Chapter 19.
Terrestrial and Close-Range Photogrammetry

19-1. Introduction

- Terrestrial photogrammetry is an important branch of the science of photogrammetry
- It deals with photographs taken with cameras located on the surface of the earth
- The cameras may be handheld, mounted on tripods, or suspended from towers or other specially designed mounts
- The term *close-range photogrammetry* is generally <u>used for terrestrial photographs having object distances up to about 300 m</u>
- With terrestrial photography the cameras are usually accessible, so that direct measurements can be made to obtain exposure station positions, similar to airborne GPS control with aerial photography
- With some terrestrial cameras, angular orientation can also be measured or set to fixed values, so that all elements of exterior orientation of a terrestrial photo are commonly known and need not be calculated
- These known exterior orientation parameters are a source of control for terrestrial photos, replacing in whole or in part the necessity for locating control points in the object space

19-1. Introduction

- Terrestrial photography may be *static* (photos of stationary objects) or *dynamic* (photos of moving objects)
- For static photography, slow, fine-grained, high resolution films may be used and the pictures taken with long exposure times
- Stereopairs can be obtained by using a single camera and making exposures at both ends of a baseline
- In taking dynamic terrestrial photos, fast films and rapid shutter speeds are necessary
- If stereopairs of dynamic occurrences are required, two cameras located at the ends of a baseline must make simultaneous exposures

19-2. Applications of Terrestrial and Close-Range Photogrammetry

- Historically the science of photogrammetry had its beginning with terrestrial photography, and topographic mapping was among its early applications
- Terrestrial photos were found especially useful for mapping rugged terrain which was difficult to map by conventional field-surveying methods
- Although it was known that topographic mapping could be done more conveniently using aerial photos, no practical method was available for taking aerial photographs until the airplane was invented
- Following the invention of the airplane, emphasis in topographic mapping shifted from terrestrial to aerial methods
- Terrestrial photogrammetry is still used in topographic mapping, but its application is usually limited to small areas and special situations such as deep gorges or rugged mountains that are difficult to map from aerial photography
- Other topographic applications of terrestrial photogrammetry are in mapping construction sites, areas of excavation, borrow pits, material stockpiles, etc

19-2. Applications of Terrestrial and Close-Range Photogrammetry

- Through the years terrestrial photogrammetry has continued to gain prominence in numerous diversified nontopographic applications
- Examples of nontopographic applications occur in such areas as aircraft manufacture, shipbuilding, telecommunications, robotics, forestry, archaeology, anthropology, architecture, geology, engineering, mining, nuclear industry, criminology, oceanography, medicine, dentistry, and many more
- In the field of medicine, Xray photogrammetry has been utilized advantageously for measuring sizes and shapes of body parts, recording tumor growth, studying the development of fetuses, locating foreign objects within the body, etc

19-2. Applications of Terrestrial and Close-Range Photogrammetry

- Figure 19-1 illustrates an application of close-range photogrammetry to antenna design
- In this figure, close-range photographs are taken of a parabolic radio antenna
- Coordinates of points on the antenna were computed to verify its dimensional integrity of the rocket system
- Figure 19-2 demonstrates the use of close-range photogrammetry to determine the dimensions of a ship's propeller
  - In this application, the propeller's size and shape were determined so that a replacement could be fabricated with the correct dimensions

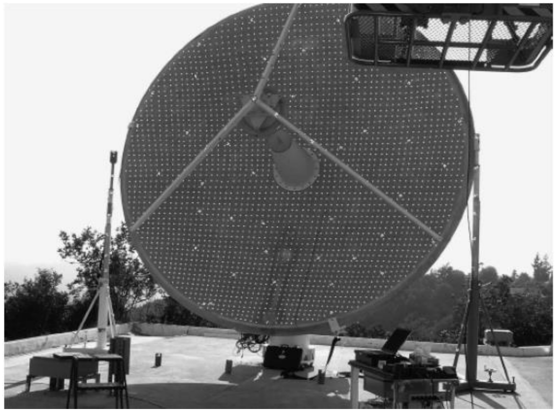


Figure 19–1. Application of close-range photogrammetry to the determination of the precise shape of a parabolic antenna. Note the artificial targets (white dots) placed on the structure. (Courtesy Geodetic Systems, Inc.)

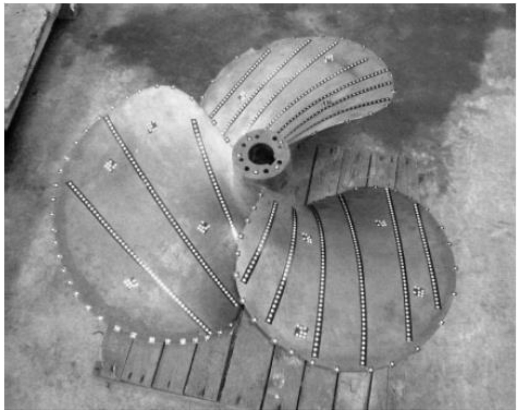


Figure 19–2. Application of close-range photogrammetry for determining the size and shape of ship's propeller. Note the artificial targets (white dots) placed on the structure. (Courtesy Geodetic Systems, Inc.)

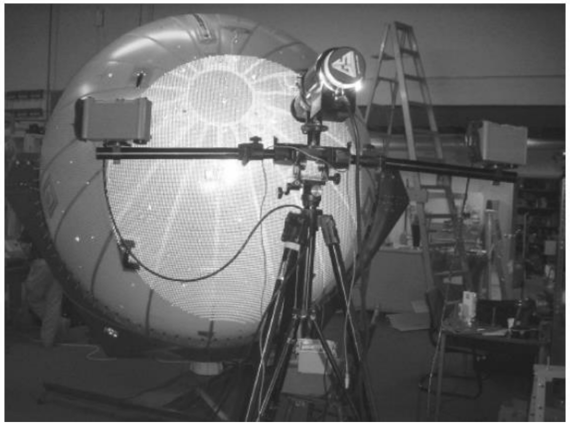
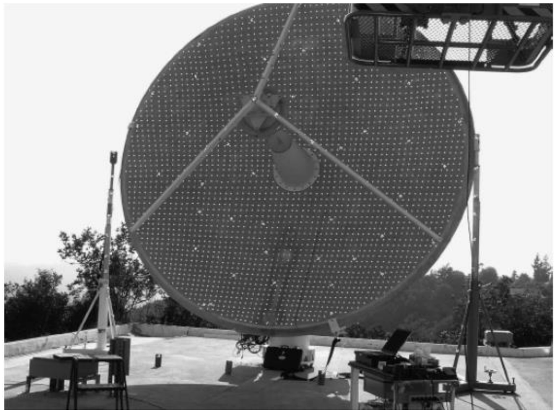


Figure 19–3. Application of close-range photogrammetry to determine the size and shape of an inflatable antenna. (Courtesy Geodetic Systems, Inc.)

