Chapter 3.
Cameras and Other Imaging Devices

3-1. Introduction

- The *Manual of Photogrammetry* defines a camera as "a lightproof chamber or box in which the image of an exterior object is projected upon a sensitized plate or film, through an opening usually equipped with a lens or lenses, shutter, and variable aperture."
- That definition has been broadened in recent years with the increased use of the *digital camera* which senses light energy through the use of semiconductor electronics instead of film
- In many cases a more general term such as *imaging device* may be more appropriate to describe the instrument used for primary photogrammetric data acquisition
- The remarkable success of photogrammetry in recent years is due in large part to the progress that has been made in developing precision cameras
- Perhaps the most noteworthy among recent camera developments has been the perfection of lenses of extremely high resolving power and almost negligible distortion
  ⇨ This has greatly increased the accuracy of photogrammetry

3-1. Introduction

❖ Imaging devices can be categorized according to how the image is formed

Type 1	Type 2	Type 3
• Devices that acquire the image simultaneously over the entire format are *frame cameras* (or *frame sensors*) • Frame cameras generally employ shutters which open and allow light from the field of view to illuminate a two-dimensional (usually rectangular) image plane before closing	• Other imaging devices sense only a linear projection (strip) of the field of view at a given time and require that the device move or sweep across the area being photographed in order to acquire a two-dimensional image • Devices of this second type are referred to as *strip cameras, linear array sensors*, or *pushbroom scanners*	• A third type of device builds an image by detecting only a small spot at a time, requiring movements in two directions (sweep and scan) in order for the two-dimensional image to be formed • These devices are often referred to as *flying spot scanners* or *whiskbroom scanners*

3-1. Introduction

- The traditional imaging device used in photogrammetry is the aerial mapping camera, and its use is widespread in the photogrammetric industry
- The primary requirement of any photogrammetric aerial camera is a lens of high geometric quality
- Aerial cameras must be capable of exposing in rapid succession a great number of photographs to exacting specifications
- Since these cameras must perform this function while moving in an aircraft at high speed, they must have short cycling times, fast lenses, and efficient shutters
- They must be capable of faithful functioning under the most extreme weather conditions and in spite of aircraft vibrations
- Aerial cameras using roll film generally have magazine capacities of several hundred exposures while digital mapping cameras typically have sufficient computer memory to store equivalent numbers of images
- It is imperative that every precaution be taken in the manufacture of aerial cameras to guarantee the quality and reliability of the photography on each mission

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- This chapter discusses various types of imaging devices, but the standard-film aerial mapping camera is presented in the greatest detail
  ⇨ This is primarily due to its continued wide usage; however, this is also a practical approach because other imaging devices can then conveniently be described as variations of this basic instrument

3-2. Metric Cameras for Aerial Mapping

- Single-lens frame cameras are the most common cameras in use today
- They are used almost exclusively in obtaining photographs for mapping purposes because they provide the highest geometric picture quality
- With a single-lens frame camera, the lens is held fixed relative to the focal plane
- The film is generally fixed in position during exposure, although it may be advanced slightly during exposure to compensate for image motion
- The entire format is exposed simultaneously with a single click of the shutter

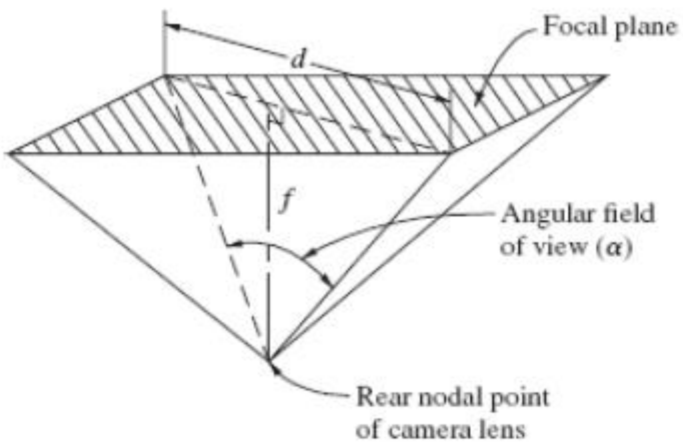

Figure 3-1. Angular field of view of a camera.

- Single-lens frame cameras are often classified according to their *angular field of view*
- Angular field of view, as illustrated in Fig. 3-1, is the angle α subtended at the rear nodal point of the camera lens by the diagonal d of the picture format (The most common frame or format size of film aerial mapping cameras is 230mm (9in) square)

3-2. Metric Cameras for Aerial Mapping

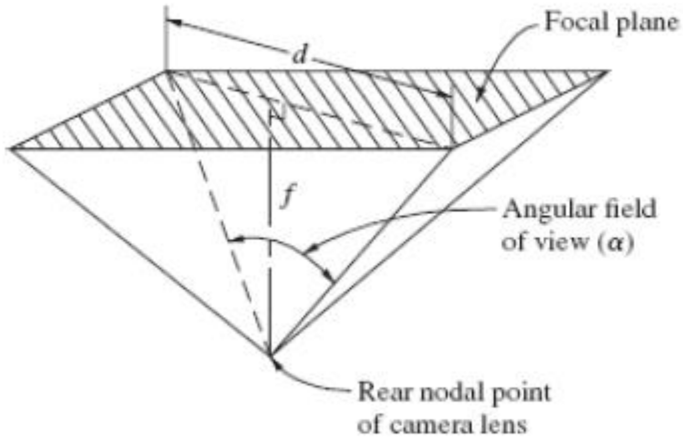

Figure 3-1. Angular field of view of a camera.

- Classifications according to angular field of view are
  1) Normal angle (up to 75°)
  2) Wide angle (75° to 100°)
  3) Superwide angle (greater than 100°)

- Angular field of view may be calculated as follows (see Fig. 3-1):

$$\alpha = 2\tan^{-1}\left(\frac{d}{2f}\right) \qquad (3\text{-}1)$$

- For a nominal 152-mm-focal-length camera with a 230-mm-square format, the angular field of view is

$$\alpha = 2\tan^{-1}\left[\frac{\sqrt{230^2 + 230^2}}{2(152)}\right] = 94° \qquad \text{wide angle}$$

3-2. Metric Cameras for Aerial Mapping

- Single-lens frame cameras are available in a variety of lens *focal lengths*, and the choice depends on the purpose of the photography
- The most common one in use today for mapping photography has a 152mm (6in) focal length and 230mm (9in) square format, although 89mm (3 ½in), 210mm (8 ¼in), and 305mm (12in) focal lengths with 230mm formats are also used
- The 152mm focal length with a 230mm format provides the best combination of geometric strength and photographic scale for mapping
- Longer focal lengths such as 305mm are used primarily for obtaining photographs for aerial mosaics and for reconnaissance and interpretation purposes
- They enable reasonably large photographic scales to be obtained in spite of high flying heights, and they reduce image displacements due to relief variations
- Digital mapping cameras come in a variety of formats and focal lengths, although most are designed to capture images in the normal angle range—narrower than those of the 152-mm focal length film camera

3-2. Metric Cameras for Aerial Mapping

$$\alpha = 2\tan^{-1}\left(\frac{d}{2f}\right) \qquad (3\text{-}1)$$

- ❖ From Eq. (3-1), it is seen that for a particular format size, the angular field of view increases as focal length decreases
- ❖ Short focal lengths, therefore, yield wider ground coverage at a given flying height than longer focal lengths
- ❖ In Fig. 1-1 the Zeiss RMK TOP 15 aerial mapping camera was shown, and Fig. 3-2 illustrates the Leica RC30 aerial mapping camera

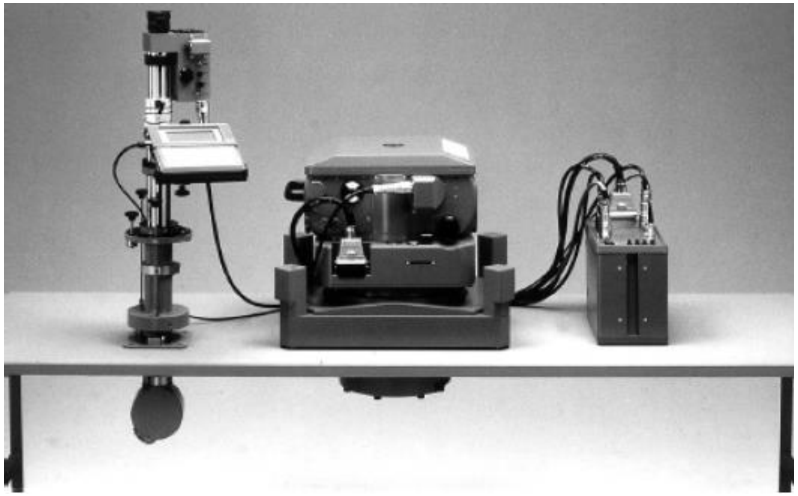

Figure 1-1. Zeiss RMK TOP 15, aerial mapping camera, with electronic controls and aircraft mountings. (Courtesy Carl Zeiss, Inc.)

Figure 3-2. Leica RC30 aerial mapping camera. (Courtesy LH Systems, LLC.)

3-2. Metric Cameras for Aerial Mapping

❖ These cameras and their predecessors, together with a few others, are being used today to take the bulk of aerial-film photography for mapping purposes

❖ Both are precision single-lens frame cameras having 230-mm-square formats and film capacities of approximately 500 exposures

❖ The TOP 15 has a nominal 152-mm-focal-length lens

❖ The RC30 is capable of accepting interchangeable cones with lenses having nominal focal lengths of 89, 152, 210, or 305mm

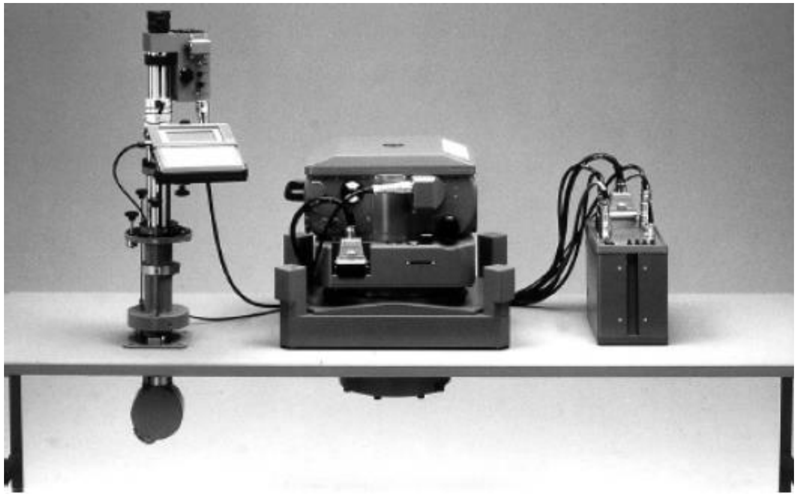

Figure 1–1. Zeiss RMK TOP 15, aerial mapping camera, with electronic controls and aircraft mountings. (Courtesy Carl Zeiss, Inc.)

Figure 3–2. Leica RC30 aerial mapping camera. (Courtesy LH Systems, LLC.)

3-2. Metric Cameras for Aerial Mapping

Figure 3-3. Hasselblad 500 ELX camera.
(Courtesy University of Florida.)

