Chapters 1 & 2

- Chapter 1: Photogrammetry
  - Definitions and applications
  - Conceptual basis of photogrammetric processing
    - Transition from two-dimensional imagery to three-dimensional information
  - Automation
- Chapter 2: Electromagnetic radiation
  - Terminology
  - Blackbody radiation
  - Active versus passive remote sensing systems
  - