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DEGROSS

AERIAL MAPPING, INC 18623 BEARDSLEE BLVD - BOTHELL, WA 98011 425-828-4448 fax 425-828-4446

PLS - EXAMINATION PREPARATION

PHOTOGRAMMETRY 101

A paper on the principles of photogrammetric mapping

Photogrammetry is the art and science of obtaining reliable measurements of physical objects through processes of recording, measuring, and interpreting photographic images and other electromagnetic radiant energy.

The American Society of Photogrammetry is the governing body for the certification of professional photogrammetrists and establishment of mapping standards thus assuring the integrity, quality and ethical practices of it's professional members.

Earth Measurements

In this paper we will confine our discussion to that portion of the Photogrammetric Science delving in land surveying and the measurement of the earth's surface for the purpose of developing topographic maps. We will review the geometry, characteristics, and equipment used in stereoscopic measurements from photographic camera exposures and touch a little on the use of lidar.

Principle

In the photogrammetric process, the object is to acquire a minimum of two aerial photographs covering a site, and then to recreate the geometry of the aerial camera used in a stereo plotting device. The photogrammetrist uses a process not unlike that of a resection process on the ground of two ground control points from three or more known stations, and then the subsequent intersection of numerous other points to determine their locations.

In the photogrammetric approach we use the ground control points provided by the surveyor to determine the location of each camera station by the resection process. This also provides us with our rotational parameters of each exposure, which are not unlike the surveyor's horizontal azimuth and vertical zenith. Basically, we have two stations high in the air now tied to the control network and ready to perform intersections on all visible points seen from each camera location. This should sound like a standard ground intersection approach to an experienced surveyor.

Equipment

There are two basic instrumental components in this process of measuring the earth's surface. The first is the **aerial camera**, which gathers a geometrical rigid image of the earth's surface on aerial film. The second is the **stereo plotter**, which recreates the same rigid geometry as the aerial camera and thus allows for the duplication of the data that the camera obtained in the mapping process.

Additional support equipment to these two basic items include the airplanes, GPS equipment, film processors, printers for contact prints and diapositives, photo enlargers, precision photo scanners, computers, software, plotters and other equipment.

The Photogrammetric Camera

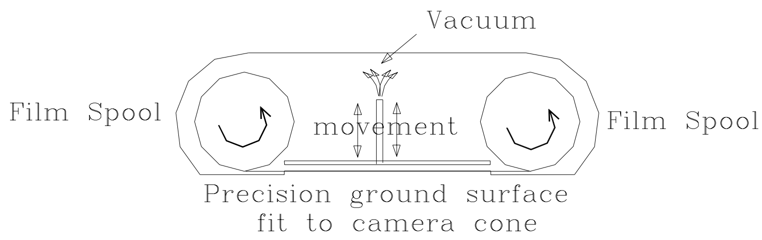
The precision photogrammetric camera used in this process is unlike your standard camera in that it has a fixed focal length, calibrated lens, flat film platen system and film centering marks called fiducials. All of which are necessary ingredients that make the photogrammetric camera a precise instrument which records image data in a rigid and angular geometrical manner about the center of the camera lens. Every aerial mapping camera undergoes a rigid calibration process to determine its precise geometry. This process provides a precision calibration report on the geometry of the camera including the focal length, lens distortion, camera axis, fiducial coordinates as well as resolution characteristics of the camera.

It is these strict geometry features of the photogrammetric camera that give it the qualities necessary for the collection of accurate angular measurements required of any surveying instrument.

The standard photogrammetric cameras weigh in at about 350 pounds and measures about 2' x 2' x 2'. The entire camera system consists of five primary components; a camera cone which houses the lens assembly and fiducials, a removable film magazine which houses 250 foot to 400 foot rolls of film, a leveling mount to accommodate airplane attitude, a view finding system to check flight alignment and photo exposures and a GPS system for added flight alignment and triggering.

The Camera Magazine

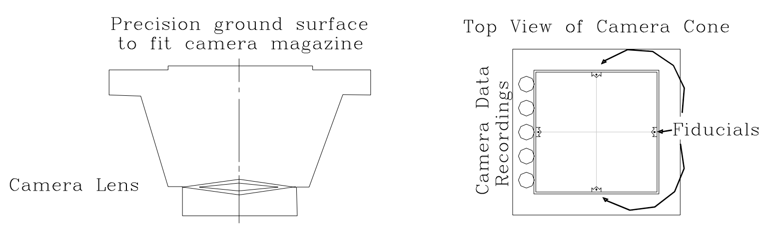
The camera magazine sits atop the camera cone and contains the aerial film with take-up spools. It houses a precisely ground flat platen and a vacuum system that holds the film perfectly flat against the platen during the exposure. When the film transports between exposures the vacuum is released and the platen rises slightly, to allow the film to roll freely between exposures. Once the film has moved, the vacuum draws the film up against the platen again and the platen drops into contact with the precision ground camera cone for the next exposure. This process establishes a fixed principal distance at the time of exposure and assures a flat projection distance over the entire frame. The standard image format for aerial photographic film is 9 inches by 9 inches. The film, itself, is about 10 inches wide and comes in standard 250' and 400’ rolls.



The Camera Cone

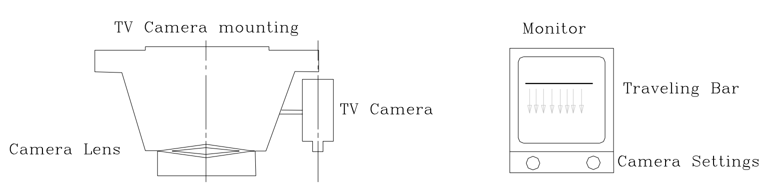
The camera cone is the heart of the geometric system in that it contains the camera lens and the precision ground focal plane surface that the film rests against at the time of exposure. This system is a precisely aligned system where the camera axis is perpendicular to the focal plane. The lens and camera is designed so that its optimum focal distance of the lens matches this projection distance for sharp imagery and solid geometry. There are 4 to 8 fiducial marks attached to this precision ground surface that defines the projection surface for the aerial film to rest on. These fiducial marks are illuminated and show up on each aerial exposure. It is these fiducial marks along with the camera calibration report that define the center of the camera axis and later allow for duplication of this geometry in the stereo plotter.

Some makes of cameras house the operational electronics of the system in the camera cone while others house the electronics in the mounting system that will be discussed below.

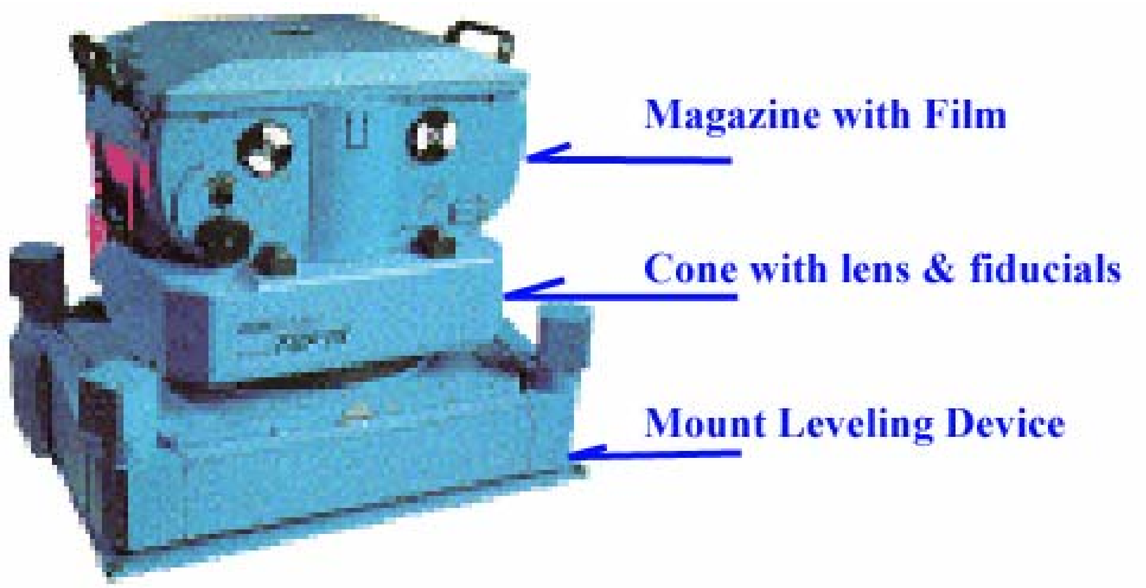


The Camera View Finder

In order to know where and when the exposures are to be made, the flight system includes a closed circuit TV camera with monitor. This camera is aligned with the aerial camera to have a coinciding axis. A monitor is mounted next to the pilot for easy viewing. Rheostats on the monitor regulate the timing of the exposures by adjusting the speed of a traveling bar on the screen to coincide with the image of the ground as it passes by. Dials allow the operator to set the desired overlap and camera focal length. Onboard GPS systems also are employed to center the pilot along each fight line and aid in photo exposures when necessary.

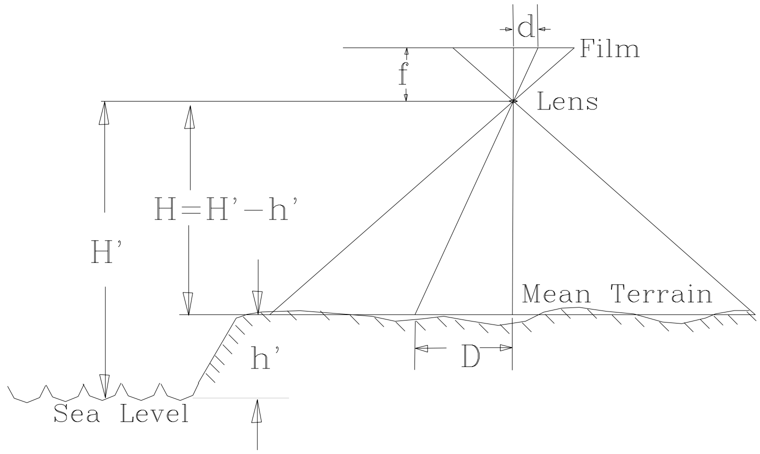


Typical Camer Configuration



Camera Geometry:

1) Scale



d = photo distance	f = focal length
D = ground distance	H = flight height above mean terrain
h' = mean terrain elevation	H' = elevation of flight above sea level

$$\textbf{Scale} = d/D = f/(H'-h') = f/H$$

Example:
Aerial camera is a 6" focal length = f
Mean terrain is 400' above sea level = H
Flight height is 3400' above sea level = H'

Expressed as a Ratio:

Use same units for focal length and elevation above mean terrain.

S = f/(H-h) = (6/12)' /(3400-400)' = 0.5/3000 = 1/6000

or 1:6000 photo scale

Expressed as Inches per Foot:

Express focal length in inches and elevation above mean terrain in feet.

S = f/(H-h) = 6"/(3400'-400') = 6"/3000' = 1"/500'

or 1"=500' photo scale

Photo Ground Coverage: Remembering that standard film is 9" x 9".

Where D = d/Scale — The total coverage of the 9" film on the ground

letting	d = 9"	for the total 9" wide aerial film
and using	Scale = 1"=500'	as in the above sample

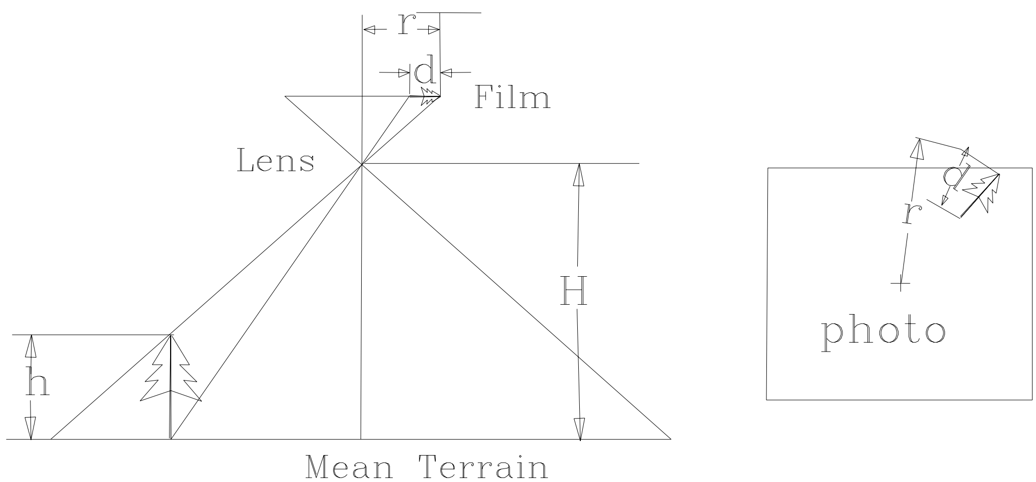
Photo Coverage d(max) = 9" /(1"/500') = 9" x 500'/1" = **4,500'** on the ground

2) Image Displacement:

Photos are perspective pictures of the ground and not orthogonal in nature, thus they DO NOT maintain a constant scale across their entire image. For this reason it must be remembered that such images cannot be enlarged to provide true orthogonal maps or photo enlargement by simple projection methods. The cause of this displacement comes from two major sources. The first being relief displacement due to changing terrain or heights of objects on the earth's surface. The second is caused by nominal tip or tilt in the camera axis from true vertical, which is a standard occurrence during aerial flights.

a) Relief displacement

The relief displacement (d) on a photograph radiates about the center of the photo on a vertical photograph. For objects above the mean terrain the displacement is always outward from the center of the photo, whereas objects below the mean terrain the displacement is inward. This height difference results in an inconsistent scale throughout the photograph.



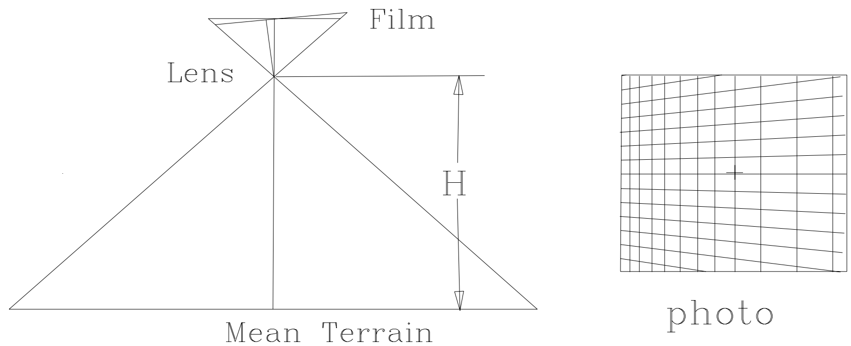
d = relief displacement | h = height of object
r = radial distance to image | H = flight height above mean terrain

Relief Displacement $d = rh/H$

Two major items for the end user to consider are brought out in this equation. First it is apparent that the displacement is minimum or nonexistent at the center of the photo and at its maximum at the outer edges. Secondly, it can be seen that the height of the object or varying terrain difference is directly related to the resultant displacement of the image placement on the film.

b) Tilt Displacement

Tilt displacement on a photograph is caused by the surface of the projection image (film) not being parallel to the plane of maps projection surface below the exposure. If the camera is tilted at the time of exposure a truly vertical photo is not achieved, thus causing an uneven scale across the photo. The lower side of the camera will view a larger distance on the ground and the raised edge will view a shorter ground distance. This will result in a displacement similar to the diagram shown below, and is typical of a slightly perspective view of the ground.



It is always important to remember that it is these two displacements, relief and tilt, that make an aerial photograph or enlargement thereof **not a true map** projection, and that they are not capable of maintaining a constant scale. Do not expect a straight photo enlargement or digital image thereof to fit final a map whether prepared by field or photogrammetric methods because of these factors. It is also important to remember that the rubber sheeting process does not take into consideration these two causes of displacement of a photography, but instead only varies the scales of the image according to specific points selected during the rubber sheeting process. **A primary premise to take from the above is that photos should only be used for visual purposes, preliminary planning, or only the roughest of measurements if any.**

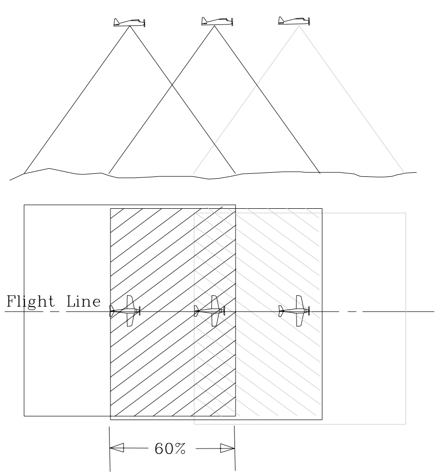
3) Stereo Coverage:

It is imperative to have stereo coverage over the entire site when using a photogrammetric approach. This provides two airborne stations to perform all ground intersections on over any given area of the site. Many sites are too large for a single stereo model thus it is necessary to fly these larger sites with multiple exposures down a flight line or even accompanying parallel flight lines. It is imperative to plan these flight lines to insure continuous stereo overlap between successive photos on a flight and also between adjacent flights when required.

Along a flight line it is desirable to design lines with 60% to 65% forward overlap between photos to insure continuous stereo coverage. The lack of precise exposure timing, camera tilt or ground relief will cause this overlap to vary slightly but these values will generally insure the needed coverage. Besides for aerial triangulation process uses, we do require an excess of 50% coverage for point transfer between models. By planning for a 60% forward overlap this produces an area of 20% under each image that will enable the photogrammetrist the ability to pass control of a given point from one stereo model to the next in our aerial triangulation process.

If a project is too large to cover in a single flight line, additional flights will be made to assure stereo coverage. These are normally parallel to the first. Side lap between the two flight lines must again be planned to assure continuous coverage between flights of the project area. A designed 20% side lap is desirable for most mapping projects. This normally assures coverage considering flight line deviations, ground relief, and ground control requirements. It is noted however, that in mountainous terrain these percentages may need to be increased to allow for terrain changes and excessive relief displacement.

Forward Overlap



Side lap between flights

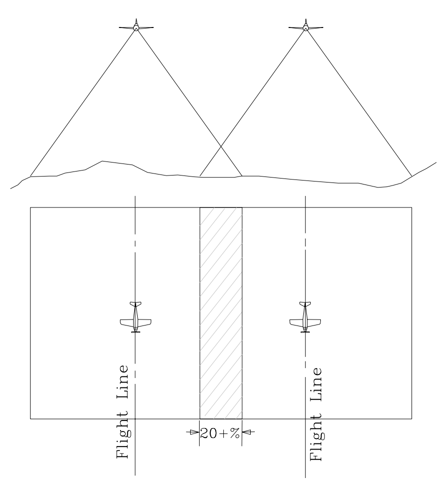
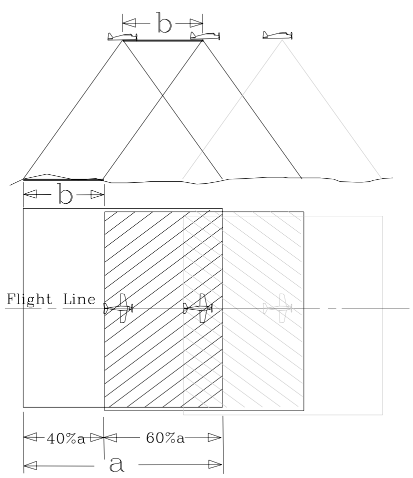


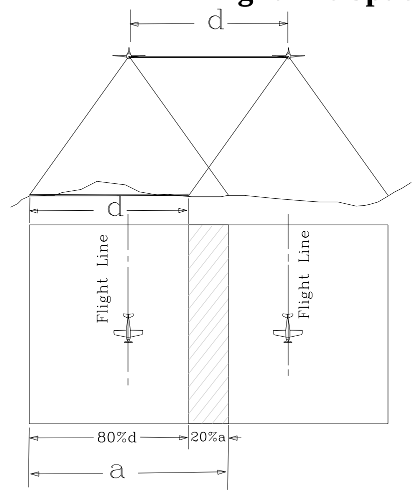
Photo Base / Flight Line Separation

When planning a flight line, a standard 60% forward overlap would correspond (1-60%) or 40% forward progression between photo exposures. Similarly a 20% side lap would correspond to (1-20%) or 80% separation between successive flight lines.

Base Between Photos



Flight line Spacing



For standard 9" aerial film and using a photo scale of 1"=500' with a standard 60% forward overlap and 20% side lap, these distances would be:

Photo Base	**Flight Separation**
Distance between exposures	Distance between flight lines
b= (500 x 9) x 40% = 1,800 feet	d= (500 x 9) x 80% = 3,600 feet

Camera Focal Lengths:
Aerial cameras come in varying focal lengths each designed for it's specific characteristics and purpose. The most common lens used in the mapping process is a 6" lens. However precision cameras are also available in 12, 8 ¼, and 3 ½ inch focal lengths all using a standard 9" image format. In general shorter focal length cameras are used for mapping purposes and longer focal length cameras are used for reconnaissance. This broad classification is primarily due to the amount of relief displacement inherent in each.

The correlation between focal length and image displacement can be seen by revising the previous equations of relief displacement (d = rh/H) from page 6 by substituting H=f/S from the scale equation (S=f/H) on page 5. We then end up with the following correlation.

$$\mathbf{d = rhS/f}$$

Many useful insights into the affects of varying focal lengths can be drawn from this equation. One primary point is that it can be seen that the displacement (d) caused by the height (h) of an object, is inversely proportional to the focal length of the camera. The longer the focal length the less the displacement an object will exhibit on a photo image. It is for this reason that longer focal length cameras are more suitable for reconnaissance purposes. Standing trees and buildings do not lean away from the center as much as they would within shorter focal length cameras, thus allowing for greater visibility behind such objects. This same principle affectively decreases the displacement caused by ground elevation changes throughout the photo providing a more homogeneous scale throughout.