19-2. Applications of Terrestrial and Close-Range Photogrammetry

- Figure 19-3 illustrates the use of close-range photogrammetry to determine the shape of an inflatable antenna
  - This information was used to verify the size and shape of the antenna after inflation
- Note that a projector is being used to produce the white dots needed to define the surface
- In addition, the use of two synchronized cameras allows three-dimensional measurement of dynamic objects



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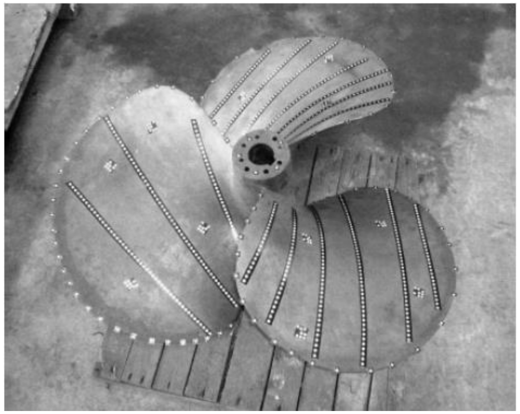

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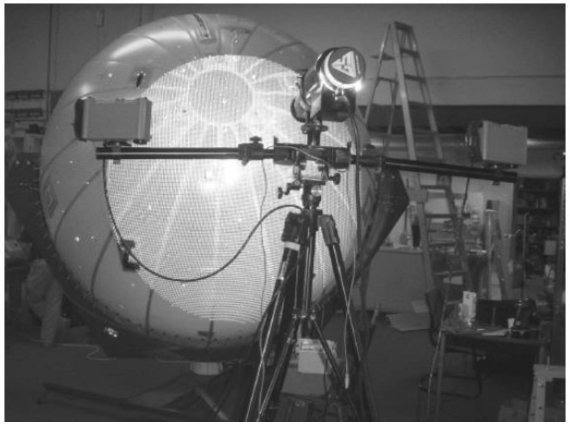

Figure 19–3. Application of close-range photogrammetry to determine the size and shape of an inflatable antenna. (Courtesy Geodetic Systems, Inc.)

19-2. Applications of Terrestrial and Close-Range Photogrammetry

- Terrestrial photogrammetry has been used to great advantage as a reliable means of investigating traffic accidents
- Photos that provide all information necessary to reconstruct the accident may be rapidly obtained
- Time-consuming sketches and ground measurements, which all too often are erroneous, are not needed, and normal traffic flow can be restored more quickly
- Terrestrial photogrammetry has become a very useful tool in many areas of scientific and engineering research for several reasons
- It makes possible measurements of objects which are inaccessible for direct measurement
- In some experiments, physical contact during measurement would upset the experiment and render it inaccurate
- Cameras which freeze the action at a particular instant of time make possible measurements of dynamic events such as deflections of beams under impact loads
- Because of the many advantages and conveniences offered by terrestrial photogrammetry, its importance in the future seems assured

19-3. Terrestrial Cameras

❖ A variety of cameras are used in terrestrial photography

❖ All fall into one of two general classifications: *metric* or *nonmetric*

❖ The term ***metric camera*** includes those cameras manufactured expressly for photogrammetric applications

❖ They have fiducial marks built into their focal planes, or have calibrated CCD arrays, which enable accurate recovery of their principal points

Figure 19-4. Dynamo close-range camera (bottom) with strobe attachment (top). (Courtesy Geodetic Systems, Inc.)

❖ Metric cameras are stably constructed and completely calibrated before use

❖ Their calibration values for focal length, principal- point coordinates, and lens distortions can be applied with confidence over long periods

❖ The Dynamo camera of Fig. 19-4 is a digital camera that is generally used as one of a synchronized pair, which can capture simultaneous images necessary for dynamic applications

19-3. Terrestrial Cameras

Figure 19–5. The INCA3 digital close–range camera. (Courtesy Geodetic Systems, Inc.)

- The INCA3 (Intelligent Digital Camera) of Fig. 19-5 is a digital terrestrial camera which is also used primarily for industrial applications
- This camera uses a CCD array having a either a 2029 × 2044 or 3500 × 2300 pixel format, with each pixel having a 12-bit gray level
- The camera's angular field of view is 77° × 56° with a 21 mm lens
- Images are recorded on a flash memory card or directly transferred to a computer in real-time
- Accuracies of better than 1 part in 200,000 of the object size can be achieved with this camera

19-3. Terrestrial Cameras

- *Phototheodolites* and *stereometric* cameras are two special types of terrestrial camera systems in the metric classification
- A **phototheodolite** incorporates a metric camera with a surveyor's theodolite
  - ⇨ Precise establishment of the direction of the optical axis can be made
- A **stereometric** camera system consists of two identical metric cameras which are mounted at the ends of a bar of known length
- The optical axes of the cameras are oriented perpendicular to the bar and parallel with each other
- The length of the bar provides a known baseline length between the cameras, which is important for controlling scale
- Nonmetric cameras are manufactured for amateur or professional photography where pictorial quality is important but geometric accuracy requirements are generally not considered paramount
  - ⇨ These cameras do not contain fiducial marks, but they can be modified to include them
- Nonmetric cameras can be calibrated and used with satisfactory results for many terrestrial photogrammetric applications

19-4. Matrix Equations for Analytical Self-Calibration

- The effects of distortion parameters must be accounted for in order to make precise photogrammetric measurements
- When using metric cameras, this is not of great concern due to the stability of the parameters over long intervals of time
  - Although they should be calibrated periodically based on the manufacturer's recommendation
- On the other hand, nonmetric cameras cannot be expected to maintain stable calibration parameters even between sessions
- In many cases, however, nonmetric cameras can provide very accurate results when using *analytical self-calibration*

