasses with shutters to force the right eye to see only the right image and left eye the left image[8].

With mechanical stereoplotters the model is constructed using mechanical linkages on the instrument instead of projection of the image onto a surface. Here the viewing system is performed through an optical train. Both mechanical and optical projection plotters are referred to as analog plotters. These instruments require the operator to introduce angular changes to the projectors for the relative and absolute orientation. Analog plotters are still occasionally used but are now interfaced with computers to help expedite the orientation process. The orientation, though, are still done manually.

[8] In older optical projection plotters, the operator did not wear glasses. Instead, they viewed the projected images through a shutter system that was placed between the operator and the viewing surface. The critical element was the synchronization of the shutters.

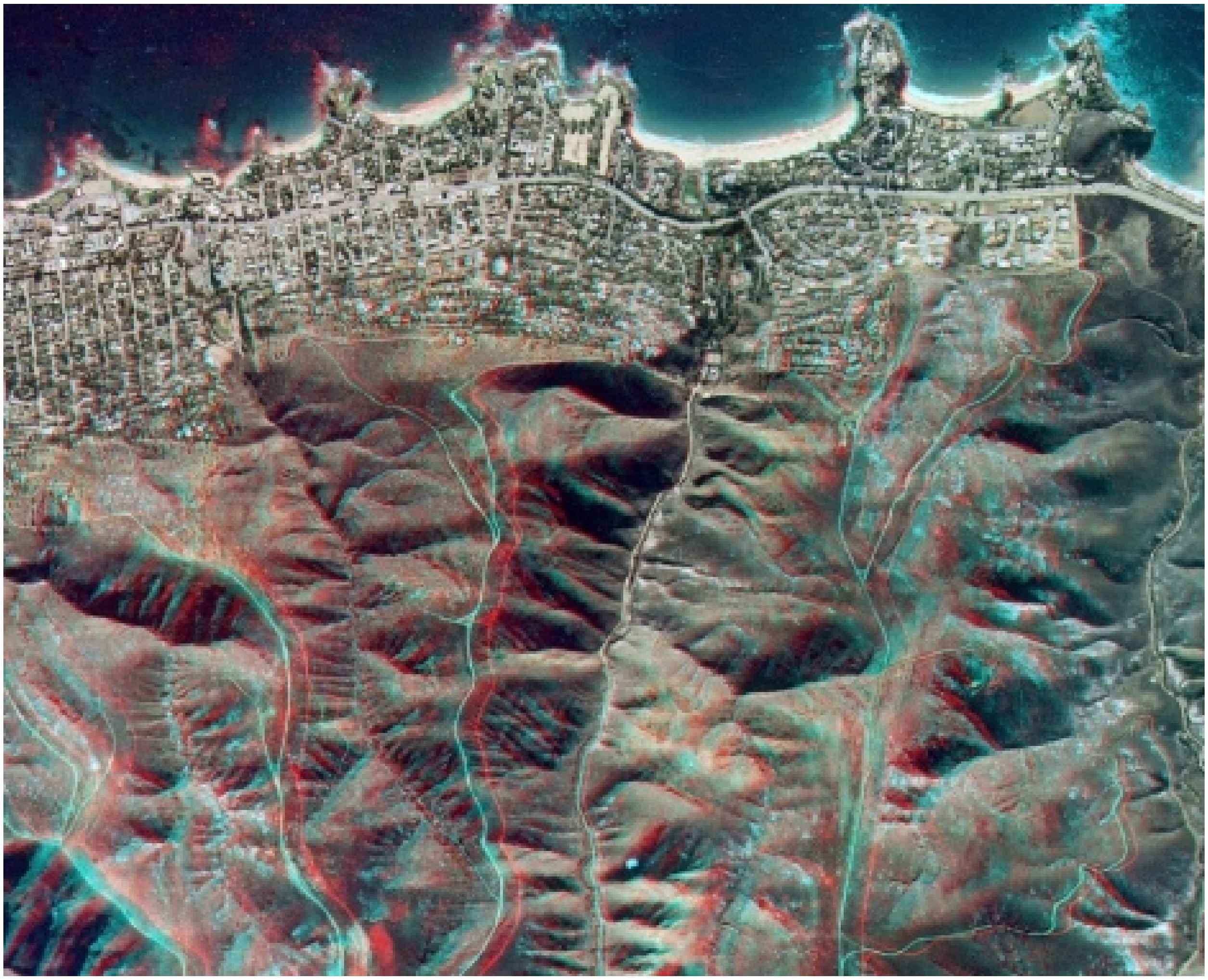


Figure 13. Example anaglyphic display of two images.