There is, however, an inherent disadvantage in using longer focal length cameras in the topographic mapping process. This is primarily related to depth perception and vertical accuracy. The increased relief displacement in shorter focal length cameras creates an enhanced or exaggerated perception of depth to the operator and increases the vertical accuracy of such measurements. This increased accuracy is due to the increased angle of intersection of rays from the two stereo photos in shorter focal length cameras. In the standard 6" mapping lens the angle of intersection over a stereo model is in the neighborhood of 32 degrees whereas a 12" camera reduces this angle of intersection down to around 17 degrees throughout the stereo model. This is not unlike accuracies associated with computing ground distances by intersection from narrow based stations.

The other 8 ¼ inch and 3 ½ inch cameras are either compromises or exaggerations on the above and are employed usually for special case scenarios.

Although it is important for the surveyor to understand these advantages and disadvantages, it is probably of most importance to remember that it will more than likely be a 6" aerial camera that will be used for your aerial mapping projects. If circumstances dictate otherwise your photogrammetrist will advise you as to the reasons.

The use of digital cameras is on the rise and will probably be dominant in the future. However, to date, the standard film camera is still the most commonly used. This is due to cost, storage capability, special equipment and the perceived reliability of digital models at the present time. The most prevalent digital camera is the spot exposure camera similar to today's film camera, which take individual exposures. However, there are push broom scanning cameras also available primarily for orthophoto mapping with totally different geometric considerations. Focal lengths and projection formats will vary on the digital cameras to accommodate manufacturing technologies and intended uses. The outlook is very good however, with technology advancing every year and the possibility of multiple bandwidth sensitivity and enhanced graphic control of contrast in shadows.

Camera Distortions and Calibration

The heart of the theory of photogrammetry lies in the aerial camera's geometric stability. It is imperative that the geometry of the camera be determined to duplicate this in the stereo plotter for future measurements. The lens must also have minimal lens distortion and high resolving power over the full image to satisfy government specifications. To this end aerial cameras are sent in for calibration every three years to assure their geometry is known and variations are within acceptable tolerances. The calibration process yields a certificate of calibration with the cameras unique geometric conditions. It is from such certificates that the photogrammetrist can apply mechanical or mathematical corrections within his stereo plotter to duplicate the camera's geometry and distortions. Modern aerial cameras have distortions ranging from about +- 4 microns, and resolving powers from about 100 lines per mm at the center of the lens to 40 lines per mm at the outer edges.

Ground Control:

The purpose of ground control is to tie all photogrammetric map data to the coordinate system being used by the client on a specific project. To this end, it is necessary for the surveyor in charge to provide horizontal and vertical coordinates on the desired projection and datum needed for the project. The locations of these points are normally defined in the planning phase of the project by the photogrammetrist and forwarded on to the surveyor in charge.

It is likely that such ground control points will be premarked prior to the flight to show the location of each control point on the photography. Premark size and configuration may vary depending on scale and use thereof, as often supplemental premarks may be put out to identify specific objects other than control points, i.e. (manholes, valves, sprinkler heads, etc)

Scaling

In order to define the scale between the photogrammetric measuring system and the desired ground survey system it is necessary to have a minimum of 2 points to complete the horizontal transformation. This is an absolute minimum, however, and not desirable since there is no check on the computations. For this reason, the photogrammetrist will require a minimum of three horizontal points for a single model project and even more on a larger project to assure accuracies throughout.

Leveling

Developing a vertical datum in the stereo plotters is likened to defining a vertical plane for the photogrammetrist to measure from. To define a plane, it is necessary to have three points that are not on a straight line. This is the minimum number of points required and again, not really acceptable as no check is possible before mapping. For this reason at least four vertical points are desirable for single models and even more on larger projects.

Optimal positions of these points are always sought for these control points. The greater the separation of the data, the better the scaling and leveling will be. It's rather like building a table. If the legs are all in the center of the table the table is not very stable. On the other hand if the legs are near the corners of the table it is a very stable surface.

Because of today's surveying equipment and capabilities, usually it is just as easy to obtain horizontal and vertical data on all control points. This is highly advisable and provides a very stable system to build on.

Types of Photogrammetric Control:

Full Ground Control:
This method of ground control requires the ground surveyor to establish enough control to satisfy the above requirements for every stereo model covering the project. Usually this will be a minimum of 4 to 5 points per model, to assure satisfying the scaling and leveling requirements of each model. This approach is a must on single model projects and highly recommended on design grade 1’ contour mapping projects.

Partial Ground Control with Aerial Triangulation:
As the number of stereo models increase over a project it becomes economical to consider photogrammetric aerial triangulation as a way of reducing ground control time and costs for the project. This approach will reduce the required control by approximately one third to one half over the full ground control method discussed above. It will, however, require the photogrammetrist to perform an aerial triangulation process over the project that is likely to be performed in either case.

In the analytical approach, the photogrammetrist will drill small holes referred to as pug holes or pass points in the aerial film. These points are established in areas of the triple overlap, and double side lap, which are common to adjoining stereo models. The stereo models are setup in the stereo plotter model by model and the plate coordinates of these pass points along with the ground control points are read. This data is run through a least square aerial triangulation program and adjusted to the ground control. This program computes ground coordinates on these pugged points so that each individual model can then be set.

In a digital softcopy approach drilling pug holes is not an option in the digital. Softcopy systems have the capabilities of automated point identification to define the pass points on multiple photos, or this can be done in a manual mode if desired. Once completed, this data is run through the aerial triangulation program. The results of this approach are somewhat different than the analytical approach in that the primary output is the stereo model set up parameters instead of point coordinates on known pugged points. Once computed the data is used within the softcopy plotter to establish the stereo model whenever the stereo set is opened up.

Airborne GPS and Aerial Triangulation with Limited Ground GPS:
As the number of stereo models increases even more or the site becomes remote or inaccessible then one should consider an Airborne GPS Aerial Triangulation approach. In this approach coordinates are determined at each photo center with onboard airborne GPS equipment for added control to the project.

Basically, on a small block jobs only four or five points will be needed at the corners of the project, and one perhaps at the center. Larger block projects will, of course, need additional points. For strip mapping along roads, power or pipelines, and shoreline, it is desirable to have control points at each end of the project and a minimal number along the route.

This approach will again reduce the required control for a project. Where a block of forty photos would require about thirty control points by conventional aerial triangulation it would only require five or six with Airborne Aerial Triangulation. In a similar manner a thirty model strip flight would require about twenty-five to thirty points with conventional aerial triangulation and only about three or four points with Airborne Aerial Triangulation.

Photogrammetric aerial triangulation procedures are practically the same as when we perform regular aerial triangulation. However, we utilize the GPS coordinates of each exposure along with the ground control points to aid in the computations and reliability.

This approach is very desirable along routes with limited access as few if any points are required in inaccessible places.

POS Airborne Control:
The newest solution to controlling aerial photography is the advent of stabilized gyros combined with airborne GPS to fully determine the full orientation of the camera at the time of exposure. The GPS system computes the position and the gyros determine the rotational parameters at the time of exposure. In theory, this eliminates the need for ground control all together except for minimal checkpoints. However, due to the reliability of the current systems as well as the associated costs, this approach has proven practical only on high altitude maps to be used for planning purposes.

Ground Control / Data Input QA
One valuable side product of the aerial triangulation process is that it is excellent for checking initial input readings and or ground control data. The software provides an individual control point residual on each horizontal and vertical control point used in this process. This allows a wide range of trouble shooting capabilities. It allows us to check for incorrect input or if control problems exist in the original ground data. Individual control points can be turned on and off and problem points can be singled out for intelligent communication with the surveyor on any and all problems suspected.