19-4. Matrix Equations for Analytical Self-Calibration

- Analytical self-calibration is a computational process wherein camera calibration parameters are included as unknowns in the photogrammetric solution, generally in a combined interior-relative-absolute orientation referred to as a *self-calibrating bundle adjustment*
  - This process can be used for both aerial and terrestrial photos
- The data acquired during a mission can be used to calibrate the camera
  - This case ensures that the solved calibration parameters represent the interior orientation of the camera at the time of exposure of the photographs
- Alternatively, a **specially-designed calibration pattern with optimally configured three-dimensional control points** can be used in conjunction with photography taken with optimally-oriented camera exposure stations
  - In this case, more precise estimates of the parameters can be obtained due to the favorable geometry
- However, there is no guarantee that they will be the same when the camera is used during the mission due to internal movement of the mechanical elements of the camera in the time between calibration and acquisition

19-4. Matrix Equations for Analytical Self-Calibration

- The process of **analytical self-calibration** uses **collinearity equations** that have been augmented with additional terms to account for adjustment of the calibrated focal length, principal-point offsets, and symmetric radial and decentering lens distortions
- In addition, the equations might include corrections for atmospheric refraction
- The classic form of the augmented collinearity equations is shown in Eq. (19-1)
- The model presented here is valid for both film and digital photos

$$
\begin{aligned}
x_a &= x_0 - \bar{x}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3 r_a^2\right)\left[p_1\left(2\bar{x}_a^2 + r_a^2\right) + 2p_2\bar{x}_a\bar{y}_a\right] - f\frac{r}{q} \\
y_a &= y_0 - \bar{y}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3 r_a^2\right)\left[2p_1\bar{x}_a\bar{y}_a + p_2\left(2\bar{y}_a^2 + r_a^2\right)\right] - f\frac{s}{q}
\end{aligned}
\qquad (19\text{-}1)
$$

where

x_a, y_a = measured photo coordinates related to fiducials
x_0, y_0 = coordinates of the principal point
$\bar{x}_a = x_a - x_0$
$\bar{y}_a = y_a - y_0$
$r_a^2 = \bar{x}_a^2 + \bar{y}_a^2$
k_1, k_2, k_3 = symmetric radial lens distortion coefficients
p_1, p_2, p_3 = decentering distortion coefficients
f = calibrated focal length
r, s, q = collinearity equation terms as defined in Eqs. (D-11) and (D-12)

19-4. Matrix Equations for Analytical Self-Calibration

- The interior orientation parameters x_0, $y_0, f, k_1, k_2, k_3, p_1, p_2$ and p_3, which appear in Eq. (19-1) are included as unknowns in the solution, together with $\omega, \phi, \kappa, X_L, Y_L,$ and Z_L for each photo and $X_A, Y_A,$ and Z_A for each object point
- These equations are nonlinear, therefore Taylor's series is used to linearize them, and an iterative solution is made
- The matrix form of the linearized augmented collinearity equations is shown in Eq. (19-2)

$$\dot{B}_{ij}\dot{\Delta}_i + \ddot{B}_{ij}\ddot{\Delta}_i + \dddot{B}_{ij}\dddot{\Delta} = \varepsilon_{ij} + V_{ij} \qquad (19\text{-}2)$$

where

$$\dddot{B}_{ij} = \begin{bmatrix} b_{1,7} & b_{1,8} & b_{1,9} & b_{1,10} & b_{1,11} & b_{1,12} & b_{1,13} & b_{1,14} & b_{1,15} \\ b_{2,7} & b_{2,8} & b_{2,9} & b_{2,10} & b_{2,11} & b_{2,12} & b_{2,13} & b_{2,14} & b_{2,15} \end{bmatrix}$$

$$\dddot{\Delta} = \begin{bmatrix} d_{x_0} \\ d_{y_0} \\ d_{k_1} \\ d_{k_2} \\ d_{k_3} \\ d_{p_1} \\ d_{p_2} \\ d_{p_3} \\ d_f \end{bmatrix}$$

19-4. Matrix Equations for Analytical Self-Calibration

$$x_a = x_0 - \bar{x}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3 r_a^2\right)\left[p_1\left(2\bar{x}_a^2 + r_a^2\right) + 2p_2 \bar{x}_a \bar{y}_a\right] - f\frac{r}{q}$$
$$y_a = y_0 - \bar{y}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3 r_a^2\right)\left[2p_1 \bar{x}_a \bar{y}_a + p_2\left(2\bar{y}_a^2 + r_a^2\right)\right] - f\frac{s}{q} \qquad (19\text{-}1)$$

- Matrix $\ddot{B}_{ij}$ contains the partial derivatives of Eq. (19-1) with respect to the camera calibration parameters evaluated at the initial approximations
- Matrix $\dddot{\Delta}$ contains the corrections for the initial approximations of the camera calibration parameters

$$\dot{B}_{ij}\dot{\Delta}_i + \ddot{B}_{ij}\ddot{\Delta}_j = \varepsilon_{ij} + V_{ij} \qquad (17\text{-}4)$$

- The matrices $\dot{B}_{ij}, \ddot{B}_{ij}, \dot{\Delta}_i, \ddot{\Delta}_j, \varepsilon_{ij}$ and V_{ij} are the same as those in Eq. (17-4), with the exception that matrices ε_{ij} and V_{ij} are computed using the augmented collinearity equations
- Weighted observations of the calibration parameters can be included in a similar way as ground control points and aerial control are, by including the observation equations shown in matrix form in Eq. (19-3)

$$\dddot{\Delta} = \dddot{C} + \dddot{V} \qquad (19\text{-}3)$$

19-4. Matrix Equations for Analytical Self-Calibration

- Normally, direct observations of the calibration parameters are not made; however, weighting provides a method of constraining them, which in some cases is necessary to produce a convergent solution

- The partitioned normal equations for a bundle adjustment with analytical self-calibration are shown in matrix form in Eq. (19-4)

$$\begin{bmatrix} \dot{N} & \bar{N} & \tilde{N} \\ \bar{N}^T & \ddot{N} & \hat{N} \\ \tilde{N}^T & \hat{N}^T & \dddot{N} \end{bmatrix} \begin{bmatrix} \dot{\Delta} \\ \ddot{\Delta} \\ \dddot{\Delta} \end{bmatrix} = \begin{bmatrix} \dot{K} \\ \ddot{K} \\ \dddot{K} \end{bmatrix} \qquad (19\text{-}4)$$

$$\begin{bmatrix} \dot{N} & \bar{N} \\ \bar{N}^T & \ddot{N} \end{bmatrix} \begin{bmatrix} \dot{\Delta} \\ \ddot{\Delta} \end{bmatrix} = \begin{bmatrix} \dot{K} \\ \ddot{K} \end{bmatrix} \qquad (17\text{-}26)$$

- Equation (19-4) is the same as the partitioned normal equations shown in Eq. (17-26), except with the following added terms:

$$\tilde{N} = \begin{bmatrix} \tilde{N}_1 \\ \tilde{N}_2 \\ \tilde{N}_3 \\ \vdots \\ \tilde{N}_m \end{bmatrix} \quad \text{where} \quad \tilde{N}_i = \sum_{j=1}^{n} \dot{B}_{ij}^T W_{ij} \dddot{B}_{ij}$$

$$\hat{N} = \begin{bmatrix} \hat{N}_1 \\ \hat{N}_2 \\ \hat{N}_3 \\ \vdots \\ \hat{N}_n \end{bmatrix} \quad \text{where} \quad \hat{N}_j = \sum_{i=1}^{m} \ddot{B}_{ij}^T W_{ij} \dddot{B}_{ij}$$

$$\dddot{N} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \dddot{B}_{ij}^T W_{ij} \dddot{B}_{ij} \right) + \dddot{W}$$

$$\dddot{K} = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \dddot{B}_{ij}^T W_{ij} \varepsilon_{ij} \right) + \dddot{W}\dddot{C}$$

19-4. Matrix Equations for Analytical Self-Calibration

❖ With the inclusion of the extra unknowns, it follows that additional independent equations will be needed to obtain a solution

➪ In addition, the numerical stability of analytical self-calibration is of serious concern

❖ It is necessary to have special constraints and/or geometric configurations to ensure a stable solution

❖ For example, with nominally vertical aerial photography if the object points are at roughly the same elevation, then $x_0, y_0,$ and f are strongly correlated with $X_L, Y_L,$ and Z_L

❖ Similarly, nominally horizontal terrestrial photography of a wall taken with the focal plane of the camera parallel to the surface of the wall results in f and x_0 being correlated with X_L and Y_L, and y_0 being correlated with Z_L

➪ Given these correlations, the solution may not produce satisfactory results

❖ This problem can be overcome or at least alleviated if there is significant variation in the depth of the object field with respect to the camera, by using highly convergent photography, by making observations of the camera position and/or attitude, or by using photos with varying rotations about the optic axis of the camera.

19-4. Matrix Equations for Analytical Self-Calibration

- In addition, to recover the lens distortion parameters accurately, it is necessary to have many redundant object points whose images are well distributed across the format of the composite of all photographs
- In other words, the combined images of objects points from all photographs should be distributed over the extents of the format
- For example, one photo may have image points only on the left half of the format and another photo may have points only on the right half of the format, but taken as a composite, images have been distributed across the extents of the format

19-5. Initial Approximations for Least Squares Adjustment

- As mentioned in the previous section, initial approximations of all unknown parameters are required for a least squares adjustment when using linearized observation equations

- Thus, one must have sufficient preliminary estimates of the position and angular orientation of the camera stations ($\omega, \phi, \kappa, X_L, Y_L,$ and Z_L), object space coordinates of all imaged points ($X_A, Y_A,$ and Z_A), and values of all camera calibration parameters (x_0, y_0, f, k_1, k_2, k_3, p_1, p_2 and p_3) prior to implementation

- Obtaining initial approximations for terrestrial photography can be much more difficult than for aerial photography

- This not only stems from the inherent differences in geometry of the configurations, but also from the fact that in many close range and terrestrial applications, the photography was taken without the intention of using it for photogrammetry (e.g., historical photos and photos used for accident reconstruction)

- In these instances, the photographer likely did not note the position and angular orientation of the camera during exposure

- There are, however, both manual and automatic methods for obtaining initial approximations for terrestrial and close range photogrammetric adjustments

19-5. Initial Approximations for Least Squares Adjustment

- ❖ Manual methods can often provide adequate initial approximations when automation is not an option
- ❖ Perhaps the most complex unknowns to estimate manually prior to adjustment using terrestrial/close range photography are the exterior orientation angles $\omega, \phi,$ and κ
- ❖ For near-vertical aerial photos, these angles can easily be estimated with sufficient accuracy by using $\omega = \phi = 0°$, and estimating κ
- ❖ In terrestrial photography, however, there is no simple method for their estimation due to the non-intuitive values of ω, ϕ , and κ
- ❖ A method for estimating the exterior orientation angles manually are as follow:
  - ① First, they are estimated using the tilt-swing-azimuth system
  - ② Then they are converted to obtain ω, ϕ , and κ
    - ⇨ In fact, a bundle adjustment solution can be implemented using tilt, swing, and azimuth
    - ⇨ However, photogrammetric software typically uses the omega-phi-kappa convention
  - ③ As for the position of the camera, one can use the conditions of acquisition and scene in a photo to estimate the position from where it was taken

19-5. Initial Approximations for Least Squares Adjustment

- For example, if a person standing and holding the camera naturally took the photo, one can estimate the height of the camera above the ground as being slightly less than the height of the photographer
- Estimates of object space coordinates for exposure stations and tie points can be deduced by approximating their positions relative to points with known coordinates and their apparent positions based on the scenes
- That is, control points can be used to determine the orientation and scale of the object space imaged in the photo
- These can then be used to estimate the distance and direction from the control points to the tie points and exposure stations yielding their object space coordinates
- This procedure requires practice to become proficient at rapidly and reliably obtaining these approximations

19-5. Initial Approximations for Least Squares Adjustment

❖ Although manual methods are often reliable for small projects when performed with care, automatic methods are preferred when there are many photos involved

❖ There are several methods for automatic initialization, only two of which are presented

1) One method begins by using space resections to solve for the exterior orientation parameters of two images

   ➪ The exterior orientation parameters are then used to find the object space coordinates of tie points in the two images via space intersection

   ➪ The object space coordinates of these tie points are used to perform space resection for other photos in the project

   ➪ The resulting exterior orientation parameters can then be used in subsequent space intersections

   ➪ The process is repeated until initial approximations for all images and tie points are found

   ➪ This method requires at least four control points in at least two images for a least squares solution of the first space resections

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1) One method begins by using space resections to solve for the exterior orientation parameters of two images

   ⇨ In industrial applications, which are usually performed in laboratory environments with metric cameras, automatic initialization is often achieved using *exterior orientation devices*

   ⇨ These devices consist of a single apparatus with several targets on it that are used to define the object space coordinate system

Figure 19-6. The AutoBar exterior orientation device (Courtesy Geodetic Systems, Inc.)

❖ Figure 19-6 shows a five-target exterior orientation device

❖ The relative positions of the targets on the device are known to a very high degree of precision, and serve as control points for the initial space resections

19-5. Initial Approximations for Least Squares Adjustment

- Although manual methods are often reliable for small projects when performed with care, automatic methods are preferred when there are many photos involved

- There are several methods for automatic initialization, only two of which are presented

2) Another method, similar to the previous one, utilizes relative orientation, and does not require that the minimum number of control points be visible in a single photo
   - This method begins by first performing relative orientation between the pair of photos with the most favorable geometry
   - Next, space intersection is used to find the model space coordinates of all tie points in the two images
   - These model space coordinates are used in a space resection to find the exterior orientation parameters—relative to the model—of the third photo
   - The model space coordinates of the remaining tie points in the third image not used for space resection are found through space intersection
   - The process is repeated on all subsequent images until all the model space exterior orientation parameters and coordinates of all tie points are found

19-5. Initial Approximations for Least Squares Adjustment

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2) Another method, similar to the previous one, utilizes relative orientation, and does not require that the minimum number of control points be visible in a single photo

- Following this, a three dimensional conformal coordinate transformation from the model space to the (ground) control system is solved using control points and applied to the model space coordinates of the tie points and exposure stations, yielding their estimates
- Finally, the initial approximations for the exterior orientation angles can be found

19-5. Initial Approximations for Least Squares Adjustment

- If **collinearity** is used in the analytical relative orientation, initial approximations are needed for the relative orientation parameters and the coordinates of the tie points
- However, the use of **coplanarity** to perform analytical relative orientation can circumvent the need for initial approximations of tie point model coordinates since they are not used in that method, although approximations of the five relative exterior orientation parameters are still required
- Also, note that **initial approximations** are also required for space resection and space intersection
- There are known, reliable methods for automatically finding initial approximations for space resection and space intersection solutions
- However, **relative orientation** continues to be an active area of research with multiple *direct* and *search-based* methods described
- These methods are beyond the scope of this book and the reader is encouraged to consult the reference section for information on them

19-6. Solution Approach for Self-Calibration Adjustment

- Carrying out a self-calibrating bundle adjustment of terrestrial/close range photography can be a complicated task
- The approach is designed for a bundle adjustment program that has input consisting of pass point measurements, control point measurements, initial approximations, and a priori standard deviations of all observations and camera calibration parameters
- Typically, there are no direct observations of the camera calibration parameters
- However, treating them as observations allows one to constrain them in the adjustment by weighting
- Approximations for the focal length, f , can be determined using the camera manufacturer's specifications
- The remaining calibration parameters can be initialized at zero

19-6. Solution Approach for Self-Calibration Adjustment

- The **first step** of the approach is to adjust two photos
- The photos selected for this initial adjustment should be convergent with a large amount of overlap between them and a sufficient amount of control points
- Starting with two photos instead of attempting to adjust the entire set of photos reduces the chances of having multiple blunders, and therefore simplifies troubleshooting
- One can attempt to adjust the two images with the calibration parameters "loosened," giving them high a priori standard deviations, and thus allowing them to be solved in the adjustment
- However, this often leads to divergence due to a combination of insufficient distribution of tie points throughout the photos, homogeneous depth of field, inadequate redundancy, and poor geometric configuration (nonconvergence) of the photos
- In this case, the calibration parameters should be constrained by assigning them very small a priori standard deviations
- If the adjustment fails to converge with constrained parameters, check for blunders and make sure initial approximations are consistent

19-6. Solution Approach for Self-Calibration Adjustment

- Once the two-photo adjustment converges, check the pass point residuals to identify any blunders, remeasuring them if found
- Add photos one at a time, rerunning the adjustment and again checking for blunders with each addition
- Previously estimated initial approximations can be updated using their solved values after each adjustment
- This will speed up subsequent solutions by reducing the number of iterations required
- After many photos have been added to the adjustment, the calibration parameters can be loosened

19-6. Solution Approach for Self-Calibration Adjustment

- If the adjustment diverges when the calibration parameters are loosened, it is advisable to loosen only f and k_1 since they are almost always significant
- If this solution converges, one can then attempt to loosen x_0, y_0, and k_2, which are often significant
- The remaining parameters require high redundancy and very strong geometry for them to be resolved
- Due to their high correlation, it may be advisable to constrain p_1 and p_2 when x_0 and y_0 are loosened or vice-versa
- One should also check the significance of each of the calibration parameters after the adjustment
- This can be done by using a *t-test* of the significance of the adjusted parameter's departure from its initial approximation

19-6. Solution Approach for Self-Calibration Adjustment

- The formula for the t-statistic is in Eq. (19-5), where is one of the estimated calibration parameters (x_0, $y_0, f, k_1, k_2, k_3, p_1, p_2$ and p_3), a_0, is its initial approximation, and $s_{\hat{a}}$ is the estimated parameter's standard error which can be calculated using Eq. (17-16)

$$t_x = \frac{a_0 - \hat{a}}{s_{\hat{a}}} \qquad (19\text{-}5)$$

$$\Sigma_{\Delta\Delta} = S_0^2 \, N^{-1} \qquad (17\text{-}16)$$

- If a calibration parameter is not significantly different from its initial approximation given its degrees of freedom, it should be excluded from the adjustment