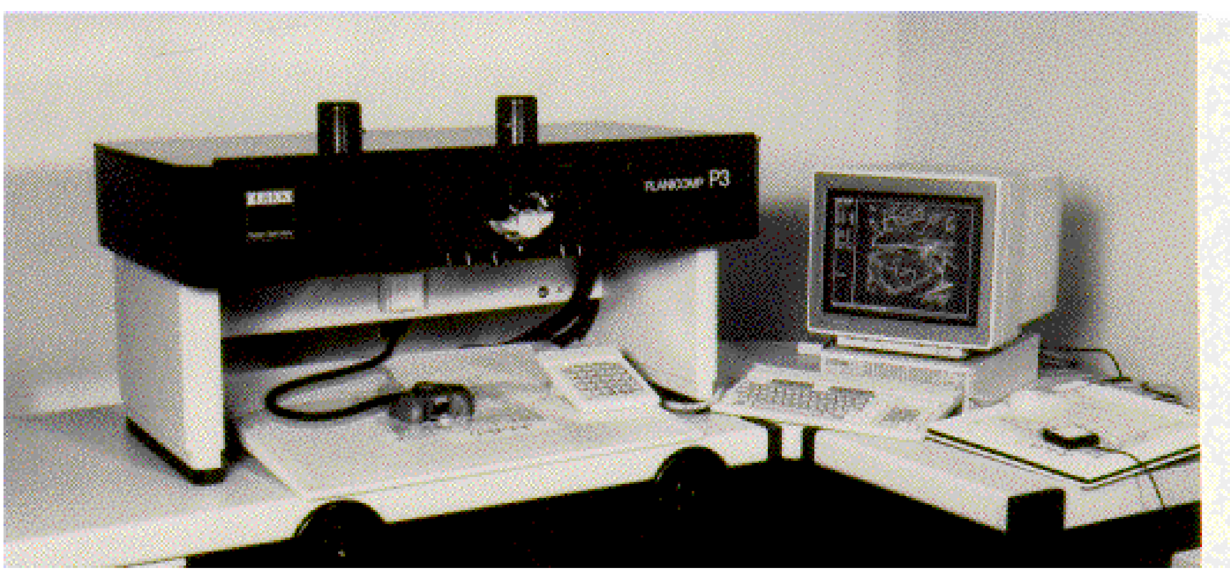


Figure 14. Zeiss P3 Planicomp analytical stereoplotter.

Analytical and digital stereoplotters are the most common types of instruments used today. They depend upon a numerical solution to the orientation processes. This speeds up the time to get a stereomodel oriented and ready for mapping. The difference between these two types of plotters is that digital plotters utilize digital images instead of diapositives. They are also capable of performing extended operations that are not available to analytical plotters, namely the creation of digital orthophotos, automatic aerotriangulation and image correlation. While digital plotters offer more flexibility, they do have some loss in resolution of the imagery because they are scanned. Figure 14 is an example of an analytical plotter, the Zeiss P-3. Figure 15 shows an example of a digital photogrammetric workstation (SOCET SET), and figure 16 shows a sample screen display from the LH System workstation.

Figure 15. LH Systems SOCET SET digital photogrammetric workstation.