- ❖ The Hasselblad camera of Fig. 3-3 is a small-format single-lens frame camera which has been employed extensively for space photography
- ❖ It uses 70-mm film and can be obtained with various focal-length lenses

3-3. Main Parts of Frame Aerial Cameras

- Although all frame aerial cameras are somewhat different in construction, they are enough alike that a general description can be given which adequately encompasses all of them

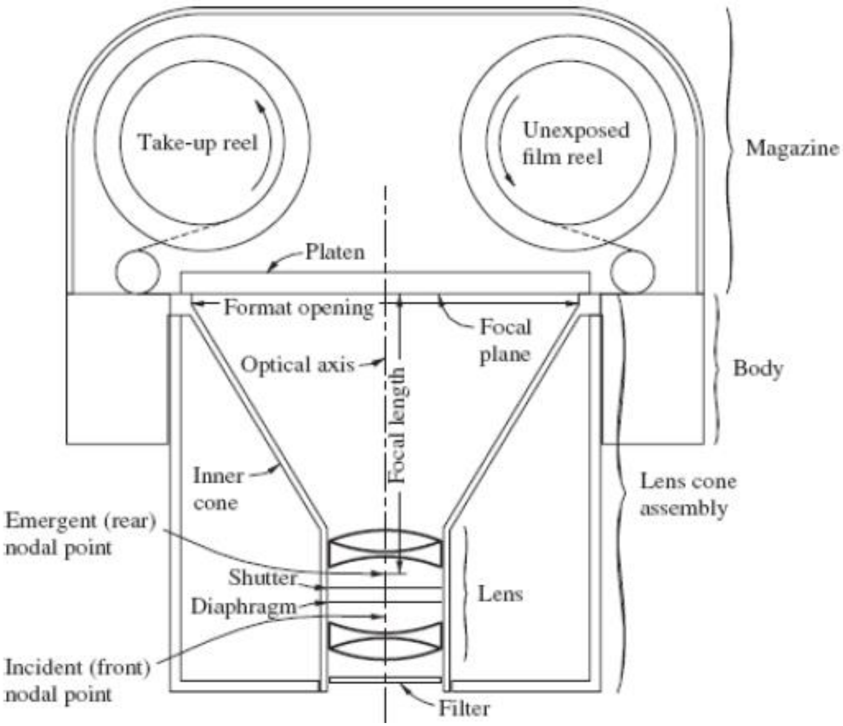

Figure 3-4. Generalized cross section of a frame aerial camera.

- The three basic components or assemblies of a frame aerial camera, as shown in the generalized cross section of Fig. 3-4, are the *magazine*, the *camera body*, and the *lens cone* assembly

3-3-1. Camera Magazine

- The camera magazine houses the reels which hold exposed and unexposed film, and it also contains the *film-advancing* and *film-flattening* mechanisms
- Film flattening is very important in aerial cameras, for if the film buckled during exposure, the image positions on the resulting photographs would be incorrect
- Film flattening may be accomplished in any of the following four ways:

First,	Second,	Third,	Fourth,
• By applying tension to the film during exposure	• By pressing the film firmly against a flat focal-plane glass that lies in front of the film	• By applying air pressure into the airtight camera cone, thereby forcing the film against a flat plate lying behind the focal plane	• By drawing the film tightly up against a vacuum plate or platen whose surface lies in the focal plane

3-3-1. Camera Magazine

- The vacuum system has proved most satisfactory and is the most widely used method of film flattening in aerial cameras
- A focal-plane glass in front of the film is objectionable because image positions are distorted due to refraction of light rays passing through the glass
  ⇨ These distortions can be determined through calibration, however, and their effect eliminated in subsequent photogrammetric operations

3-3-2. Camera Body

- The camera body is a one-piece casting which usually houses the drive echanism
- The drive mechanism operates the camera through its cycle
  ⇨ The cycle consists of (1) advancing the film (2) flattening the film (3) cocking the shutter (4) tripping the shutter
- Power for the drive mechanism is most commonly provided by an electric motor
- The camera body also contains carrying handles, mounting brackets, and electrical connections

3-3-3. Lens Cone Assembly

❖ The lens cone assembly contains a number of parts and serves several functions

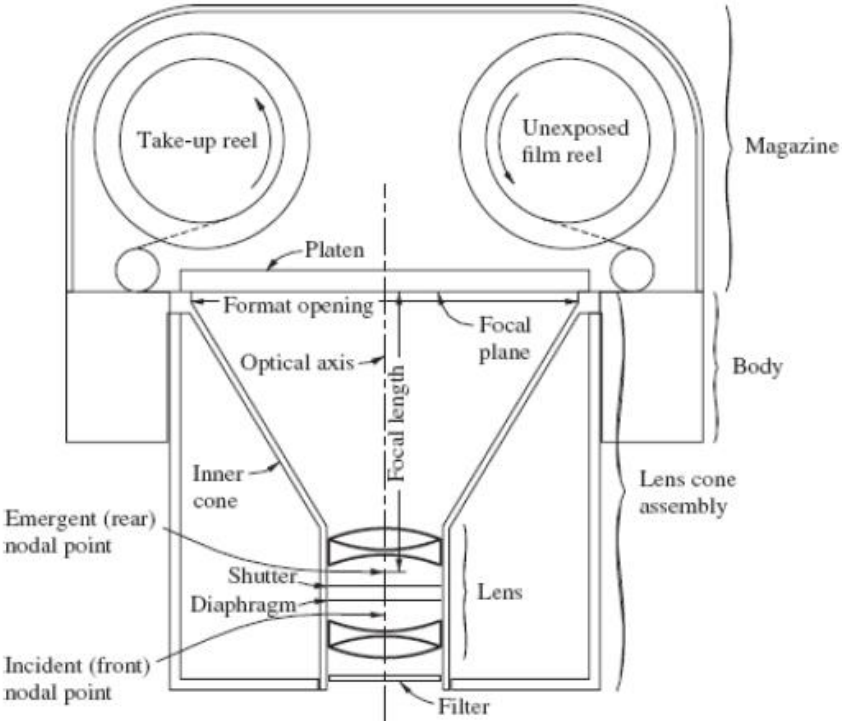

Figure 3-4. Generalized cross section of a frame aerial camera.

❖ Contained within this assembly are the *lens*, *shutter*, and *diaphragm* (see Fig. 3-4)

❖ With most mapping cameras, the lens cone assembly also contains an *inner cone* or *spider*

❖ The inner cone rigidly supports the lens assembly and focal plane in a fixed relative position
- ⇨ This fixes the so-called elements of *interior orientation* of the camera
- ⇨ These elements are carefully determined through camera calibration so that they are available for photogrammetric calculations

3-3-3. Lens Cone Assembly

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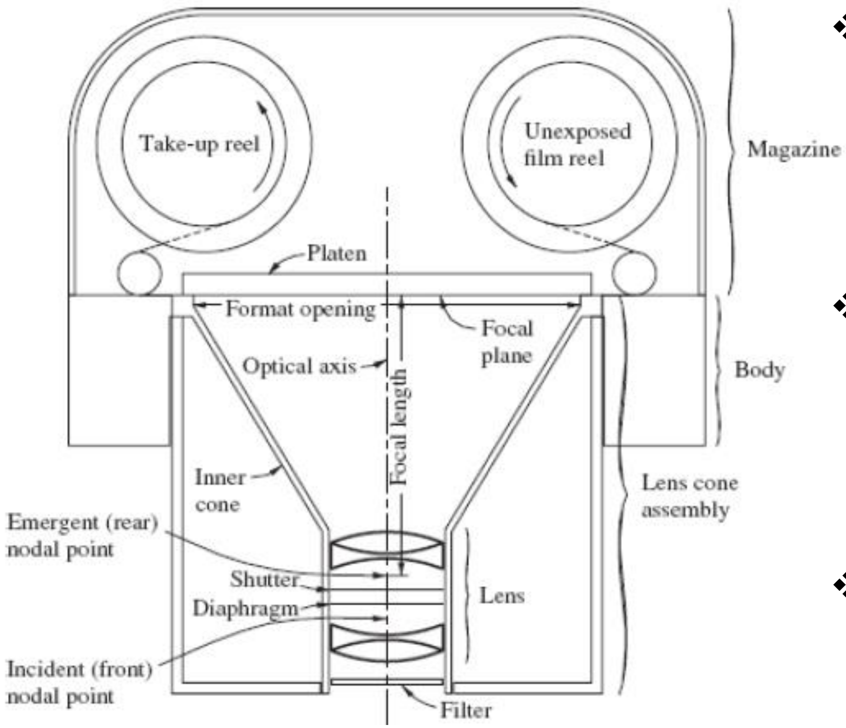

Figure 3-4. Generalized cross section of a frame aerial camera.

- The inner cone is made of metal having a low coefficient of thermal expansion, so that changes in operating temperatures do not upset the calibration
- In some aerial cameras which do not have inner cones, the body and outer lens cone act together to hold the lens with respect to the focal plane
- The *camera lens* is the most important (and most expensive) part of an aerial camera

- It gathers light rays from the object space and brings them to focus in the focal plane behind the lens
- Lenses used in aerial cameras are highly corrected compound lenses consisting of several elements

3-3-3. Lens Cone Assembly

- The *filter* serves three purposes:
  - (1) It reduces the effect of atmospheric haze
  - (2) it helps provide uniform light distribution over the entire format
  - (3) it protects the lens from damage and dust
- The *shutter* and diaphragm together regulate the amount of light which will expose the photograph
  - ⇨ The shutter controls the length of time that light is permitted to pass through the lens
- The diaphragm regulates the f-stops of the camera by varying the size of the aperture to control the amount of light passing through the lens
  - ⇨ Typically f -stops of aerial cameras range from about f-4 down to f-22
  - ⇨ Thus, for a nominal 152-mm-focal-length lens, the diameter of the aperture ranges from about 38 mm at f -4 to about 7 mm at f -22
  - ⇨ The diaphragm is normally located in the airspace between the lens elements of an aerial camera and consists of a series of leaves which can be rotated to vary the size of the opening

3-4. Focal Plane and Fiducial Marks

- ❖ The *focal plane* of an aerial camera is the plane in which all incident light rays are brought to focus

- ❖ The focal plane is defined by the upper surface of the focal-plane frame
  ⇨ This is the surface upon which the film emulsion rests when an exposure is made.

- ❖ Camera *fiducial* marks are usually four or eight in number, and they are situated in the middle of the sides of the focal plane opening, in its corners, or in both locations

- ❖ Blinking lamps cause these marks to be exposed onto the negative when the picture is taken

- ❖ Modern mapping cameras generally expose the fiducials at the midpoint of the duration that the shutter is open
  ⇨ This defines the instant of exposure, which is critical when incorporating airborne GPS control

3-4. Focal Plane and Fiducial Marks

- Camera *fiducial* marks are usually four or eight in number, and they are situated in the middle of the sides of the focal plane opening, in its corners, or in both locations
- The aerial photographs of Figs. 1-2, 1-6, and 1-7 have four corner and four side fiducial marks

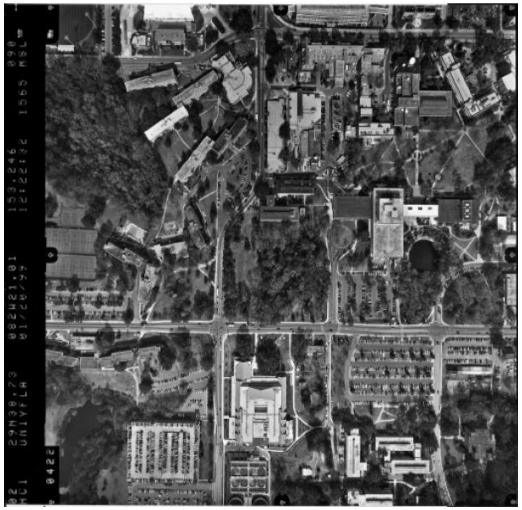

Figure 1–2. Vertical aerial photograph.