19-6. Solution Approach for Self-Calibration Adjustment

- The standard error of unit weight, S_0 should be close to one if all observations are properly weighted
- If S_0 is too high, then estimated a priori standard deviations are too low and should be increased
- If S_0 is too high, then estimated a priori standard deviations are too high, and should be decreased
- A chi-squared can be used to test whether or not S is significantly different than 1 by using the formula in Eq. (19-6)
- In Eq. (19-6), r is the degrees of freedom, and $\sigma^2 = 1$

$$\chi^2 = \frac{rS_0^2}{\sigma^2} \qquad (19\text{-}6)$$

- Description of the t-test, chi-squared test, and their associated tables can be found in most introductory statistics textbooks

19-7. Control for Terrestrial Photogrammetry

- In **terrestrial photogrammetry**, the object space is often relatively close to the camera
- **Object distances** vary from a few centimeters up to 300 m or more, and the objects photographed vary in size from articles as small as human teeth and smaller, to very large buildings or ships
- In any case, if accurate maps are to be made of photographed objects, control will be required
- There are basically four different methods of establishing control in terrestrial photogrammetry :
  (1) imposing the control on the camera by measuring its position and orientation with respect to a coordinate system or with respect to the photographed object
  (2) locating control points in the object space in a manner similar to locating control for aerial photography
  (3) combining camera control and object space control points
  (4) using a free-network adjustment with scale control only

19-7. Control for Terrestrial Photogrammetry

- In the first method, no control points need appear in the object space
- Rather, the position and orientation of the camera or cameras are measured with respect to the object itself
- If a planar object is being photographed from a single camera station, control requirements may be satisfied by measuring the distance from the camera to the plane surface and orienting the camera optical axis perpendicular to the surface
- Perpendicular orientation can be accomplished by mounting a plane-surfaced mirror parallel to the object plane and then moving the camera about until the reflection of the camera lens occupies the center of the field of view
- If the camera focal length is known, a complete planimetric survey of the object can then be made

19-7. Control for Terrestrial Photogrammetry

- If stereopairs of photos are taken, the control survey can consist of measuring the horizontal distance and difference in elevation between the two camera stations and also determining the orientations of the camera optical axis for each photo
- Phototheodolites enable a complete determination of camera orientation and direction of optical axis
- Stereometric cameras automatically provide control by virtue of their known baseline length and parallel optical axes
- In exposing stereopairs with less elaborate cameras, horizontal orientation can be enforced by using level vials or tilt sensors, and parallel orientation of the camera axes can be accomplished by reflection from parallel mirrors

19-7. Control for Terrestrial Photogrammetry

- In the second method of controlling terrestrial photos, points should be selected in the object space which provide sharp and distinct images in favorable locations in the photographs
- Their positions in the object space should then be carefully measured
- If no satisfactory natural points can be found in the object space, artificial targets may be required
- Targets should be designed so that their images appear sharp and distinct in the photos
- White crosses on black cards may prove satisfactory
- If the object space is small and the control points are close together, measurements for locating the targets may be made directly by means of graduated scales
- If the object space is quite large or if the control points are inaccessible for direct measurement, triangulation with precise theodolites set up at the ends of a carefully measured baseline may be necessary
- In some cases a premeasured grid pattern may be placed in the object space and photographed along with the object, thereby affording control

19-7. Control for Terrestrial Photogrammetry

- If the object being photographed is stationary, control points may be located on the object
- Corners of window frames, for example, may be used if a building is being photographed
- If a dynamic event is being photographed at increments of time, for example, photographing beam deflections under various loads, then targets may have to be mounted on some stationary framework apart from the object
- By means of surveyor's levels, targets may be set at equal elevations, thereby providing a horizontal line in the object space
- Vertical lines may be easily established by hanging plumb bobs in the object space and attaching targets to the string
- The third method of controlling terrestrial photography is <u>a combination of the first two methods</u>
- This third approach is generally <u>regarded as prudent</u> because it provides redundancy in the control, which prevents mistakes from going undetected and also enables increased accuracy to be obtained

19-7. Control for Terrestrial Photogrammetry

- The fourth control method uses an arbitrary coordinate system, with the scale of the model being defined through one or more known lengths that appear in the object space
- The known lengths may be based upon distance measurements made between target points on the object
- By placing one or more scale bars in proximity to the object, photo coordinate measurements can be made on the images of the ends of the bar, thus including the scale bar in the three-dimensional model of the object space
- By constraining the distances between these endpoints to their known values, the scale of the overall object will be established
- The arbitrary coordinate system can be established by either setting the position and angular attitude of one of the exposures to some nominal set of values (say, $\omega = \phi = \kappa = X_L = Y_L = Z_L = 0$) or through the use of an exterior orientation device
- The remaining exposures and/or object points will then be determined relative to this set of defined values
- After all coordinates have been obtained, a three-dimensional conformal coordinate transformation can be used to relate the arbitrary system to any desired frame of reference

19-8. Analytical Self-Calibration Example

Figure 19–7. Photo 4 used in the adjustment

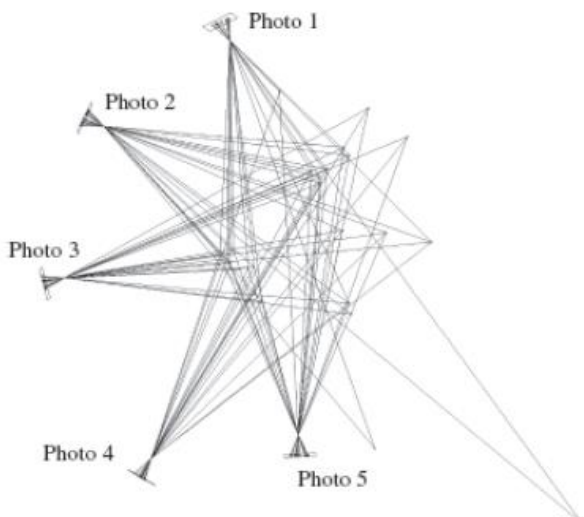

Figure 19–8. Graphical representation in plan view of the block of photos used in the example with 93 light rays representing the measured photo coordinate pairs.