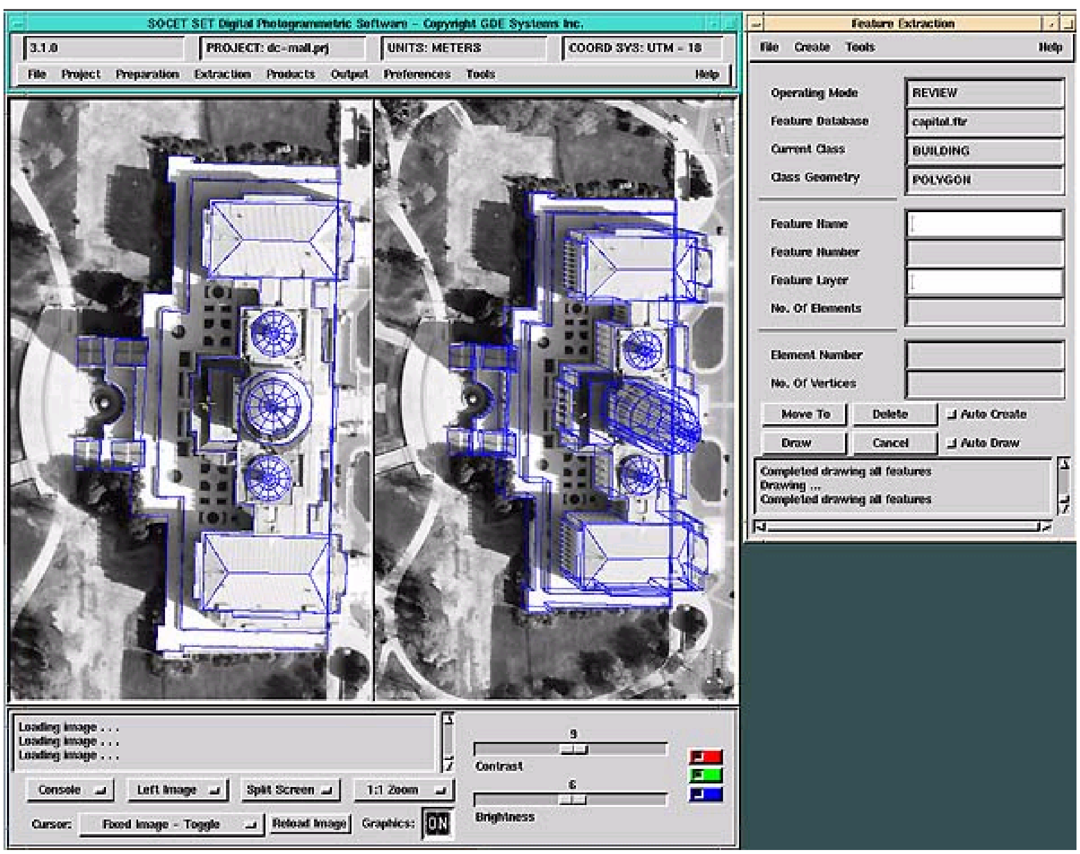


Figure 16. Sample screen display from the LH Systems SOCET SET workstation.

Whether one is using an old analog stereoplotter or a newer analytical stereoplotter or digital workstation, the process of orientation is the same. The advantage of the latter two instruments is that they are capable of mathematically modeling the parallaxes within the model. These mathematical models make the mapping process easier to perform and increase productivity.

Softcopy photogrammetry

The newest technology used in photogrammetry is softcopy or digital photogrammetry. It involves using digital imagery with digital viewing systems, such as a digital stereoplotter. Softcopy is changing the world of mapping. The production of orthophotography, aerial triangulation and DEM (digital elevation model) extraction are being used in a production environment by a growing number of companies.

Taken to its theoretical limit, softcopy photogrammetry will automate the mapping process. This should significantly increase productivity and reliability. But, since this is a technology at its infancy, there is still a lot of development necessary before the full benefits of softcopy are realized. One of the reasons is that the process mimics the conventional process currently being used in mapping. For example, photography, for the most part, still has to be obtained using conventional analog cameras.