Figure 1–7. High oblique photograph of Tampa, Florida

Figure 1–6. Low oblique photograph of Madison, Wisconsin

3-4. Focal Plane and Fiducial Marks

- Fiducial marks (or fiducials) serve to establish a reference xy photo coordinate system for image locations on the photograph

- In essence, fiducials are two-dimensional control points whose xy coordinates are precisely and accurately determined as a part of camera calibration

- Lines joining opposite fiducials intersect at a point called the *indicated principal point*, and aerial cameras are carefully manufactured so that this occurs very close to the true *principal point*, which is defined as the point in the focal plane where a line from the rear nodal point of the camera lens, perpendicular to the focal plane, intersects the focal plane

- Besides providing a coordinate reference for the principal point and image points, fiducials allow for correction of film distortion (shrinkage and expansion) since each photograph contains the images of these stable control points

- *Forward-motion compensation* (FMC) is usually accomplished by moving the film slightly across the focal plane during exposure, in the direction of, and at a rate just equal to, the rate of image movement

3-5. Shutters

- If exposure times are long or flying heights low, blurred images may result
  ⇨ It is important, therefore, that the shutter be open for a very short duration when aerial photographs are taken
- Short exposure times also reduce the detrimental effects of aircraft vibrations on image quality
- The shutter speeds of aerial cameras typically range from about $\frac{1}{100}$ to $\frac{1}{1000}S$
- Shutters are designed to operate efficiently so that they open instantaneously, remain open the required time, and then instantaneously close, thus enabling the most uniform exposure possible over the format
- Shutters used in aerial cameras are generally classified as either *between-the-lens shutters* or *focal-plane shutters*

3-5. Shutters

- Between-the-lens shutters are most commonly used in mapping cameras
  - These shutters are placed in the airspace between the elements of the camera lens
  - Common types of between-the-lens shutters are the *leaf* type, *blade* type, and *rotating-disk* type

- A schematic diagram of the **leaf type** is shown in Fig. 3-5
  - It consists usually of five or more leaves mounted on pivots and spaced around the periphery of the diaphragm
  - When the shutter is tripped, the leaves rotate about their pivots to the open position of Fig. 3-5b, remain open the desired time, and then snap back to the closed position of Fig. 3-5a
  - Some camera shutters use two sets of leaves, one for opening and the other for closing This increases shutter efficiency, shutter speed, and shutter life

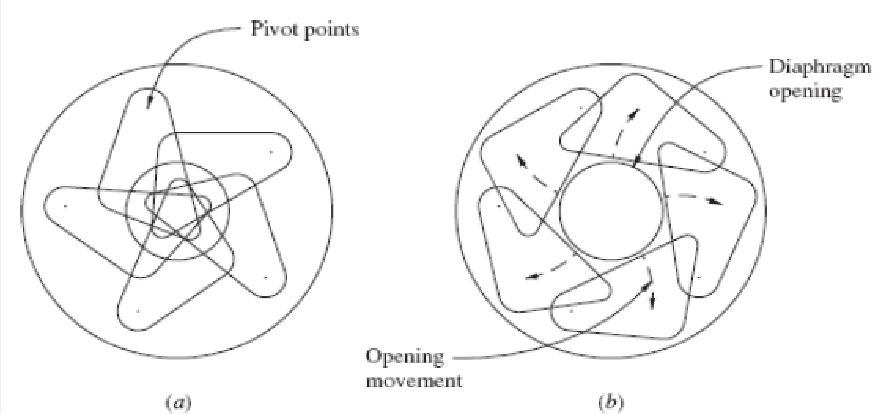

Figure 3-5. Schematic diagrams of a leaf-type shutter. (a) Shutter closed; (b) Shutter open

3-5. Shutters

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- The **blade-type** shutter consists of four blades, two for opening and two for closing. Its operation is similar to that of a guillotine
  - ⇨ When the shutter is triggered, the two thin *opening* plates or blades move across the diaphragm to open the shutter
  - ⇨ When the desired exposure time has elapsed, two *closing* blades close it

- The **rotating-disk type** of shutter consists of a series of continuously rotating disks
  - ⇨ Each disk has a cutaway section, and when these cutaways mesh, the exposure is made
  - ⇨ The speed of rotation of the disks can be varied so that the desired exposure times are obtained
  - ⇨ This type of shutter is very efficient because no starting or stopping of parts is required, as is with other types

3-6. Camera Mounts

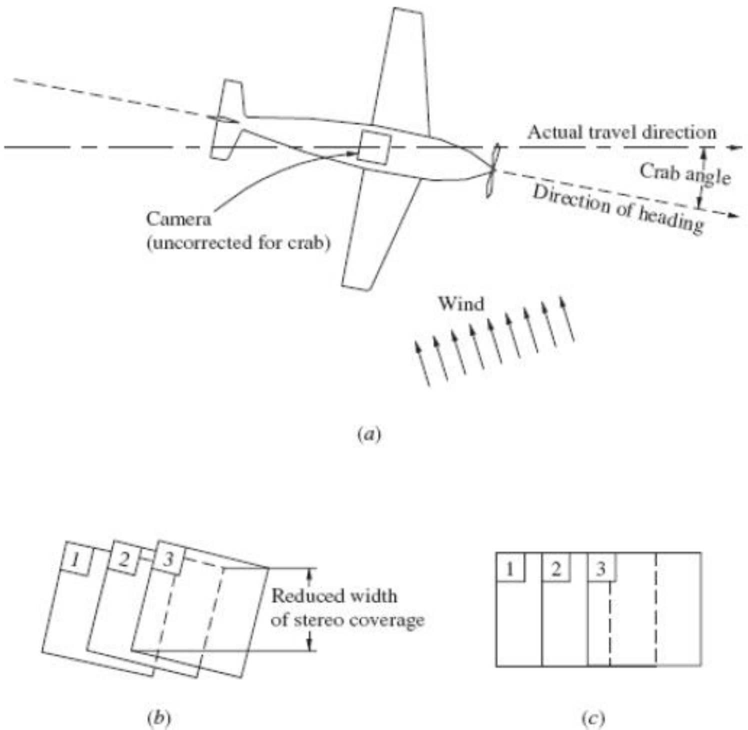

Figure 3-6. (a) Camera exposing aerial photography with crab present. (b) Crabbed overlapping aerial photographs. (c) Overlapping aerial photographs with no crab.

- The camera mount is the mechanism used to attach the camera to the aircraft
- Its purpose is <u>to constrain the angular alignment of the camera so that the optical axis is vertical and the format is squarely aligned with the direction of travel</u>
- A minimal mount is equipped with dampener devices which prevent (or at least reduce) aircraft vibrations from being transmitted to the camera, and a mechanism that allows rotation in azimuth to correct for *crab*

3-6. Camera Mounts

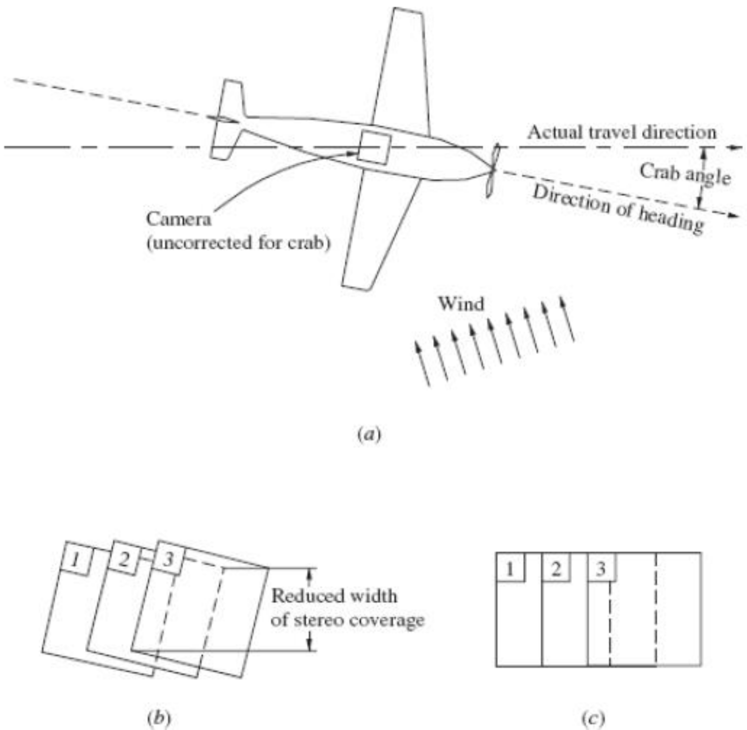

Figure 3-6. (a) Camera exposing aerial photography with crab present. (b) Crabbed overlapping aerial photographs. (c) Overlapping aerial photographs with no crab.

- Crab is a disparity in the orientation of the camera in the aircraft with respect to the aircraft's actual travel direction
- It is usually the result of side winds which cause the aircraft's direction of heading to deviate from its actual travel direction, as shown in Fig. 3-6a
- Crab can be of variable amounts, depending on the wind velocity and direction
- It has the undesirable effect of reducing the stereoscopic ground coverage of aerial photos, as shown in Fig. 3-6b
- Figure 3-6c shows the ground coverage when the camera has been rotated within the mount in the aircraft to make two sides of the format parallel to the actual direction of travel

3-6. Camera Mounts

- ❖ More elaborate mounts like the Leica PAV 80, shown in Fig. 3-7, provide gyro stabilization of the camera
- ❖ Gyroscopic devices in the housing or in an external device sense the rotational movements of the aircraft, which in turn are counteracted by microprocessor-controlled motors that keep the camera properly oriented
- ❖ Control is provided in three directions
  ⇨ rotation about the longitudinal axis (roll), rotation about the transverse axis (pitch), and rotation about the optical axis (yaw or drift)

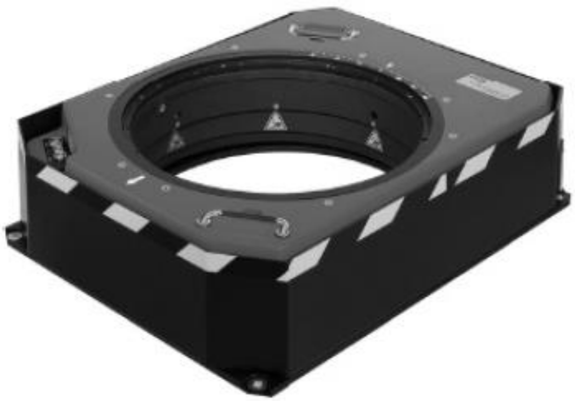

Figure 3-7. Leica PAV 80 gyro-stabilized aerial-camera mount. (Courtesy Leica Geosystems)

- ❖ In addition to simply counteracting the aircraft's rotational movements, the three rotations are measured and can be recorded at the instant of exposure
- ❖ <u>These three rotational quantities are essential for proper data reduction when using airborne GPS control</u>
- ❖ When combined with forward motion compensation, a gyro-stabilized mount results in the sharpest images by minimizing image movement during exposure

3-7. Camera Controls

- Camera controls are those devices necessary for operating the camera and varying settings according to conditions at the time of photography
- The *intervalometer* is <u>a device which automatically trips the shutter and actuates the camera cycle as required by the flight plan</u>
- The disadvantage of this type of intervalometer is that with fixed time intervals, variations in end lap occur with variations in terrain elevation, flying height, or aircraft velocities
- Subsequent intervalometer designs, include integrated automatic control unit that incorporates a GPS receiver, enabling the exposures to be made at preprogrammed locations as dictated by the flight plan

- Another aerial camera control device is the *exposure control*
- This consists of an exposure meter which measures terrain brightness and correlates it with the optimum combination of aperture size and shutter speed, given a particular film speed and filter factor
- Exposure control units are available which operate automatically, and they constantly vary camera settings to provide optimum exposures.