Premark Size:

The desired size of premarks is determined by the photo scale to be used on a project. The higher the flight then the larger the premark must be.

Since either the final map scale or desired contour interval will determine the flight height for a project, the following can be used as a minimal size approximation.

Premark width should be the lesser of:

$$W = 0.3 \times CI \qquad \text{or} \qquad W = 0.01 \times S$$

Where	W = width of each leg on a premark
and	CI = Contour interval
and	S = Map Scale

Therefore for a 1"=100' map with 1' contours this would yield:

from the contour interval	w = 0.3 x 1'	= 0.3 feet wide
from the map scale	w = 0.01 x 100'	= 1.0 foot wide

The lesser of the two comes from the contour equation and is 0.3 feet or about 4 inches. This indicates that the contour interval is the controlling factor in determining the desired flight height and should control the width of the premark.

The length of each leg should be about five times the width computed above.

$$\mathbf{L = 5 \times W}$$

Materials:

Paved Surfaces:	White latex paint
Dirt surfaces:	White plastic garbage bags “torn & folded to desired size”, Sheet rock, white plastic visqueen, torn sheets,

Several products are available in the market place one such item is: Griffolyn T-55 a product of Reef Industries, Inc. (www.reefindustries.com) phone 1-800-231-6074, P.O. Box 750250, Houston TX 77275-0250.

Camera Restitution

"Determining the location and orientation of the camera station"

1) Determine the camera's **interior orientation** parameters: Focal length, center, and distortion characteristics. "Physical plotter adjustments or data input."
2) Determine the **relative orientation** between any two-camera exposures. Or determining the relative translational and rotational elements. This is performed by clearing parallax or measure plate coordinates in six primary locations in the stereo model.
3) Determine the **absolute camera orientation**. Or determining the actual location for both the translational and rotational elements in the mapping coordinate system. This is performed by reading ground control coordinates in the stereo model.

Once completed this process yields a stereo model that is scaled and leveled to the ground coordinate system and map ready.

(Interior Orientation) Reconstructing the camera's geometry
The stereo plotter must be able to duplicate the camera's focal length, distortion pattern, and be able to center the film about the instruments projection axis. The geometry of the rays that passed through the camera lens onto the film must be duplicated in the instrument so that this image data can be projected back through the instrument's projection center at precisely these same geometric angles.

To this end, stereo plotters have the capabilities of accommodating variable projection centers, different camera distortions, and are equipped with film centering devices.

On analog instruments the calibrated focal length is set mechanically with an adjustable graduated screw ring. This adjustment varies the principal distance between the film plane and the gimbals that emulate the lens centers. The camera's lens distortion pattern is compensated for by a variable diameter cam that transforms radial camera distortion into slight changes in the principal distance of the instrument. The film image is centered above the projection center by aligning the cameras fiducial marks with special calibration marks on each plate holder, or secondary centering devices.

On analytical and softcopy plotters, interior orientation is performed by entering the calibrated focal length, distortion data, and fiducial coordinates into the computer database. This allows the software to compute the center of the camera axis.

(Relative Orientation): translational and rotational elements between cameras
The next phase is to create a stereo model by determining the relative translational and rotational elements between the two camera stations. This is done by a procedure of measuring image parallax in 6 primary positions in the stereo model to determine the three relative rotational unknowns about the x, y, and z axis and the two translational relative to the base as set in the instrument.

On analog instruments this is an iterative process of clearing parallax at the 6 primary positions. Successive iterations close in on the desired rotational and translational settings of each projection center. When the operator observes no residual parallax the solution is complete and a stereo model exists with no perceivable parallax.

On analytical or softcopy instruments this iteration process is eliminated. Only one reading is needed at 6 primary locations in the stereo model and the computer solves for the final relative orientation solution.

In either case, this model cleared of parallax and 3D viewing is achieved, but the working coordinate system is just sitting in arbitrary model space and is not oriented or scaled to the ground control or map datum.

(Absolute Orientation): Scaling and leveling to the ground control

This is the final step to setting up a photogrammetric stereo model. It is in this phase that the ground control is incorporated into the process.

In an analog plotter scaling is accommodated for by moving the plotter projection centers apart or closer and leveling is accomplished by rotating the projection plates about the x and y axis to bring the model coordinate system to match the vertical mapping datum. Again, this is an iterative process that is repeated until all control residuals are acceptable.

In the analytical plotters, scaling is accomplished by reading model coordinates on the available control points within the stereo model. The computer then has the translational and rotational parameters necessary to scale and level the model system to the final mapping system and ready for digital output. This data is permanently stored and ready for set-ups at later dates if needed. All that is necessary is for the film plates to be re-centered and you need only check the relative and absolute orientations before adding additional detail to the map file.

The softcopy plotter works in a similar manner as the analytical plotter but has an edge when set-ups are required at a later date. In the softcopy all data is permanent even the digital image, so nothing has changed since the initial solution was made. Set up is immediate by calling up the model and mapping can start at once.

The Stereo Plotter

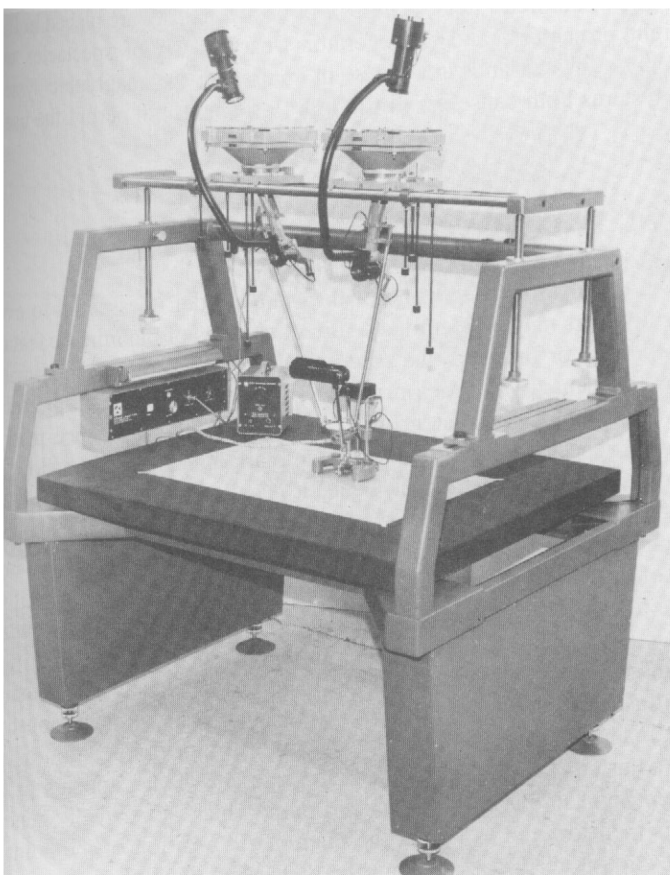
The stereo plotter is an instrument capable of reconstructing the translational and rotational conditions of two or more aerial cameras at the time of exposure, and also having the ability to measure and record three-dimensional data from such photos.

Types

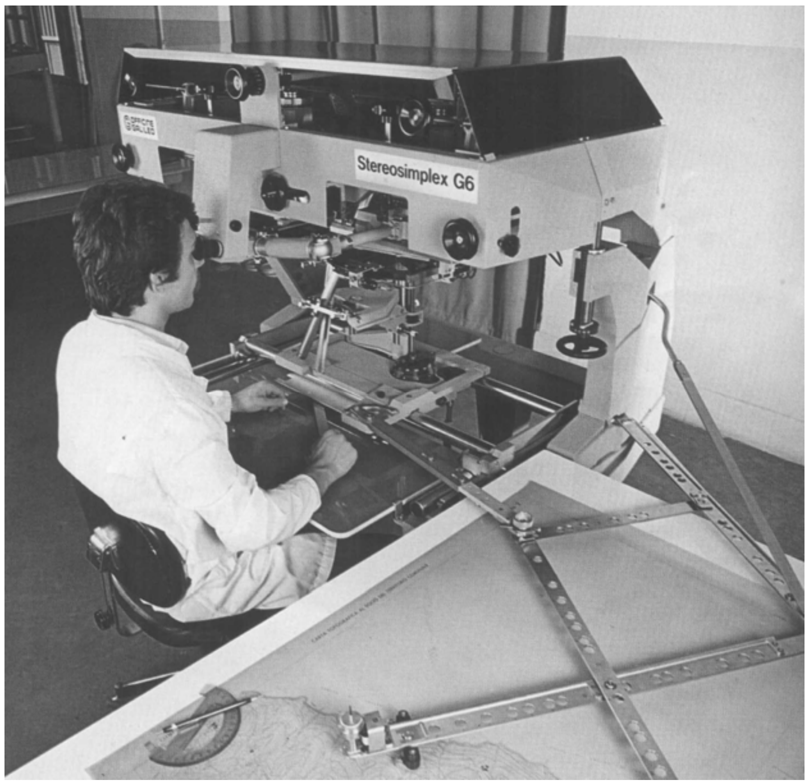
Historically photogrammetric plotters originated in the form of **projection instruments**, advanced to **optical-mechanical** instruments, then to **digital analog instruments**, and then to **analytical instruments**, and now to **soft-copy analytical** instruments.

Projection Instruments

The original projection instrument was a direct reversal of the taking camera. Their use was commonplace between the 1940's and the 1960's. A light source projected light through the positive transparent photo image (the diapositive), then through a lens that projects onto a movable tracing table platen with drawing capabilities. The projection buckets had full translational and rotational movements to reconstruct the camera conditions at time of exposure. Two such projectors made up a stereo model, which was viewed in a darkened room. These instruments are not in use today, due to a number of inherent limitations, such as fixed magnification in system, poor optical resolution, relative accuracy deficiencies compared to newer designs, and poor working conditions.



Optical-mechanical
The optical-mechanical analog instrument was the next advancement in stereo plotters. This instrument corrected the deficiencies of the earlier projection instrument. Camera restitution is made by full translational and rotational movements of the film carriages about each projection center similar to the projection plotters. The image is viewed through precision binocular optics providing exceptional resolution and, as such, this instrument does not need to be operated in a dark room. The model rays are created mechanically through metal space rods and not through a fixed focal length lens. Because of this, and the use of a pantograph, a wide variation in map scales can be accommodated from a given photo scale in this instrument. The precise optical-mechanical designs of these instruments increased the accuracy of the total mapping system by about 50% over the projection plotters.



Digital Optical-mechanical
The next advancement in stereo plotters was the addition of the computer to optical-mechanical analog instrument. This system discards the pantograph drawing table and utilizes three encoders to measure x, y, z model coordinates. These instrument coordinates are translated into ground coordinates and stored as digital map files. The operator can view this map file on the computer's color monitor. This advancement gives the photogrammetrist a whole new outlook on mapping. Now computer files in earth units can be generated with relative ease. Control point error analysis is greatly enhanced as is recording for independent model aerial triangulation. Digital DTM's, digital maps and cross sections are standard outputs on this instrument. With this improvement, no physical restriction in the instrument exists between flight height and map scale. Instead it is only the horizontal and vertical map accuracy, as well as required detail that dictate the maximum flight height for a project.

Analytical

This instrument again uses precision binocular optics for superb resolution. Instead of mechanical scaling and leveling the analytical plotter measures x, y plate coordinates only. The servo driven x and y mechanism for each plate holder is the only moving parts in the instrument. The restitution of each photo is made through strict mathematical computations within its computer utilizing the camera data, measured plate coordinates, and ground control points. This plotter relies on the computer to store the transformation formulas and then compute x, y plate coordinates for any model coordinate measured. The computer drives the x, y servos of each individual plate to the corresponding plate coordinate for each x,y,z model coordinate as visited by the operator.

This instrument allows for automatic x, y scanning of the stereo model, for 3D DTM's, centerlines or cross sections. Previous designs could not perform this automated movement. Also, since this instrument works in plate coordinates, it has the ability to provide direct data for full bundle aerial triangulation programs, which again was not possible on previous plotters. The speed of model set ups, automatic scanning function, full aerial triangulation capabilities, service needs and reliability are all great improvements over previous designs. Additionally, this instrument will accept any camera focal length or distortion data, making it able to accept all cameras. The accuracy of the final product did not significantly improve over the previous digital optical-mechanical instrument, but it’s versatility, speed and operation characteristics defiantly made it the instrument of choice.

“SoftCopy” Digital Image Processing Analytical Instrument

This is the leading edge of the photogrammetric instrumental development. These instruments utilize scanned photographs as input instead of transparent film positives. The system consists of a high-end workstation, monitor, special viewing system and some very heavy software. The only moving parts are the hard drive and fan in the computer and the operator.

The geometry of the camera is maintained through precision photo scanning with scanners capable of maintaining placement accuracy of 2 to 3 microns. The original film is normally scanned at an image resolution of 12 to 16 micron pixels or about 2,100 to 1800 dpi.

Model set up is similar to the analytical instrument only the image is portrayed on the computer monitor. The image on the monitor alternates between the two scanned stereo images at about 60 cps. Two viewing systems are in production for stereo observation by the operator. In one system an operator wearing similarly synchronized glasses can view the left and right image with the respective eye thereby seeing a stereo image on the monitor. In the other system a polarizing plate on the screen alternates the polarization of each photo as it is displayed. The operator wears polarized glasses aligned to receive the appropriate image in the left and right eye.

Currently these instruments have automatic image recognition for creating automatic fully automated DTM's and orthophoto projections from the pixilated photo image without significant operator interference. These same functions can now be used in aerial triangulation for the automatic picking pass points to use between models and strips. At present these techniques are working but refinements are needed to improve their reliability and eliminate the amount of data review and correction required to provide a final product meeting national map accuracy standards. The solution to these technical problems I am sure will be concurred in time and will allow faster and reliable data from these automated modes.

System Accuracy:

The accuracy of the entire mapping system is designed toward meeting the National Map Accuracy Standards as published by the American Society of Photogrammetry. The 1968 standards stipulate that 90% of the contours shall fall with in 1/2 of a contour interval, and 90% of the spot heights shall fall within 1/4 of a contour interval. For planimetric detail 90% of all well-defined map detail shall fall with 1/40th of an inch at design map scale. These standards have recently been updated to more stringent constraints, but as of this writing I do not have the final form to provide.

The accuracies stated above depend upon the total mapping system employed in the mapping process. The major factors in this system are the camera, the film medium, the stereo plotter, and the operator. The better each of these factors are the more accurate the final map will be for a given photo scale.

All else considered the same, today's modern analytical and softcopy plotters maintain about the same mapping accuracies, with in my opinion the edge going to the analytical plotter for vertical accuracy. The older projection and analog plotters cannot compete with the speed and functions provided in these newer systems. However a few are being used today.