Being a digital mapping system, one of the first tasks of the photogrammetrist is to create the digital data. Recently, four different manufacturers have introduced large-format digital photogrammetric cameras. Because it is difficult to manufacture an effective 23 x 23 cm format array of CCDs to capture the image in one array, two different methods of data collection have been devised. Leica Geosystems offers the ADS40 Airborne Digital Sensor (figure 17). This camera utilizes the three-line-scanner principle to provide multiple views of the terrain in both the panchromatic and multispectral bands. Z/I Imaging has introduced the Digital Mapping Camera (DMC) system (figure 18). Their approach is different than Leica's in that the camera consists of 4 high-resolution 7k x 4k panchromatic and 4 multispectral 3k x 2k cameras that expose their sensors simultaneously. The images are then "stitched" together. This approach by Z/I has also been used by Vexcel in their UltraCam digital camera (figure 19).

Figure 17. Leica Geosystems ADS40 digital camera.

Figure 18. Z/I Imaging DMC digital camera.

Figure 19. UltraCam digital camera from Vexcel.

If conventional film is used to acquire the image it needs to be scanned. This can be done using two different types of scanners: flatbed or drum scanners (see figure 20). The flat-bed scanner is generally used for precision scanning. It has greater accuracy and better stability.

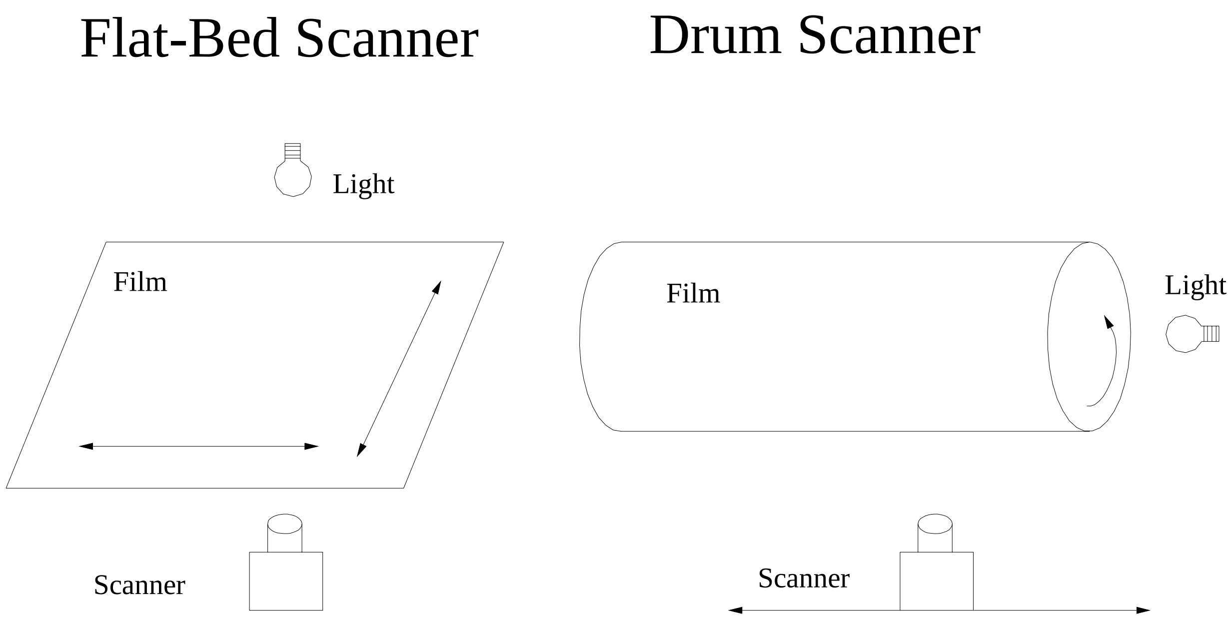


Figure 20. Flatbed and drum scanners.

When a photo is scanned the resultant image is composed of an array or raster of picture elements called pixels or cells. The size of these cells gives us the resolution of the image. Figure 21 shows the effects of creating a raster image containing a straight line such as a road. On the left size, the cells are overlaid the straight line. Then, let each pixel containing the line be classified as a road. The right hand side depicts the result of this process. You will note that the road has a step-like structure. This is referred to as pixelization. If the pixels are smaller then the effects are lessened, but the storage of the data increases.