3-7. Camera Controls

- Modern camera controls consist of integrated navigation and sensor control units that are highly automated
- By incorporating precise GPS and inertial navigation devices, these systems relieve the pilot and photographer of many routine in-flight monitoring and adjustment functions, resulting in reduced human error

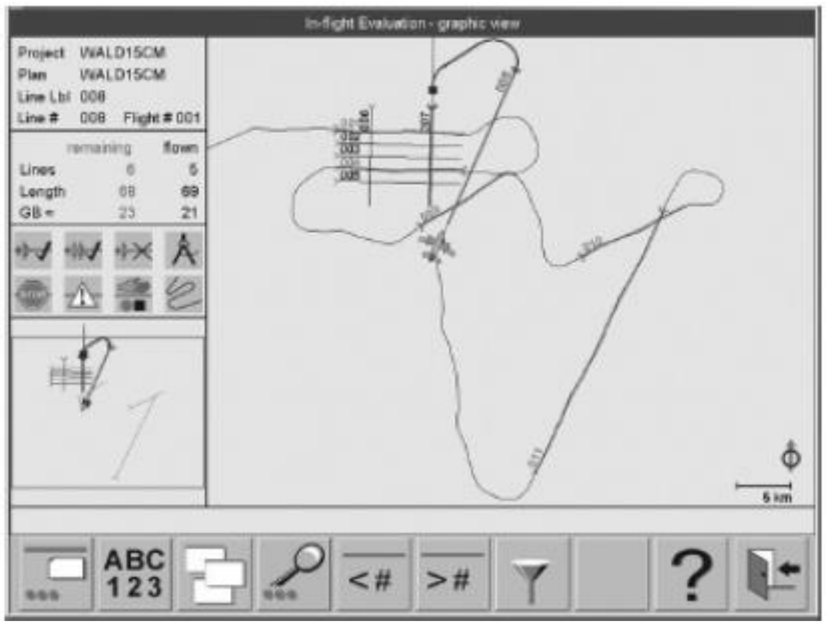

Figure 3-8. Flight and Sensor Contral Management System (Courtesy Leica Geosystems)

- In addition, flights can be made more efficient by reducing excessive side lap and avoiding gaps in ground coverage
- The Flight and Sensor Control Management System shown in Fig. 3-8 can be used to automate a substantial portion of the image acquisition mission

3-8. Automatic Data Recording

- Most modern aerial mapping cameras are equipped with a data-recording system which automatically produces pertinent data on the pictures
- The usual data consist of date, flying altitude, calibrated focal length of the camera, photograph number, job identification, etc
- This information is entered on a *data block*, which is exposed onto the film when the photograph is taken
- The images of an automatic data-recording system are shown along the left border of the aerial photograph in Fig. 1-2
- Automatic data recording is a convenience which saves time and prevents mistakes in later use of the photographs

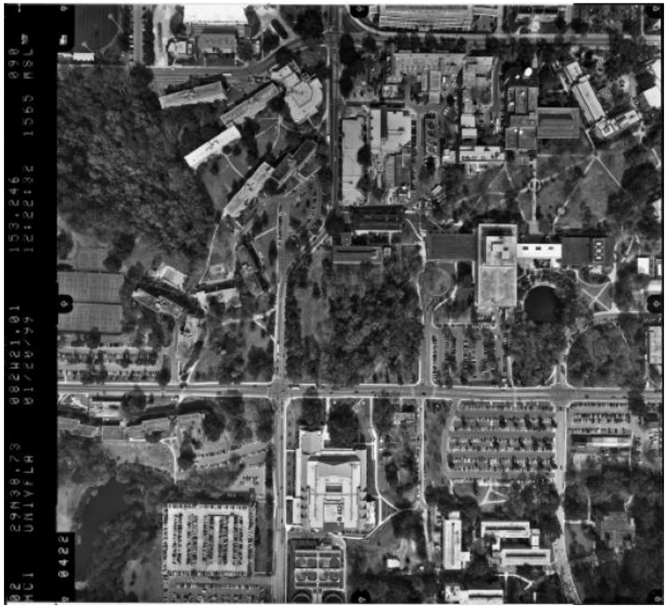

Figure 1–2. Vertical aerial photograph.
(from an altitude of 470 meters (m) above the terrain)

3-9. Digital Mapping Cameras

- An alternative to film cameras is the digital imaging device
- A digital image is a rectangular array of pixels in which the brightness of a scene at each discrete location has been quantified
- Rather than record the reflected electromagnetic energy through silver halide crystals as in a film emulsion, digital imaging devices use solid-state detectors to sense the energy
- A common type of solid-state detector in current use is the *charge-coupled device* (CCD)
- At a specific pixel location, the CCD element is exposed to incident light energy, and it builds up an electric charge proportional to the intensity of the incident light
- The electric charge is subsequently amplified and converted from analog to digital form
- A large number of CCDs can be combined on a silicon chip in a one-dimensional or two-dimensional array
- While other solid-state sensors such as Complimentary Metal-Oxide Semiconductor (CMOS) devices are used in some applications, the term CCD will be used throughout this text to represent all solid state image sensors

3-9-1. Digital-Frame Cameras

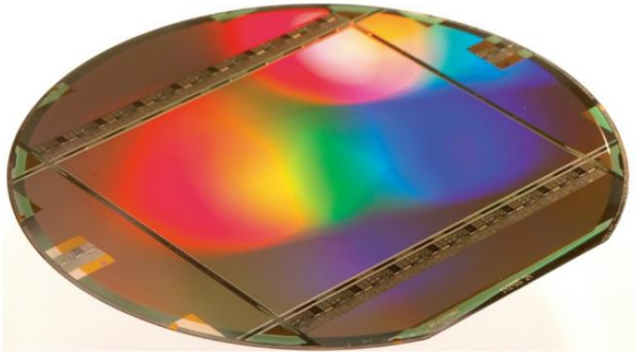

Figure 3-9. Solid-state CCD imaging array of 14,600X17,200 (250million) pixels. (Courtesy Teledyne DALSA.)

- A digital-frame camera has similar geometric characteristics to a single-lens frame camera that employs film as its recording medium
- It consists of a two-dimensional array of CCD elements, called a *full-frame sensor*
- The sensor is mounted in the focal plane of a single-lens camera
- Acquisition of an image exposes all CCD elements simultaneously, thus producing the digital image
- Figure 3-9 shows a full-frame sensor
- Figure 3-10 shows a schematic illustration of a digital-frame camera capturing an image of the ground
- Light rays from all points in the scene pass through the center of the lens before reaching the CCD elements, thus producing the same type of point-perspective image as would have occurred if film were used

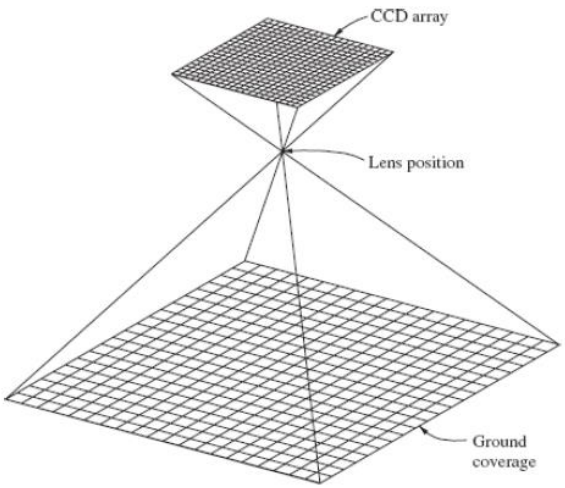

Figure 3-10. Geometry of a digital frame camera.

3-9-1. Digital-Frame Cameras

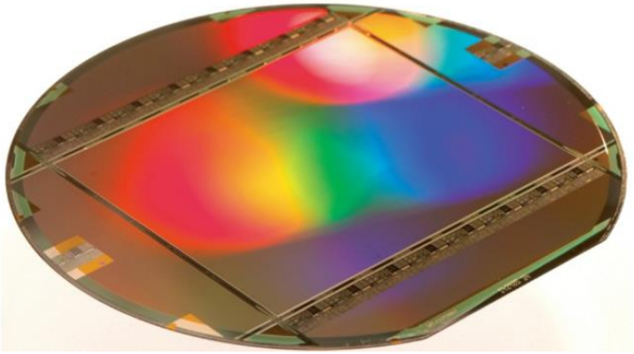

Figure 3-9. Solid-state CCD imaging array of 14,600X17,200 (250million) pixels. (Courtesy Teledyne DALSA.)

- ❖ Digital-frame cameras can be classified in terms of the number of pixels in the digital image
- ❖ Currently the term *megapixel* (1 million pixels) is used for indicating common image sizes
- ❖ Inexpensive digital cameras may have arrays of roughly 2500 rows and 3500 columns for a total of 2500 × 3500 = 8,750,000 pixels or 8.7 megapixels

- ❖ Large arrays such as that of Fig. 3-9 may have 250 million or more
- ❖ Current technology can produce chips with individual CCD elements approximately 5 μm in size or even smaller
- ❖ The array of Fig. 3-9 has a 5.6 μm pixel size and thus can capture an 82 × 99 mm image in the focal

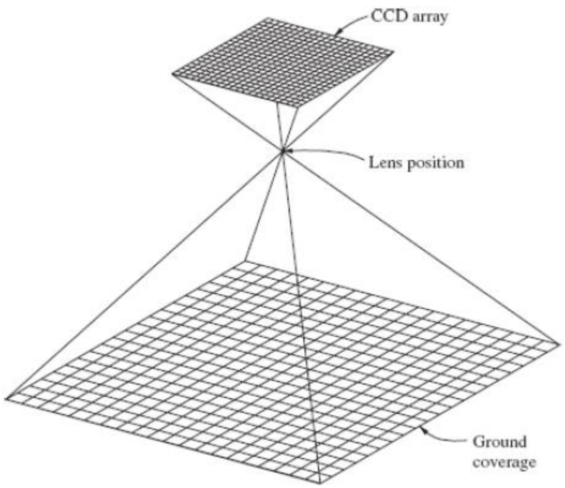

Figure 3-10. Geometry of a digital frame camera.

3-9-1. Digital-Frame Cameras

❖ Figure 3-11 is a digital mapping camera that incorporates the CCD array shown in Fig. 3-9 along with a 112-mm-focal length lens

❖ In addition to the ability to capture 250 megapixel panchromatic images, it is equipped to take lower resolution color and infrared images simultaneously

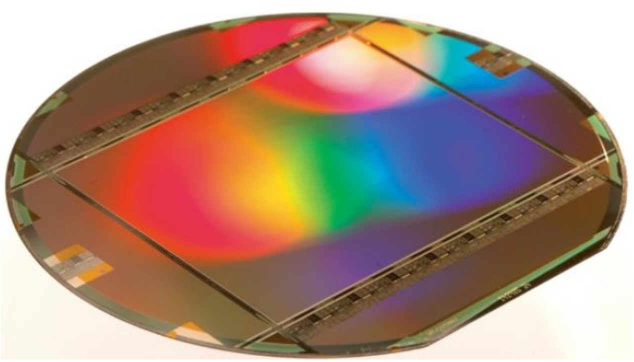

Figure 3-9. Solid-state CCD imaging array of 14,600X17,200 (250million) pixels. (Courtesy Teledyne DALSA.)