The **"C Factor**" of a mapping system is often referred to as a systems accuracy rating.

It is an expression for the maximum elevation above the mean terrain that can be flown to maintain National Map Accuracy Standards for producing a 1' contour interval.

An accepted value for this C Factor for today's modern equipment is:

"C" = 1,800

Therefore: if

Contour interval (x) "C" = Max. Flight Ht. and **S = f/H**

for 1' contours the maximum altitude above mean terrain for a 6" camera would be

1' x 1,800 = 1,800 feet or a Scale of 6"/1,800' = 1" = 300'

for 2' contours the maximum altitude above mean terrain would be

2' x 1,800 = 3,600 feet or a Scale of 6"/3,600' = 1" = 600'

for 5' contours the maximum altitude above mean terrain would be

5' x 1,800 = 9,000 feet or a Scale of 6"/9,000' = 1" = 1,500'

Orthophotos

Orthophotos are a true orthogonal representation of a photo image as projected to the surface of the earth. It must be understood that this is true only at the DTM surface created during the mapping process that represents the ground surface. Objects above this surface are still subject to some differential relief displacement due to their height above the surface of the ground DTM model. This is evident by the lean observed in orthophoto images of buildings trees and other objects not represented in the surface DTM. Normally major bridges and overpasses are included in the base DTM when creating orthophotos and the possition of these objects will be shown in their correct map position.

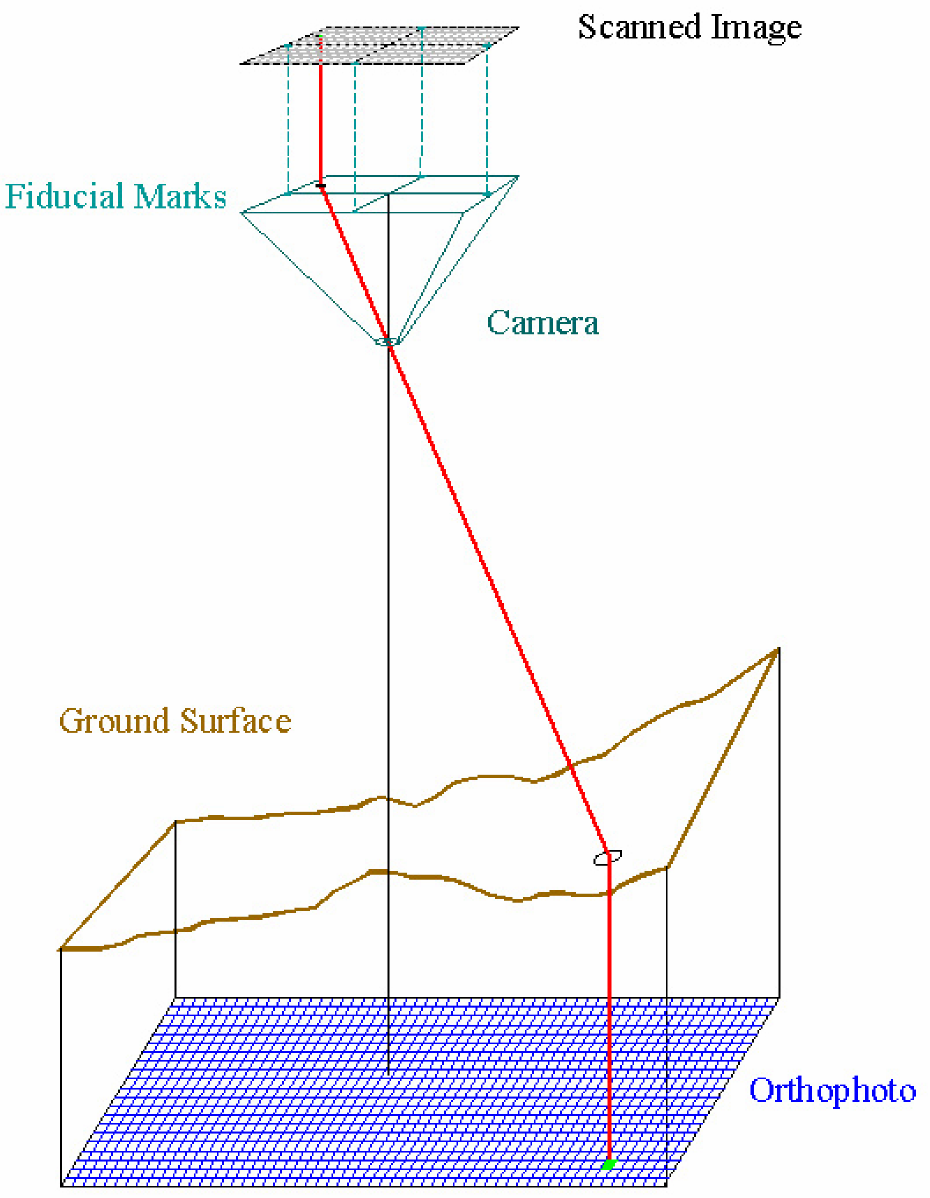
The ortho process requires four primary ingredients: knowledge of the camera geometry, the location and rotational parameters of the camera, a digital photo of the site and a ground surface model.

The camera calibration certificate obtained periodically on all mapping cameras provides for the camera geometry. The location and rotational parameters of the camera at the time of exposure are determined during the aerial triangulation phase of the mapping process. Digital images are prepared from the original film acquired in the mapping process. The film is scanned on a high-resolution scanner with a technique that eliminates any film scratches or dust that may be present during the scanning process. The ground surface model prepared during the topographic mapping phase is used to calculate the ground elevation of every object in the photo during the ortho rectification process. With this data in hand the ortho rectification process can begin.

The final resolution of the finished orthophoto is directly related to the photo scale of photography acquired. The resolving power of most available aerial films is about 12 to 16 microns or 2,100 to 1,600 dpi and as such scanned accordingly. During the ortho process this raw scan data is resampled at a fixed pixel resolution normally about 20% less than the raw data to assure minimal loss in the resolution of the original data. It is this fixed ground resolution that will make up the matrix for thousands of small ortho computations to be performed to generate the final overall ortho corrected image file.

In essence the true map plane of the job site is divided up into a grid of incremental (x, y) segments the size of the final desired pixel resolution. The center coordinate of each pixel location is then projected up to the surface model to determine the elevation of individual particular pixel location. Since we know the location and rotational parameters of the camera, we can perform a resection of each ray to determine the (x, y) image point location on the original film. This image point (x, y) location can then be related (through the fiducials) to the corresponding color of the pixel in the original scanned image at that point. This color is then transferred to the desired starting possition in the final ortho to paint the final ortho image. This process is repeated thousands of times over the extent of the site until the entire image is completed.

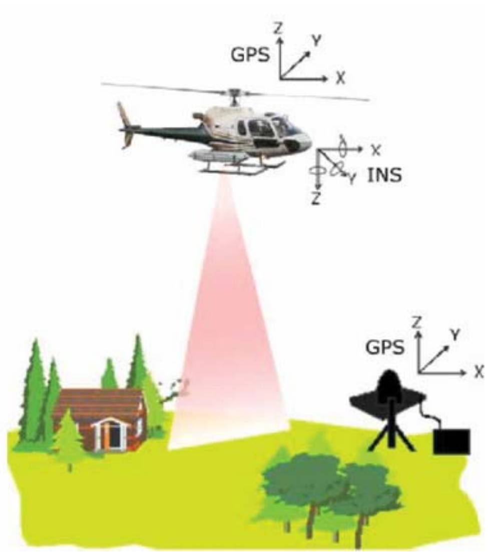
Orthophoto Geometry



In TIFF image format, a single color image will be approximately 500 mg in size and manageable on most software. On larger projects tiled TIFF images area prepared in a grid pattern to cover the project for easy local viewing and a compressed Mr. Sid image file is provided for overall project coverage. All images are geo-referenced to the ground survey system of the project.