- ❖ This section describes a **self-calibration example using close-range terrestrial photography**
- ❖ The block included five photos taken with an off-the-shelf digital SLR camera, and one of the photos used is shown in Fig. 19-7
- ❖ There were 23 unique feature points used to generate 93 photo-coordinate pairs
- ❖ One vertical control point and two three-dimensional control points were obtained using traditional field surveying techniques
- ❖ The block is illustrated in Fig. 19-8
- ❖ Photos 1 and 5 were about 20 m away from each other

19-8. Analytical Self-Calibration Example

- Notice the convergent photography and varying depth of field leading to strong geometry for the adjustment
- The focal length, f, was estimated using the manufacturer's specifications
- In order to obtain pass points in millimeters—the units of f —the images were scaled and placed in a computer-drafting program, wherein the photo measurements were made, such that the ratio of focal length to format was nominally correct and the center of the photo was at the coordinate system origin
- The rest of the camera calibration parameters were initialized at zero
- Since the focal length was 7.1 mm and the equivalent focal length for 35 mm film is 28 mm, the equivalent format is 8.8 mm: $\frac{7.1mm}{28mm}35mm = 8.8mm$

19-8. Analytical Self-Calibration Example

$$\frac{7.1mm}{28mm} 35mm = 8.8mm$$

- Note that the above formula is purely based on **manufacturer's specifications**, and that the calibrated focal length is based on the photo measurements made on scaled photos
- Thus the adjustment-resolved f , along with the other camera calibration parameters, is not the true physical focal length of the camera
- However, this does not affect the adjusted object space coordinates of points since the calibration parameters are restricted to the image-space components of the collinearity equations
- That is, the **adjusted object space parameters** are related only to the object space observations, which are the control points in this example
- The initial approximations for the ground coordinates of pass points and exterior orientation parameters of the camera stations were found using manual methods

19-8. Analytical Self-Calibration Example

- On the first execution of the adjustment, the calibration parameters were constrained by giving the initial approximations very small standard deviations to help ensure convergence
- The selected values for input and the output are shown in Table 19-1 and Table 19-2, respectively where σ_x and σ_y are the a priori standard deviations of the photo-coordinate measurements, and $\bar{\alpha}_X, \bar{\alpha}_Y$ and $\bar{\alpha}_Z$ are the average adjusted ground coordinate standard deviations

Table 19–1. Selected Input Parameters of the First Adjustment with All Camera Calibration Parameters Constrained

Parameter	Value
f	Constrained
x_0	Constrained
y_0	Constrained
k_1	Constrained
k_2	Constrained
k_3	Constrained
p_1	Constrained
p_2	Constrained
σ_x, σ_y	0.005 mm

Table 19–2. Selected Output values of the First Adjustment with All Camera Calibration Parameters Constrained

Output	Value
S_0	1.49
$\bar{\sigma}_X$	0.026 m
$\bar{\sigma}_Y$	0.028 m
$\bar{\sigma}_Z$	0.011 m

19-8. Analytical Self-Calibration Example

- Since the adjustment converged and there were no detectable blunders, the calibration parameters were loosened by effectively giving the initial approximations zero weight, allowing them to be adjusted
- The selected input and output are shown in Tables 19-3 and 19-4

Table 19–3. Selected Input Parameters of the Second Adjustment with All Camera Calibration Parameters Loosened

Parameter	Value
f	Loosened
x_0	Loosened
y_0	Loosened
k_1	Loosened
k_2	Loosened
k_3	Loosened
p_1	Loosened
p^2	Loosened
σ_x, σ_y	0.005 mm

Table 19–4. Selected Output values of the Second Adjustment with All Camera Calibration Parameters Loosened

Output	Value
S_0	0.41
$\bar{\sigma}_X$	0.016 m
$\bar{\sigma}_Y$	0.018 m
$\bar{\sigma}_Z$	0.005 m

19-8. Analytical Self-Calibration Example

- Notice in Table 19-4 that the adjusted object space coordinate standard deviations, $\bar{\sigma}_X, \bar{\sigma}_Y$ and $\bar{\sigma}_Z$ indicate more precise results than when the calibration parameters were constrained
- Also, note that the standard error of unit weight, S_0, is lower than one indicating that the a priori standard deviations of the photo coordinate measurements were overly pessimistic. The t-statistics for the solved calibration parameters are shown in Table 19-5
- The values revealed that y_0, p_1, and p_2, and were not resolved such that their value was significantly different than their initial approximations at the 90 percent confidence level

Table 19−5. T−Statistics for the Second Adjustment with All Camera Calibration Parameters Loosened

Parameter	t-Statistic
x	2.34
x_0	2.22
y_0	1.08
k_1	2.23
k_2	2.09
k_3	2.43
p_1	1.27
p_2	0.53

- This is due to insufficient redundancy and perhaps geometry of the photography to properly model these distortions

19-8. Analytical Self-Calibration Example

- Following an adjustment where y_0, p_1, and p_2 were removed from the adjustment by constraining their values to zero, it was found that k_2 was also not significant at the 90 percent confidence level with a t-statistic of 0.78

- Its higher t-statistic in the second adjustment may have stemmed from correlation with, and compensation for, the three other insignificant parameters

Table 19–5. T–Statistics for the Second Adjustment with All Camera Calibration Parameters Loosened

Parameter	t-Statistic
x	2.34
x_0	2.22
y_0	1.08
k_1	2.23
k_2	2.09
k_3	2.43
p_1	1.27
p_2	0.53

19-8. Analytical Self-Calibration Example

- The final adjustment used the selected input parameters shown in Table 19-6
- The insignificant calibration parameters were constrained and the a priori photo-coordinate standard deviations were lowered as shown in Table 19-7

Table 19–6. Selected Input Parameters of the Final Adjustment

Parameter	Value
f	Loosened
x_0	Loosened
y_0	Constrained
k_1	Loosened
k_2	Constrained
k_3	Loosened
p_1	Constrained
p_2	Constrained
σ_x, σ_y	0.002 mm

Table 19–7. Selected Output of the Final Adjustment

Output	Value
S_0	1.07
$\bar{\sigma}_X$	0.008 m
$\bar{\sigma}_Y$	0.009 m
$\bar{\sigma}_Z$	0.004 m

19-8. Analytical Self-Calibration Example

- A chi-squared test on S_0 indicated that the a priori photo coordinate standard deviations are appropriate since its value is not significantly different from one with 95 percent confidence
- Notice that the adjusted ground coordinates of the points had horizontal standard deviations roughly half of those for the second adjustment
- This shows the effect that overparameterization can have on the adjustment solution
- Finally, the t-statistics in Table 19-8 confirm that the adjustable camera calibration parameters were significantly resolved