How the pixels are created depends on the scanner being used. With the flatbed scanner, the photo is placed in a plate carrier and a light is illuminated from above. Below is the actual scanner, which measures the amount of energy, received after the light has passed through the film. A digital number (DN) that represents the illumination in an area is then assigned that pixel. With the flatbed scanners, the film moves first along a row before moving to the next row. The drum scanner operates in a similar fashion, except that the drum rotates. Once the sensor has captures a line of data, it moves longitudinally to the next line.

Increasing the resolution of a digital image results in a corresponding increase in the file size. Table 1 shows the size of a neat model for different scan rates. A neat model is a part of the overlap area between two successive photos that are usable for mapping[9]. The edges of the

[9] The neat model width is generally defined as being the area within the overlap area between the two principal points. If we define this distance as b then the depth of the neat model is usually described as ±b from the base line between the two principal points.

photo are usually not usable because distortions can become larger the farther away from the center of the photo. In this case, a model of 7.2 inches by 6.6 inches is used. The latter value is in the direction of flight while the 7.2 inches is the width of the coverage. The values in table 1 are valid for uncompressed black and white imagery. Color photography would be three times larger. Table 2 shows the pixel size in ground units for different photo scales and the same scan sample rates. Note that the pixel sizes are in inches except for the last photo scale of 1": 1 mile, which is in feet. (Tables modified from informational packet by Air-Land Surveys, Inc.)

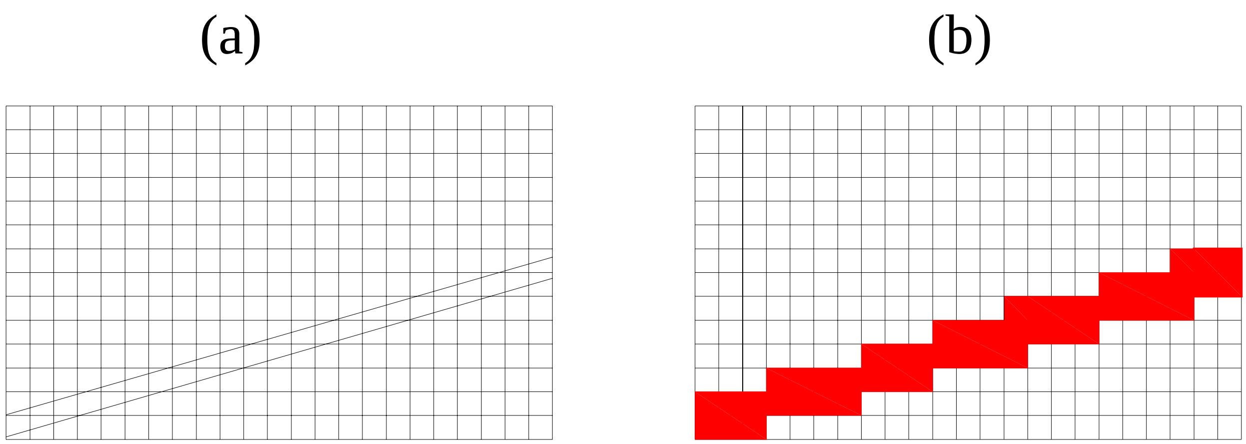


Figure 21. Converting vector data into raster data.

Scan Sample Rate								
micrometers	7.5	15	22.5	30	45	60	90	120
dots per inch	3386	1693	1128	846	564	423	282	211
File Size in megabytes	496	124	55	31	14	7.7	3.4	1.9

Table 1. Sample scan rates.

Photogrammetric Specifications

Specifications for photogrammetric mapping will lay the foundation for a good mapping product. They need to be carefully constructed so as to match both the intended purpose and accuracy of the mapping while, at the same time, provide the economy that photogrammetry offers over conventional surveying techniques.