Topographic Lidar Mapping

Lidar mapping is a method of gathering topographic DEM information from an airborne platform using a laser measuring system. The primary components of this system include an onboard GPS system, inertial measurement unit and the laser-measuring unit with scanning capabilities.



Data Collection

The GPS system is used to compute the positional component (x, y, z) of the laser unit at ½ second or 1 second intervals along a flight. The inertial measurement unit (IMU) records the attitude and heading or the translational components of the laser-measuring unit during flight. Finally the laser-measuring unit sends a laser pulse toward the earth and measures the distance from the unit to the ground.

The laser produces an optical pulse that is transmitted toward the earth, reflected off an object and returned to the receiver. The receiver measures the round trip travel time and can compute the distance for each pulse to the reflected object on the ground. The scanning from side to side along a flight line is accomplished using a highly calibrated rotating mirror system. This rotating mirror system changes the angle of incident that individual rays are sent thus allowing a scan width perpendicular to the flight.

The resultant accuracy of the final coordinate of the reflected object is dependent upon the obtainable accuracy of each component in this system. The laser measurement itself is highly accurate, a few millimeters, and is not a major contributor to the loss of accuracy in the overall system. It is rather the determination of the translational and rotational components of the airborne unit that is the major obstacle in refining the systems accuracy. With present technology the positional and translational characteristics of the onboard GPS and IMU systems allow the accuracy of data points to approach 1.5 to 2.5 feet horizontally and 0.5 foot vertically on individual returns.

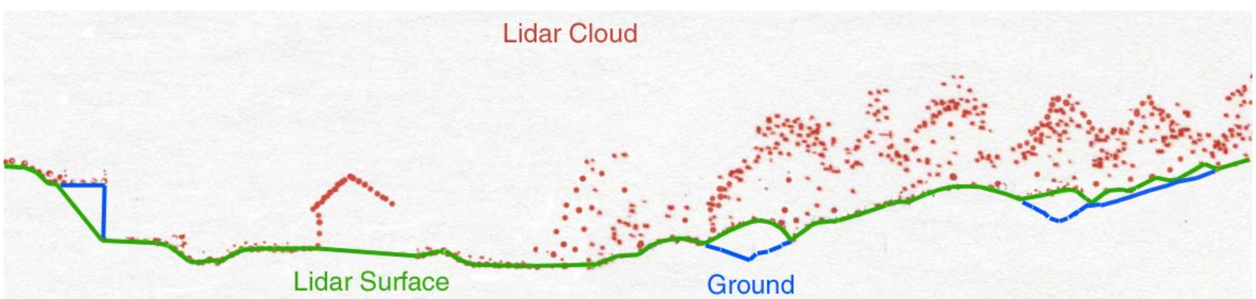
Data Reduction

When discussing topographic lidar mapping of the earth's surface, the data collection is but one phase in the process. Massive mounts of data reduction are required in the office once the data has been collected. The data just collected consists of a massive data cloud of points that have been returned off numerous objects that may or may not represent the ground surface. In all but cleared and open areas, these data points are an array of points with depth not unlike a massive bait ball in the ocean. It is the successful separation of the useful ground data from other cloud data that determines the accuracy of the resultant topographic map obtained by lidar.

Specialized software is employed to analyze the data cloud to extract unneeded data from the data set. Physical structures such as building bridges and other structures representing sharp angles are filtered in the processing procedure, as are all but the lowest points in the cloud data set in vegetated areas.

LIDAR CLOUD DATA

Lidar Cross Section



Brown ---- Lidar cloud
Green ---- Lidar interpreted surface
Blue ---- Earth Surface

The above cross-section shows a typical data set that may be obtained in a lidar data set. It is apparent that there are returns off the top buildings, trees, within trees as well as underling brush and finally some hits off the ground itself. The points at the bottom or lowest point of the cloud data set are referred to as last returns and are the data used to define the grounds surface. If the vegetation canopy is open enough a good sampling of the ground hits can be obtained. However, under dense vegetation there may not be sufficient points to accurately define the ground surface as none penetrate the ground cover.

Accuracy

The obtainable accuracy in measuring ground elevations throughout a site is then dependent on the density of actual returns being off the ground itself and not some overlying vegetation.

The inherent accuracy of the system on measuring any one point in a cloud may be two feet horizontally and one-half foot vertically. However, the question is, is the return off the ground's surface or an overlying feature.

Lidar suppliers provide accuracy statements based on vegetation types and ground slope, and these are realistic once we understand the meaning of the vegetation types being referred to. Typical statements may be worded as seen below:

hard surface and open regular terrain	+-.5 foot
light vegetated surfaces in flat rolling terrain	+-.8 foot
light vegetated surfaces in hilly rolling terrain	+1.5 foot
dense vegetation -second growth forests	Dependent on tree density

We have had several lidar projects performed in the Pacific Northwest under varying conditions. From these we have found that vegetation is the major obstacle in obtaining reliable lidar ground data, and to a lesser extent the airborne system. By analyzing these lidar data sets in different vegetation types we have developed a clearer understanding of the vegetation classifications listed above as they may pertain to ground conditions in the northwest. In each case we had reliable ground surface data to analyze the lidar data. In some cases this was from conventional ground test points, wetland surveys or photogrammetric mapping of subsequent logged off areas. The following is a summary of our findings.

Clear and open areas such as fields, roads and paved areas.
Standard error 0.5 foot
Range + 1 foot
Bell curve bias + 0.5 foot high

Leaf off data in typical northwest brush
Standard error 2.5 feet
Range +8'

Leaf off data in typical northwest deciduous trees and underbrush
Standard error 2.5 feet
Range + 10'

Deciduous forested areas with leaf on deciduous tree conditions
No complete analysis has been made however errors in the range of 15' to 30' above ground are not uncommon

Dense conifer forested second growth trees.
No complete analysis has been made however errors in the range of 15' to 30' above ground are not uncommon

It is the author's conclusion in vegetated areas, often the accepted last return data is, in fact, made up of both ground points as well as some points from overlying vegetation. Where vegetation is dense, the sparser are the actual ground hits and more above ground returns are accepted as last returns in the final data set. As such the normal lidar model normaly depicts either the true ground surface or an elevated surface in areas of poor penetration.

In general we have found that lidar data is very reliable on open and lightly vegetated areas and only minimal field checking is required. However, in densely vegetated brush areas we have found that false hummocks or unusual knobs appear in data sets for flatter areas. We have also found that in densely forested areas drains or low spots may be lost to the lidar data from lack of penetration. Under these conditions ground surveys and checks are required to assure an accurate map.

If additional information is desired regarding the digital mapping techniques described above please contact our office at 425-828-4448, or a copy of this paper may be downloaded from our web site at http://www.dammaps.com.

Thank You!

Gerrie E. DeGross P.L.S.
Photogrammetric Consultant

DeGross Aerial Mapping Inc.
18623 Beardslee Boulevard
Bothell, WA 98011
425-828-4448
425-828-4446 fax
gerrie@dammaps.com