Figure 3-11. Z/I DMC II-250 digital mapping camera. (Courtesy Z/I Imaging)

3-9-1. Digital-Frame Cameras

- Some digital-frame cameras use an approach of combining multiple image subsets to produce a composite image that has the geometric characteristics of a single-frame image
- An image is acquired by rapidly triggering four in-line sensors that combine to acquire nine image patches as shown in Fig. 3-12
- The four sensors are aligned with the flight line and by precisely timing the image acquisitions to correspond to the aircraft velocity, all of the images will effectively be taken from a common location

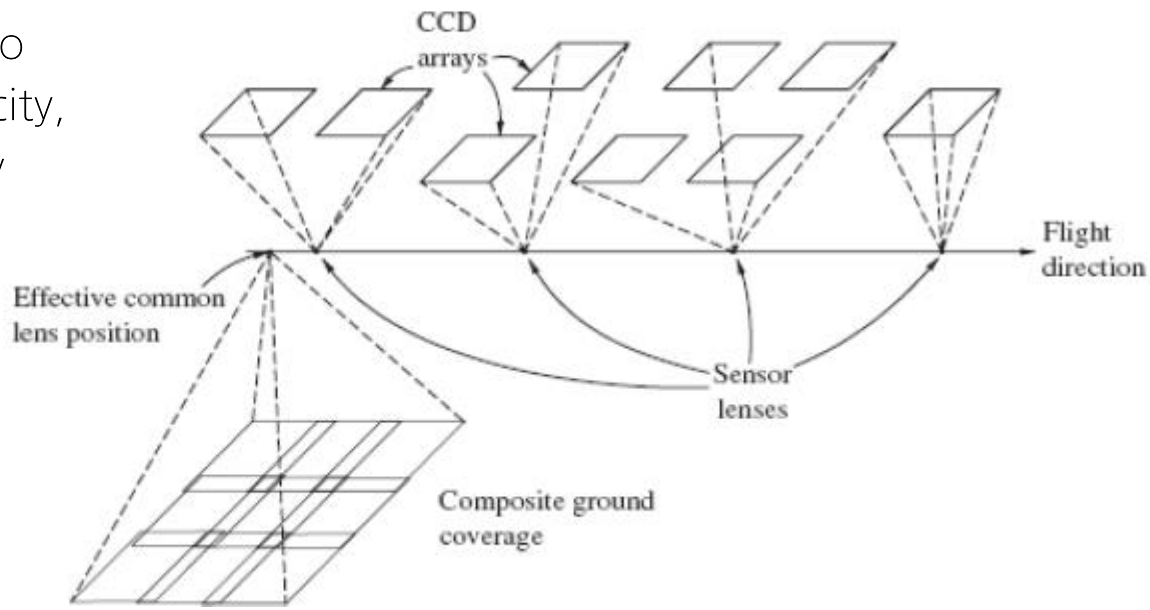

Figure 3-12. Multiple frame capture method of the UltraCam Eagle.

3-9-2. Linear Array Sensors

- The geometric characteristics of a linear array sensor are different from those of a single-lens frame camera
- At first glance, an image obtained from a linear array sensor may appear to be the same as a digital frame camera image, but there are subtle geometric differences
- A linear array sensor acquires an image by sweeping a line of detectors across the terrain and building up the image
- A linear array sensor consists of a one-dimensional array or strip of CCD elements mounted in the focal plane of a single-lens camera
- Since the two-dimensional image is acquired in a sweeping fashion, the image is not exposed simultaneously

3-9-2. Linear Array Sensors

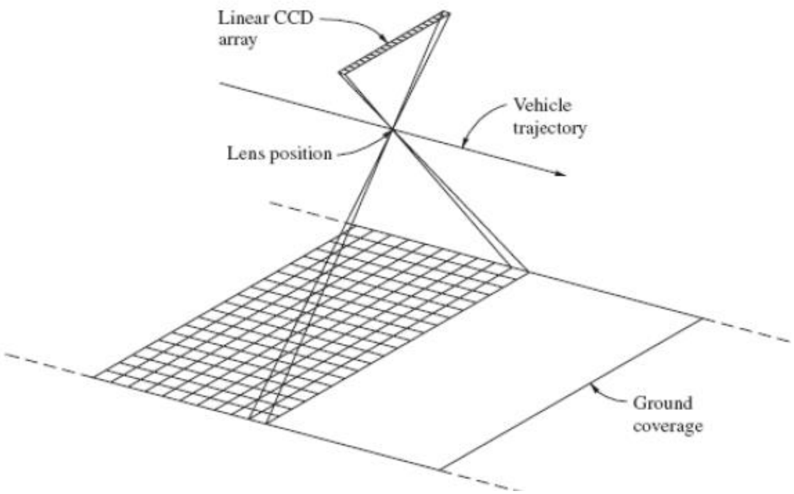

Figure 3-13. Geometry of a linear array sensor.

- ❖ Figure 3-13 shows a schematic illustration of a linear array sensor capturing an image of the ground, assuming a smooth trajectory
- ❖ At a particular instant, light rays from all points along a perpendicular to the vehicle trajectory pass through the center of the lens before reaching the CCD elements, thus producing a single row of the two-dimensional image
- ❖ An instant later, the vehicle has advanced to its position for the next contiguous row, and the pixels of this row are imaged
- ❖ The sensor proceeds in this fashion until the entire image is acquired
- ❖ Since the image was acquired at a multitude of points along the line of the vehicle's trajectory, the resulting geometry is called *line perspective*
- ❖ Acquisition of an image as depicted in Fig. 3-13 is characteristic of a linear array image captured from a satellite where the lack of atmospheric turbulence allows a smooth trajectory

3-9-2. Linear Array Sensors

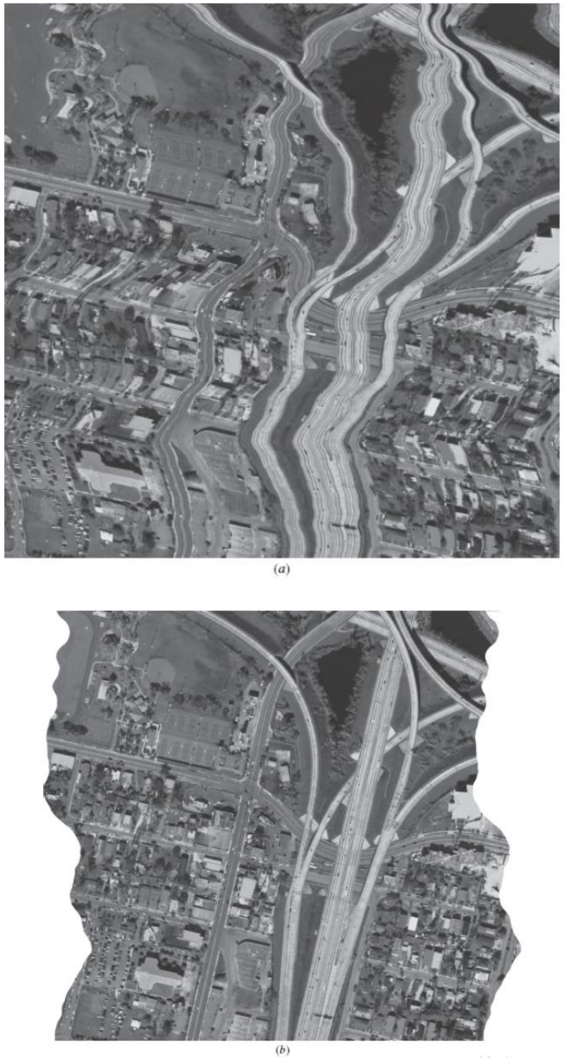

Figure 3-14. Raw image (a) from an airborne linear array sensor exhibiting distortion caused by air turbulence. Rectified image (b) obtained by correcting the raw image using GPS/INS measurements.

- When linear array images are acquired from a sensor carried by an airborne platform, atmospheric turbulence will cause the resulting image to be distorted due to pitching and rolling of the aircraft
- In order to correct for this motion, simultaneous data must be collected by a GPS/INS system to measure the position and angular attitude of the sensor
- By processing the image to take into account the sensor motion, a nondistorted image can be produced
- Figure 3-14(a) shows a raw image collected by a linear array camera similar to that of Fig. 1-4

Figure 1-4. Leica ADS80 airborne digital sensor

3-9-2. Linear Array Sensors


(a)


(b)

Figure 3-14. Raw image (a) from an airborne linear array sensor exhibiting distortion caused by air turbulence. Rectified image (b) obtained by correcting the raw image using GPS/INS measurements.

- Figure 3-14(a) shows a raw image collected by a linear array camera similar to that of Fig. 1-4
- Notice the wavy appearance of streets and other linear features in this uncorrected image
- After rectifying the image based on the GPS/INS data, a corrected image shown in Fig. 3-14(b) is the result
- This rectified image no longer shows the effects of the sensor motion and the linear features appear straight

Figure 1-4. Leica ADS80 airborne digital sensor

3-9-2. Linear Array Sensors

- Another aspect of linear array sensors is that unlike frame sensors, they lack the ability to provide stereoscopic coverage in the direction of flight
  - ⇨ This problem can be solved by equipping the sensor with multiple linear arrays pointed both forward and aft

- The sensor of Fig. 1-4 has linear arrays that point forward, down, and backward as illustrated in Fig. 3-15

- By using the images acquired by the forward-looking and backward-looking arrays, objects on the ground are imaged from two different vantage points, thus providing the required stereo view

Figure 1-4. Leica ADS80 airborne digital sensor

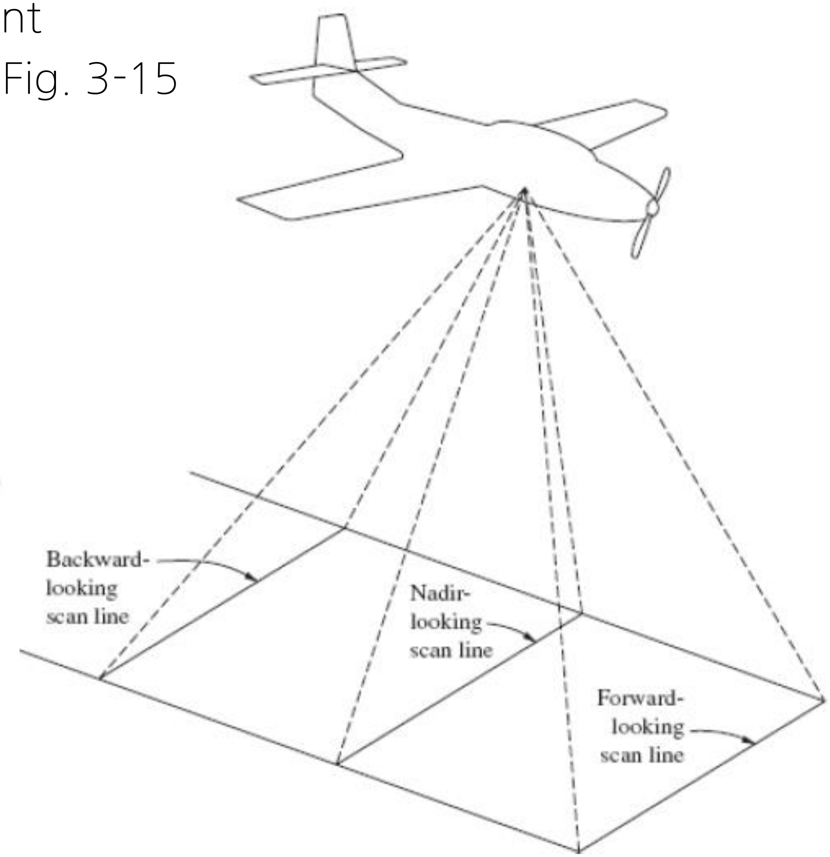

Figure 3-15. Geometry of a three-line scanner.