Scan Sample Rate in micrometers								
Photo Scale	7.5	15	22.5	30	45	60	90	120
1" = 200'	0.7"	1.4"	2.1"	2.8"	4.2"	5.7"	8.5"	11.3"
1" = 300'	1.1"	2.1"	3.2"	4.3"	6.4"	8.5"	12.7"	17.0"
1" = 400'	1.4"	2.8"	4.3"	5.7"	8.5"	11.3"	17.0"	22.7"
1" = 500'	1.8"	3.5"	5.3"	7.1"	10.6"	19.2"	21.2"	28.3
1" = 800'	2.8"	5.7"	8.5"	11.3"	17.0"	22.7"	34.0"	45.3"
1" = 1000'	3.5"	7.1"	10.6"	14.2"	21.3"	28.4"	42.5"	56.7"
1" = 4000'	14.2"	28.3"	42.5"	56.7"	85.0"	113.4"	170.1"	226.8"
1" = 63360 (1" = 1 mile)	1.6'	3.1'	4.7'	6.2'	9.4'	12.5'	18.7'	24.9'

Table 2. Sample scan rates in micrometers.

One of the most important considerations is weather. Haze, snow, foliage, flooding, clouds, and shadows can all obscure detail on the ground. In northern climates where deciduous trees drop their leaves in the fall, photography is generally taken during these leaf-off times. Unfortunately, it is also during this time when the sun angle is low thereby casting longer shadows. Some specifications will indicate a minimum sun angle, such as 30^o used by the New Jersey Department of transportation (NJDOT)[10]. Clouds also create a shadow that may hide detail. NJDOT, for example, rejects photography when cloud shadow occurs on more than 5% of any single photograph.

Calibration Item	**Value**
Average radial lens distortion	≤ 10 μm
Area weighted average resolution	≥ 60 cycles/mm
Lines intersection opposite fiducials	90^o ±30" (arc)
Indicated principal point location with respect to the principal point of autocollimation	≤ 25 μm
Filters parallelism	≤ 10" (arc)
Magazine platen flatness	≤ 13 μm
Stereomodel flatness of any test point	≤ 25 μm
Accuracy of Calibrated Focal Length	5 μm
Shutter Efficiency	≥ 75%
Shutter speed accuracy	≤ 10%

Table 3. New Jersey Department of Transportation camera specifications.

[10] New Jersey Department of Transportation Minimum Guidelines for Aerial Photogrammetric Mapping, BDC98PR-009.

The aerial camera is the primary data collection instrument used in photogrammetry and it needs to be calibrated. Normally, under routine operation, the camera is calibrated every 2-3 years. If problems occur or when routine maintenance or modifications are made to the camera, it is then the responsibility of the photogrammetrist to have it recalibrated. NJDOT outlines minimum specifications for cameras as shown in table 3.

Acquisition of the aerial photography requires careful planning. Again, NJDOT has a number of minimum criteria for acceptable photography. Crab shall not exceed 3^o for any photograph and tilt must not be greater than 4^o with the average being 1^o. At each end of the flight strip, the first and last exposure must be entirely outside of the project area. For strips along the boundary, 15 - 55% of the strip must be outside of the project. Endlap requires ranges from 57 - 62% while the average sidelap is 30% ±10%.

The scale of the photography is dictated by the purpose of the imagery, accuracy requirements, and in some cases, limitations of the stereoplotter. Scale is important because it gives us the flying height. There are a number of issues, often times competing, that help the photogrammetrist determine the optimum flying height for a project. One is the size of the smallest feature that needs to be imaged on the photography. NJDOT specifies that the flying height should not be greater than six times the photo scale. Recall the relationship for computing flying height given the scale of a photograph (see page 7), and assuming a 153-mm focal length camera, then if a photo scale is 1:3,000 the flying height above ground will be

$$H' = \frac{f}{S_{\text{Photo}}} = \frac{0.153\,\text{m}}{1/3{,}000} = 459\,\text{m}$$

The second important aspect is the contour interval of the map. This value is used, in conjunction with the flying height, to define the C-factor, which is defined as

$$C - \text{factor} = H'/CI$$

where H’ is the flying height above the terrain and
CI is the contour interval.

The C-factor is used primarily in the U.S. Each stereoplotter is usually assigned a value that describes the accuracy one would expect that it could meet in drawing contours. Additionally, there is no standard as to what C-factor is appropriate for each instrument. Therefore, a list of plotters may yield slightly different values. Moreover, there are also two different types of C-factor, one for the commercial sector and the other for federal agencies, which is a little more conservative than the commercial values. Table 4[11] gives some representative values.