Table 19-8. T-Statistics for the Final Adjustment with All Camera Calibration Parameters Loosened

Parameter	**t-Statistic**
f	2.88
x_0	3.87
k_1	22.00
k_3	3.85

19-8. Analytical Self-Calibration Example

- Note that, unlike in aerial adjustments, the X and Y components of the ground coordinates are more weakly resolved than the Z component
- This is a result of the different geometry of the terrestrial/close range configuration
- The mostly horizontal direction of the light rays leads to weaker triangulation on the horizontal components relative to vertical
- That is, errors in the image measurements lead to errors in the best estimate of the position of the intersection of rays more in the horizontal direction than the vertical

Table 19–8. T–Statistics for the Final Adjustment with All Camera Calibration Parameters Loosened

Parameter	t-Statistic
f	2.88
x_0	3.87
k_1	22.00
k_3	3.85

19-9. Planning for Close-Range Photogrammetry

- In some cases, close-range photogrammetric analyses are done with existing amateur photography
- For example, a police officer may have taken photographs of the scene of a vehicle accident, and subsequent photogrammetric analysis may be needed to determine the positions of the vehicles, tire marks, and other evidence
- Such photography may not be ideally exposed, well focused, or generally in an optimal geometric configuration for photogrammetric analysis
- On the other hand, under controlled situations (e.g., industrial applications), preliminary planning can be performed so as to control such factors as type of camera, lighting, and camera orientation

19-9. Planning for Close-Range Photogrammetry

- Three main considerations for pictorial quality are **resolution**, **depth of field**, and **exposure**
- Whether one is using digital or film cameras, **resolution** is important in that all points of interest must be clearly visible on the resulting image
- A preliminary assessment should be made to ensure that the resolution is sufficient to adequately capture the smallest necessary details
- **Depth of field** is particularly important for ensuring proper focus
- In close-range photogrammetry, since object depth is typically of significant size relative to the distance from the camera, a large f -stop setting may be required to ensure that the entire object is in focus
- Proper **exposure** is necessary for the image points being measured to have sufficient contrast and definition
- Particular attention should be paid to avoiding shadows on the object, especially when a flash is used for illumination

19-9. Planning for Close-Range Photogrammetry

- In some cases, special **retro-reflective targets** may be attached to points of interest prior to exposing the photographs
  - This allows the photographer to underexpose the background, with the targets remaining clear and bright
- There are also some **physical constraints** which must be considered in planning close-range photography
- A number of different camera locations may need to be considered in order to meet this constraint
- In many applications, objects may be enclosed in confined spaces which makes effective determination of camera positions more difficult
- An important geometric consideration for close-range photography is the angular orientation of the camera exposure stations
- Accuracy of the analytical solution depends, to a large extent, upon the angles of intersection between rays of light
- The highest overall accuracy will be achieved when angles of intersection are near 90°.

19-9. Planning for Close-Range Photogrammetry

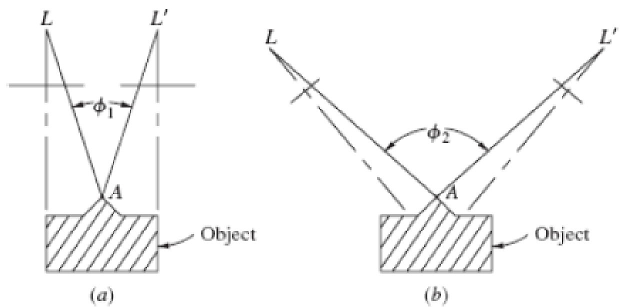

Table 19–9. (a) Close–range stereo coverage of an object with parallel camera axes. (b) Close–range stereo coverage with convergent photography.

- ❖ Figure 19-9a illustrates stereo photographic coverage of an object where the camera axes are parallel
- ❖ In this figure, the parallactic angle f_1 to object point A is approximately 35°
- ❖ In Fig. 19-9b, stereo coverage of the same object is obtained from convergent photos
- ❖ In this figure, the corresponding parallactic angle f_2 is approximately 95°
- ❖ Since f_2 is closer to 90° than f_1 , the overall accuracy of the computed coordinates of point A will be higher in the configuration of Fig. 19-9b
- ❖ Notice also that the stereoscopic coverage in Fig. 19-9a is only approximately 50 percent of the field of view, while, the stereoscopic coverage of Fig. 19-9b is 100 percent of the field of view
- ❖ This enables the full format of the camera to be used, resulting in greater efficiency and higher effective image resolution

19-9. Planning for Close-Range Photogrammetry

- For the highest level of accuracy in close-range photogrammetry, a fully analytical solution is preferred
- By applying the principles of analytical photogrammetry, precisely measured photo coordinates of images can be used to directly compute X, Y, and Z coordinates in object space
- The foundation of the analytical solution is the collinearity condition which gives rise to the collinearity equations [see Eqs. (11-1) and (11-2)]
- These equations can be directly applied to terrestrial as well as aerial photographs

$$x_a = x_o - f\left[\frac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \qquad (11\text{-}1)$$

$$y_a = y_o - f\left[\frac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \qquad (11\text{-}2)$$

19-9. Planning for Close-Range Photogrammetry

- In the preferred analytical method, the self-calibration approach is used
- This gives a calibration of the camera under the actual conditions (temperature, humidity, etc.) which existed when the photographs were taken
- Certain geometric requirements must be met in order to effectively perform analytical self-calibration
- First, numerous redundant photographs from multiple locations are required, with sufficient *roll diversity*
  - Roll diversity is a condition in which the photographs have angular attitudes that differ greatly from each other
- Another requirement is that many well-distributed image points be measured over the entire format
  - This is important for accurate determination of lens distortion parameters

19-9. Planning for Close-Range Photogrammetry

- Accurate measurement of photo coordinates is necessary to ensure accurate results from the analytical solution
- High-precision comparators are generally used for film-based photographs
- Digital camera systems, on the other hand, rely upon image-matching techniques to obtain accurate photo coordinates
- In any case, it is essential to properly identify object points as they appear on the different photos
- Mislabeled points will result in an inaccurate analytical solution or, in some cases, will cause the solution to fail completely