3-10. Camera Calibration

❖ After manufacture and prior to use, aerial cameras are carefully calibrated to determine precise and accurate values for a number of constants

⇨ These constants, generally referred to as the elements of interior orientation, are needed so that accurate spatial information can be determined from photographs

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods

(2) Stellar methods

(3) Field methods

⇨ Of these, laboratory methods are most frequently utilized and are normally performed by either camera manufacturers or agencies of the federal government

3-10. Camera Calibration

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods

(2) Stellar methods

(3) Field methods

- In one particular method of laboratory calibration, which uses a *multicollimator*, as well as in the field and stellar procedures, the general approach consists of photographing an array of targets whose relative positions are accurately known
- Elements of interior orientation are then determined by making precise measurements of the target images and comparing their actual image locations with the positions they should have occupied had the camera produced a perfect perspective view
- In another laboratory method, which employs a *goniometer*, direct measurements are made of projections through the camera lens of precisely positioned grid points located in the camera focal plane
- Comparisons are then made with what the true projections should have been

3-10. Camera Calibration

❖ The elements of interior orientation which can be determined through camera calibration are as follows:

1. Calibrated focal length (CFL)
   - This is the focal length that produces an overall mean distribution of lens distortion
   - Actually this parameter would be better termed *calibrated principal distance* since it represents the distance from the rear nodal point of the lens to the principal point of the photograph
   - When aerial mapping cameras are manufactured, this distance is set to correspond to the optical focal length of the lens as nearly as possible, hence the more common, though somewhat misleading, term *calibrated focal length*

3-10. Camera Calibration

❖ The elements of interior orientation which can be determined through camera calibration are as follows:

2. Symmetric radial lens distortion

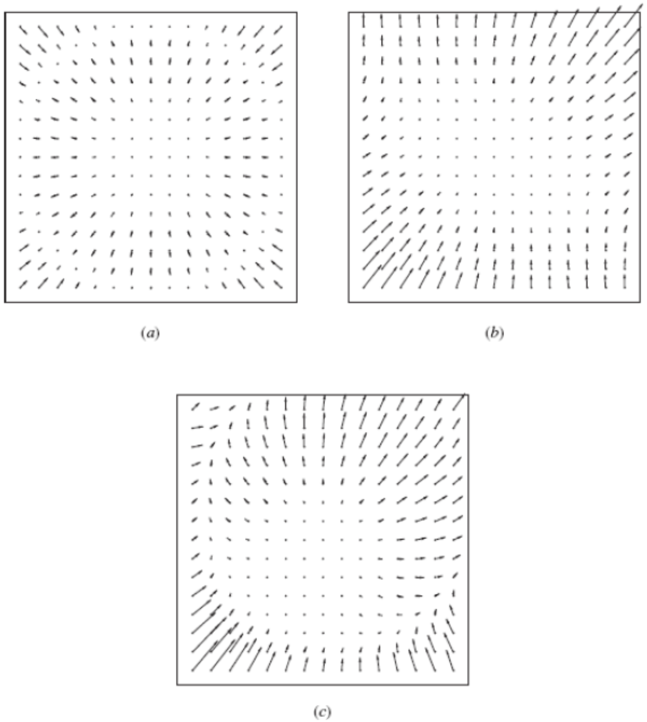

Figure 3-16. Lens distortion patterns: (a) symmetric radial, (b) decentering, and (c) combined symmetric radial and decentering.

- This is the symmetric component of distortion that occurs along radial lines from the principal point
- Although the amount may be negligible, <u>this type of distortion is theoretically always present even if the lens system is perfectly manufactured to design specifications</u>
- Figure 3-16a shows a typical symmetric radial lens distortion pattern with magnitudes of distortion greatly exaggerated
- Notice that distortion occurs in a direction inward toward, or outward from, the center of the image

3-10. Camera Calibration

❖ The elements of interior orientation which can be determined through camera calibration are as follows:

3. Decentering lens distortion

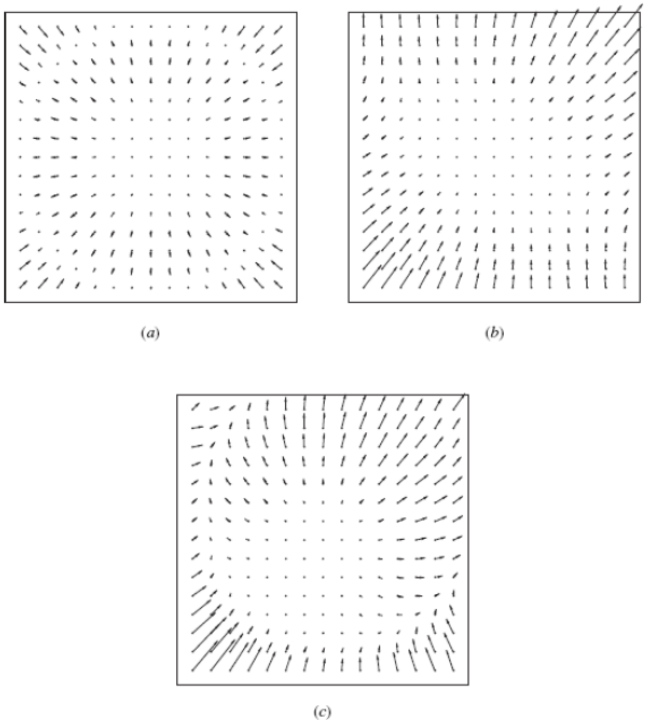

Figure 3-16. Lens distortion patterns: (a) symmetric radial, (b) decentering, and (c) combined symmetric radial and decentering.

- This is the lens distortion that remains after compensation for symmetric radial lens distortion
- Decentering distortion can be further broken down into ***asymmetric radial*** and ***tangential*** lens distortion components
- These distortions are caused by <u>imperfections in the manufacture and alignment of the lens system</u>
- Figure 3-16b shows a typical decentering distortion pattern, again with the magnitudes greatly exaggerated
- Figure 3-16c shows a typical pattern of combined symmetric radial and decentering distortion

3-10. Camera Calibration

- The elements of interior orientation which can be determined through camera calibration are as follows:

4. Principal point location
   - This is specified by coordinates of the principal point given with respect to the x and y coordinates of the fiducial marks
   - For a digital camera, the principal point is nominally located at the center of the CCD array, but calibration can determine the offset from this location

5. Fiducial mark coordinates
   - These are the x and y coordinates of the fiducial marks which provide the two-dimensional positional reference for the principal point
   - A digital camera does not have fiducial marks so these values are not determined from its calibration - Instead, the dimensions and effective shape of the CCD array are sometimes determined as part of the calibration
   - While the physical locations of the CCD elements tend to be highly accurate, the method by which the rows or columns of CCD elements are electronically sampled <u>may cause a difference in the effective pixel dimensions in the x versus y directions</u>

3-10. Camera Calibration

- In addition to the determination of the above elements of interior orientation, several other characteristics of the camera are often measured
- *Resolution* (the sharpness or crispness with which a camera can produce an image) is determined for various distances from the principal point
- Due to lens characteristics, highest resolution is achieved near the center, and lowest is at the corners of the photograph
- *Focal-plane flatness* (deviation of the platen from a true plane) is measured by a special gauge
- Since photogrammetric relationships assume a flat image, the platen should be nearly a true plane, generally not deviating by more than 0.01 mm
- For digital cameras, direct measurement of the out-of-plane deviations is generally not feasible and therefore this distortion goes largely uncorrected
- Often the *shutter efficiency*— the ability of the shutter to open instantaneously, remain open for the specified exposure duration, and close instantaneously—is also quantified

3-11. Laboratory Methods of Camera Calibration

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods | (2) Stellar methods | (3) Field methods

- The *multicollimator* method and the *goniometer* method are two types of laboratory procedures of camera calibration
- A **single collimator** consists of a lens with a cross mounted in its plane of infinite focus
  - ⇨ Therefore, light rays carrying the image of the cross are projected through the collimator lens and emerge parallel
  - ⇨ When these light rays are directed toward the lens of an aerial camera, the cross will be perfectly imaged on the camera's focal plane because aerial cameras are focused for parallel light rays
- The **multicollimator** method consists of photographing, onto a glass plate, images projected through a number of individual collimators mounted in a precisely measured angular array

3-11. Laboratory Methods of Camera Calibration

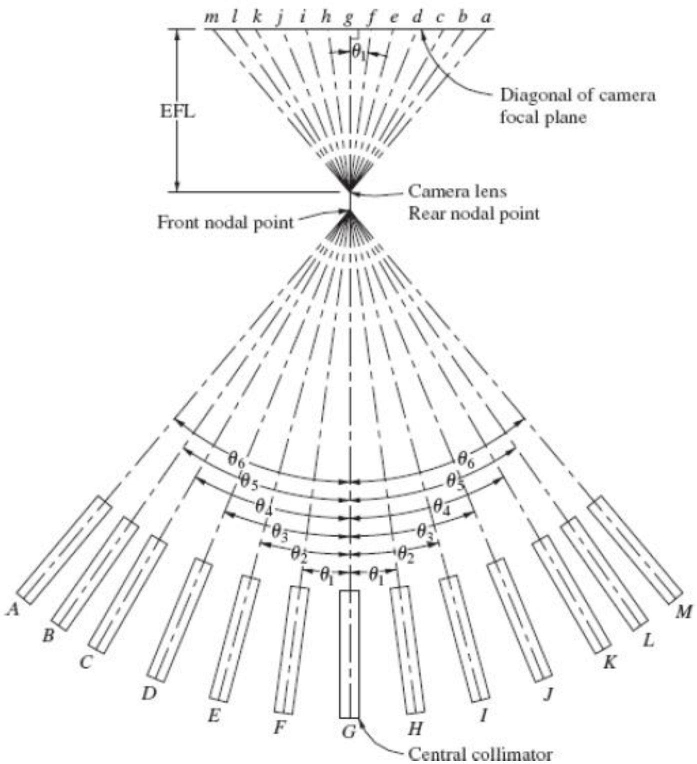

Figure 3-17. Bank of 13 collimators for camera calibration.

- A multicollimator for camera calibration consists of several individual collimators mounted in two perpendicular vertical planes (often, more than two planes are used)
- One plane of collimators is illustrated in Fig. 3-17
- The individual collimators are rigidly mounted so that the optical axes of adjacent collimators intersect at known (measured) angles, such as θ_1 of Fig. 3-17

- The equivalent focal length (EFL) is a computed value based on the distances from the center point g to each of the four nearest collimator crosses (h, f are shown in Fig. 3- 17 and the other two are in a perpendicular plane)
- Using the average of the four distances and the fixed angle θ_1 the EFL value is computed from the tangent ratio

3-11. Laboratory Methods of Camera Calibration

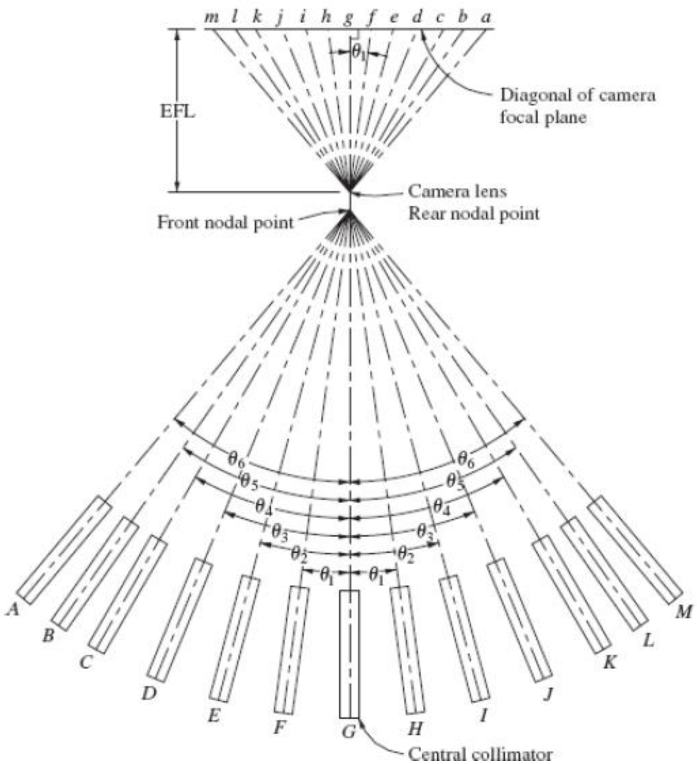

Figure 3-17. Bank of 13 collimators for camera calibration.

- The camera to be calibrated is placed so that its focal plane is perpendicular to the central collimator axis and the front nodal point of its lens is at the intersection of all collimator axes
- In this orientation, <u>image *g* of the central collimator</u>, which is called the ***principal point of autocollimation***, occurs very near the principal point, and also very near the intersection of lines joining opposite fiducials

3-11. Laboratory Methods of Camera Calibration

- The camera is further oriented so that when the calibration exposure is made, the collimator crosses will be imaged along the diagonals of the camera format, as shown in Fig. 3-18
- Figure 3-18 also contains a magnified view of the very center, which illustrates several key features In the close-up, the fiducial lines are indicated which are simply lines joining opposite pairs of fiducials, and their intersection defines the indicated principal point
- The position of the center collimator cross (principal point of autocollimation) typically serves as the origin of the photo coordinate system for film cameras

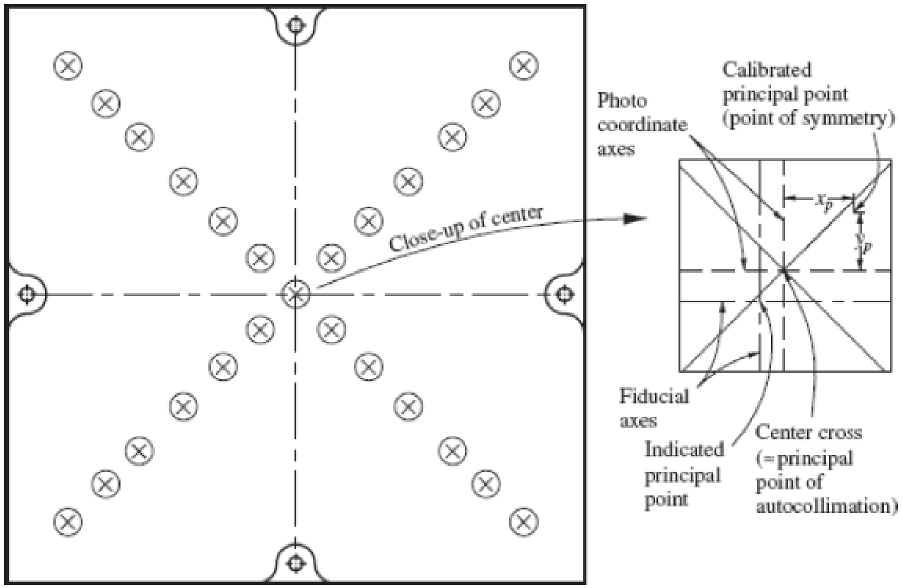

Figure 3-18. Images of photographed collimator targets and principal point definitions.

3-11. Laboratory Methods of Camera Calibration

- In a digital camera, the coordinates of the CCD elements are typically determined relative to an origin at one corner of the array
- In this case, the principal point of autocollimation will have nonzero coordinates
- The calibrated principal point (also known as the point of best symmetry) is the point whose position is determined as a result of the camera calibration
- This point is the principal point that should be used to make the most precise and accurate photogrammetric calculations

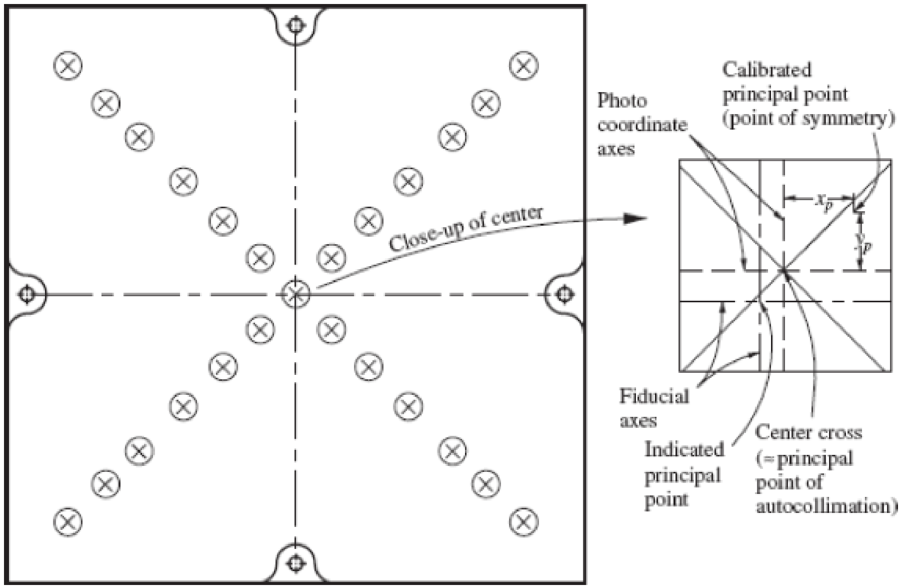

Figure 3-18. Images of photographed collimator targets and principal point definitions.

3-11. Laboratory Methods of Camera Calibration

- In determining the calibration parameters, a complex mathematical model is used which includes terms for the calibrated focal length and calibrated principal point coordinates as well as coefficients of symmetric radial lens distortion and decentering distortion
- A least squares solution is performed which computes the most probable values for the above-mentioned terms and coefficients
- The goniometer laboratory procedure of camera calibration is very similar to the multicollimator method, but consists of centering a precision grid plate in the camera focal plane
- The grid is illuminated from the rear and projected through the camera lens in the reverse direction
- The angles at which the projected grid rays emerge are measured with a goniometer, a device similar to a surveyor's theodolite
- CFL and lens distortion parameters are then computed with a mathematical model similar to that used in the multicollimator approach

3-12. Stellar and Field Methods of Camera

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods	(2) Stellar methods	(3) Field methods

- ❖ Both the multicollimator and goniometer methods of laboratory camera calibration require expensive and precise special equipment
- ❖ An advantage of stellar and field methods is that this special equipment is not necessary

3-12. Stellar and Field Methods of Camera

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods

(2) Stellar methods

(3) Field methods

- In the stellar method, a target array consisting of identifiable stars is photographed, and the instant of exposure is recorded
- Right ascensions and declinations of the stars can be obtained from an ephemeris for the precise instant of exposure so that the angles subtended by the stars at the camera station become known
- Then these are compared to the angles obtained from precise measurements of the imaged stars
- A drawback of this method is that since the rays of light from the stars pass through the atmosphere, compensation must be made for atmospheric refraction
- On the other hand, there will be a large number of stars distributed throughout the camera format, enabling a more precise determination of lens distortion parameters

3-12. Stellar and Field Methods of Camera

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods | (2) Stellar methods | (3) Field methods

- Field procedures require that an array of targets be established and that their positions with respect to the camera station be measured precisely and accurately in three dimensions ⇨ This can be achieved conveniently using GPS methods
- The targets are placed far enough from the camera station so that there is no noticeable image degradation
- In this configuration, the camera must be placed in a special apparatus such as a fixed tower, so that camera station coordinates are correctly related to target coordinates
  ⇨ This enables the CFL and principal point location to be determined as well as lens distortion parameters, even if the target configuration is essentially a two-dimensional plane
- If the targets are well distributed in depth as well as laterally, accurate location of the camera is less important

3-12. Stellar and Field Methods of Camera

In general, camera calibration methods may be classified into one of three basic

(1) Laboratory methods | (2) Stellar methods | (3) Field methods

- A variation of the field method described above, termed *in-flight* camera calibration, can also be employed
  - ⇨ In this approach, the aircraft carrying the camera makes multiple passes in different directions over a target range
- Based on a high number of redundant measurements of target images, additional parameters (i.e., calibration parameters) can be calculated
  - ⇨ This method has become more practical due to advancements in airborne GPS techniques which enable accurate camera station coordinates for each exposure
- The in-flight method can also be generalized to the point where calibration parameters are determined in conjunction with the photographs taken during the actual job
  - ⇨ This approach, known as *analytical self-calibration*

3-13. Calibration of Nonmetric Cameras

- In certain situations where accuracy requirements and budgets are low, photogrammetrists may employ nonmetric cameras for acquisition of imagery
- Nonmetric cameras are characterized by an adjustable principal distance, no film flattening or fiducial marks, and lenses with relatively large distortions
- Calibration of a nonmetric camera allows at least some compensation to be made for these systematic errors
- The problems caused by the lack of fiducial marks and film flattening mechanisms presented a challenge when calibrating nonmetric film cameras
- Fortunately nearly all nonmetric camera applications currently use digital cameras, so these issues are no longer present
- However, the issue of the effective distorted shape of the CCD array must be addressed in order to obtain the highest degree of accuracy from digital cameras
  - ⇨ Mathematical models can be used to correct for this effect, although the distortion from nonflatness remains

3-13. Calibration of Nonmetric Cameras

- A further complication in the calibration of nonmetric cameras arises when one is dealing with different focusing distances
- Lens distortion values vary with different focus settings (i.e., different principal distances), thereby requiring a more general lens distortion model
  - ⇨ This problem can be avoided by setting the focus of the camera to infinity during calibration as well as during normal use
  - ⇨ That way, one set of lens distortion parameters can be determined to account for this consistent focus setting
- If the camera is used for close-range work, the aperture size should be minimized in order to produce the sharpest images
- The stability of focusable lenses—particularly zoom lenses—should be considered with suspicion
- The calibration parameters for nonmetric cameras will often change significantly, particularly if the camera has been bumped or subjected to vibrations
- Nonmetric cameras should be calibrated both pre- and postmission to determine whether parameters have significantly changed

3-14. Calibrating the Resolution of a Camera

- In addition to determining interior orientation elements, laboratory methods of camera calibration provide an evaluation of the camera's resolving power

- There are two common methods of specifying lens resolving power
  - ① One is a direct count of the maximum number of lines per millimeter that can be clearly reproduced by a lens
  - ② The other is the *modulation transfer function* (MTF) of the lens

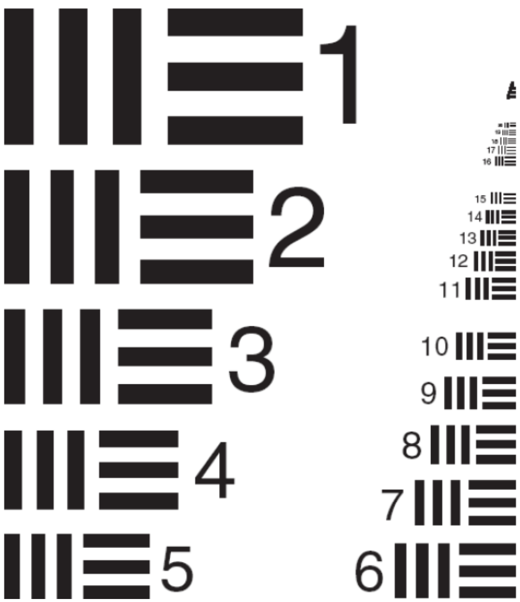

Figure 3-19. Resolution test pattern for camera calibration.

- The method of calibration employed to determine the line count consists of photographing resolution test patterns using a very high-resolution emulsion

- The test patterns (an example is shown in Fig. 3-19) are comprised of numerous sets of *line pairs*
  - ⇨ The measure of line thickness for each set is its number of line pairs per millimeter

3-14. Calibrating the Resolution of a Camera

❖ Line thickness variations in a typical test pattern may range from 10 to 80 or more line pairs per millimeter

❖ If the multicollimator method is used to calibrate a camera, the test patterns may be projected by the collimators simultaneously with the collimator crosses and imaged on the diagonals of the camera format

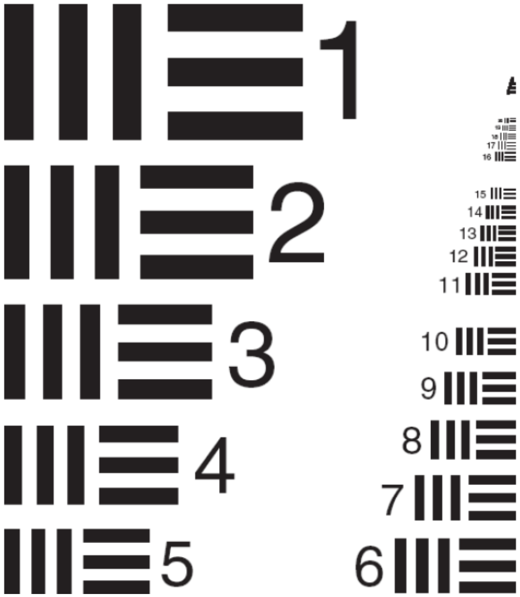

Figure 3–19. Resolution test pattern for camera calibration.

❖ After the photograph is made, the resulting images are examined under magnification to determine the finest set of parallel lines that can be clearly resolved

❖ The average of the four resolutions at each angular increment from the central collimator is reported in the calibration certificate

❖ Another parameter generally reported is the *area-weighted average resolution* (AWAR), which is an indication of resolution over the entire format

3-14. Calibrating the Resolution of a Camera

- Shortcomings of above-described maximum-line-count method : In the line count procedure, with each succeedingly smaller test pattern, the sharpness of distinction between lines and spaces steadily diminishes, and the smallest pattern that can clearly be discerned becomes somewhat subjective
  ⇨ The preferred measure of resolution is the modulation transfer function.

- A fundamental concept involved in quantifying the modulation transfer function is the notion of *spatial frequency*

- Spatial frequency is a measure of the number of cycles of a sinusoidal wave per unit distance, and units of spatial frequency are typically given in terms of cycles per millimeter

- A black-and-white line pair corresponds to the up-and-down pulse of a sine wave and thus can be defined as one cycle of a wave
  ⇨ Therefore the number of line pairs per millimeter is equivalent to cycles per millimeter, or spatial frequency

- Images that contain areas of rapidly changing levels of brightness and darkness have high spatial frequency, whereas images that contain areas of gently changing levels have low spatial frequency

3-14. Calibrating the Resolution of a Camera

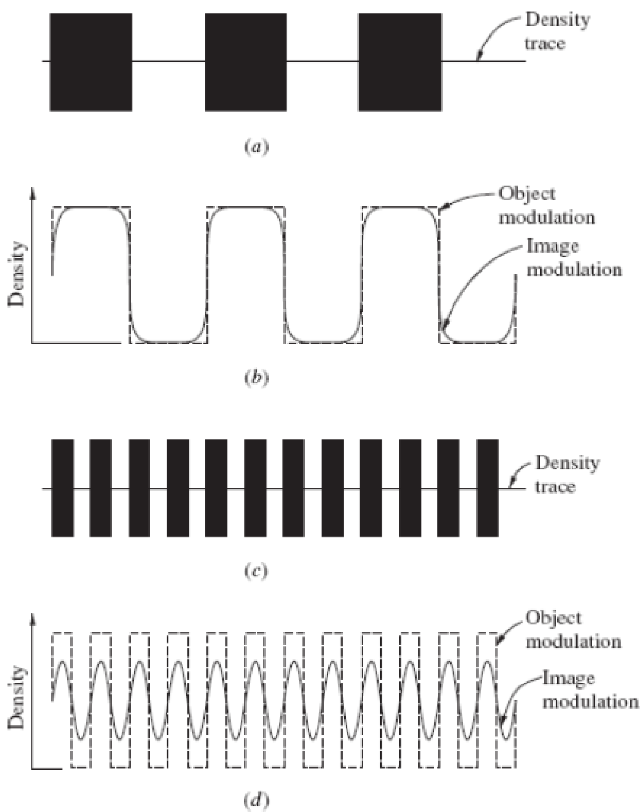

Figure 3-20. (a) Test object at low spatial frequency with density trace. (b) Density modulation of object (dashed) and image (solid). (c) Test object at high spatial frequency with density trace. (d) Density modulation of object (dashed) and image (solid). [Note that in part (b), the amplitude of the image modulation is the same as that of the object, corresponding to 100 percent modulation transfer. In (d) however, amplitude of the image modulation is one-half that of the object, corresponding to reduced modulation transfer.]

- To determine modulation transfer, density scans using a photogrammetric scanner are taken in a single trace across test patterns similar to those used in the line count procedure, as shown in Fig. 3-20a and c
- For heavy lines with wide spacing, the actual distribution of density (brightness variations) across the object pattern would appear as the dashed lines shown in Fig. 3-20b, whereas brightness distributions measured with a densitometer across the image of this pattern would appear as the solid lines
- Note that the edges of the image patterns are rounded somewhat in Fig. 3-20b, but the amplitude of brightness differences is the same as that for the original object
  ⇨ Thus at this spatial frequency of the pattern, modulation transfer is said to be 100 percent

3-14. Calibrating the Resolution of a Camera

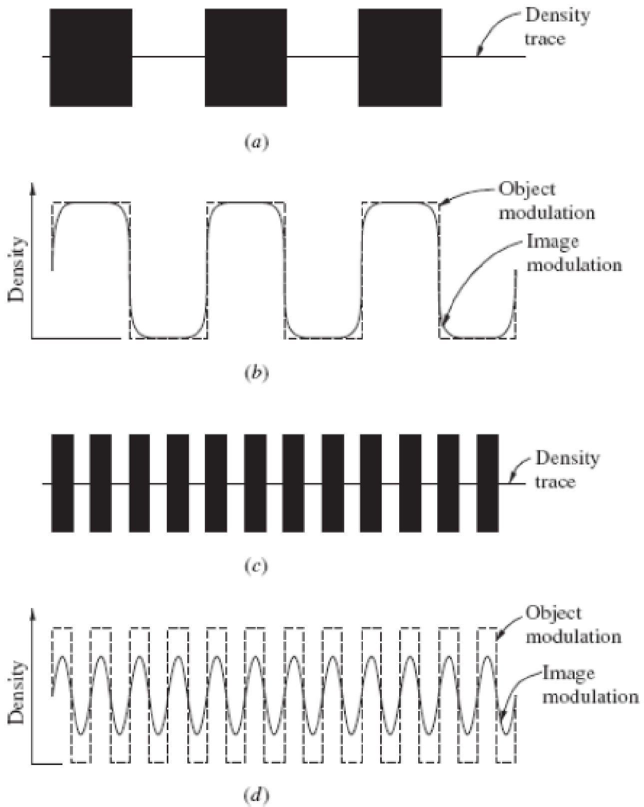

Figure 3-20. (a) Test object at low spatial frequency with density trace. (b) Density modulation of object (dashed) and image (solid). (c) Test object at high spatial frequency with density trace. (d) Density modulation of object (dashed) and image (solid). [Note that in part (b), the amplitude of the image modulation is the same as that of the object, corresponding to 100 percent modulation transfer. In (d) however, amplitude of the image modulation is one-half that of the object, corresponding to reduced modulation transfer.]

- Figure 3-20c shows an object pattern at a frequency four times that of the pattern shown in Fig. 3-20a
- The density distributions of the object and resulting image of this higher-frequency pattern are shown in Fig. 3-20d
  - ⇨ In this figure, not only are the edges rounded, but also the amplitude of brightness differences is about one-half that of the original object
  - ⇨ This indicates a modulation transfer of 50 percent from object to image
- Fig. 3-20 is a somewhat simplified illustration of the quantification of modulation transfer
  - In the rigorous determination of modulation transfer, exposure values (rather than densities), which have a logarithmic relationship to density, are employed

3-14. Calibrating the Resolution of a Camera

- By measuring densities across many patterns of varying spatial frequencies, and plotting the resulting modulation transfer percentages on the ordinate versus corresponding spatial frequencies on the abscissa, a curve such as that illustrated in Fig. 3-21 is obtained ⇨ This curve is the *modulation transfer function (MTF)*
- The MTF has a number of advantages over the simple line count method

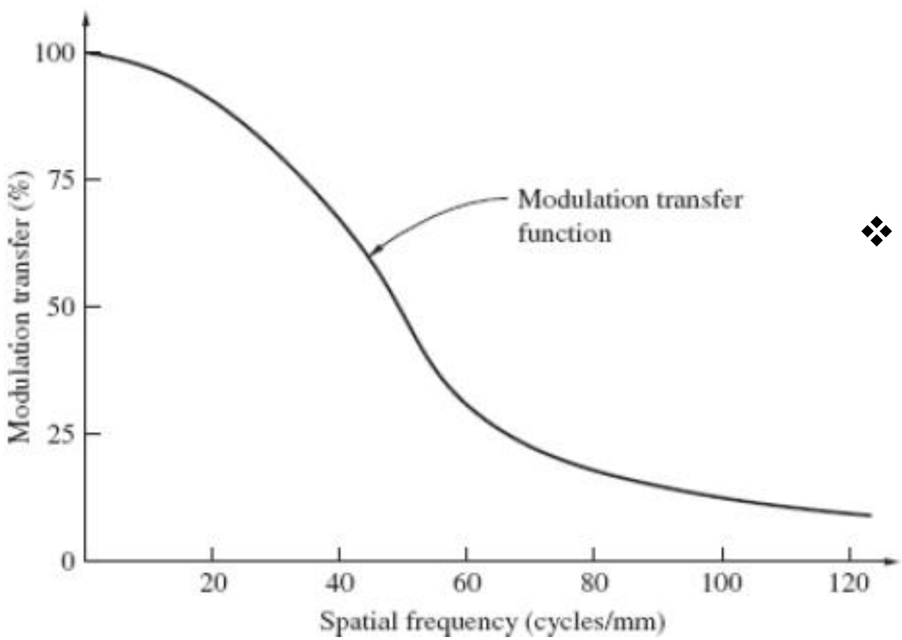

Figure 3-21. Curve of modulation transfer function (MTF).

- It is a very sensitive indicator of edge effects, and it also affords the capability of predicting the resolution that may be expected at any given degree of detail
- Furthermore, MTF curves can be combined for different lenses, films, and film processes; thus, it is possible to estimate the combined effects of any given imaging system
    - For these reasons, the MTF has become the preferred method of expressing resolution

3-14. Calibrating the Resolution of a Camera

- The upper limit of resolution for a digital frame camera is absolutely fixed because of sampling into discrete elements
- Since a full cycle of a wave in terms of spatial frequency must consist of a dark-to-light transition (line pair), two CCD elements are the minimum number that can capture information at the highest frequency
- Thus the maximum spatial frequency (best resolution) at image scale that can be detected is

$$f_{max} = \frac{1}{2w}$$

where w = width between centers of adjacent CCD elements
f_{max} = maximum detectable frequency