Example: What is the maximum flying height for a topographic mapping project where the contour interval is 2’ using an analytical stereoplotter for a local client?

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[11] Table from Thorpe, J., 1984. “CPS: Computed Photo Scale”, Photogrammetric Engineering and Remote Sensing, 50(11):1565-1569.

	C-factor	
Instrument	Commercial	Federal Agencies
Analytical Plotters	3000	2500
Zeiss Planimat	2400	2100
Wild A10	2400	2100
Kern PG3	2400	2100
Wild AG1	2000	1800
Kelsh	1500	1200

Table 4. Example C-factor values for different stereoplotters.

Solution: The C-factor for the analytical plotter is 3,000. Therefore, rearrange the C-factor formula.

$$\begin{aligned} H' &= (CI)(C - \text{factor}) \\ &= (2')(3{,}000) = \underline{6{,}000'} \end{aligned}$$

While the C-factor is useful, in reality there are more factors that need to be considered when determining the flying height. John Thorpe has indicated that one must also evaluate the radial lens distortion of the camera, its focal length, nature of the ground control, calibration of the stereoplotter, capabilities of the operator and the maximum number of models bridged between ground control. Additionally, when it comes to digital photogrammetry, determination of the C-factor becomes a function of the imagery and its resolution, making the calculations a little more difficult to quantify. Therefore, while the C-factor is still used in the industry, even for digital photogrammetry, many in the industry take a conservative estimate based on their experiences when assigning a C-factor to a digital photogrammetric workstation/image product.

For typical transportation mapping projects, the contour interval, photo scale, and flying height recommendations from NJDOT are given in table 5.

Mapping Scale	Contour Interval	S_{Photo}	Flying Height
1:300	0.5 m	1:3,000	459 m
1:500	0.5 m	1:4,000	612 m
1:1,000	1.0 m	1:8,400	1,285 m
1:2,000	2.0 m	1:16,800	2,570

Table 5. Contour interval, photo scale, and flying height above the ground.

The intent of this general overview on photogrammetric specifications is to make the contracting agency aware of some of the issues that need to be considered in obtaining photogrammetric services. There are a myriad of other issues that need to be studied and addressed before a request for proposal (RFP) is sent out. One issue, thought, should be stressed. Despite dwindling budgets, agencies should use a qualifications-based selection (QBF) process.

Conclusion

What we have seen is that while a photograph has the advantage of viewing a large area, it needs to undergo further processing if we want to use it for mapping purposes. Scale is not uniform throughout the photo but, instead, changes due to relief. Moreover, for accurate measurements, it is critical that errors or distortions that occur with the photography need to be taken into account. In the next lesson we will learn how the photographic image can be used as a map by the process of orthophotography.

Review questions

1. Explain the advantages of photogrammetry in mapping.

2. How does the photograph differ from a map?

3. If the effects of relief displacement can be reduced by flying at a higher altitude, who don't photogrammetrist fly higher?

4. Describe the major distortions associated with photogrammetry and how they are handled in the mapping process.

5. A photograph was taken at a flying height of 10,000' above sea level (datum). The focal length of the camera is 5.75". The elevation of point A is 200' above sea level and B is 540' above sea level. What is the scale at each point?

6. Stereo photography was obtained over an area with a camera having a 6.1" focal length lens at an altitude of 6,750' above sea level. The elevation at point A was known to be 738'. The parallax measured at point a on the photos was 2.82" while the parallax at point b was measured as 2.97". What is the elevation of point B?

7. What are the advantages of softcopy photogrammetry?

8. Describe, in general terms, why the photogrammetric process requires three different steps in orientation. Explain the purpose and result of each operation.

9. A metric camera is more accurate than a non-metric camera. True or false? Justify your answer.

10. Briefly describe the difference between the Leica DS40 digital camera and either Intergraph's DMC or Vexcel's UltraCam. Visit each company's web site for background information.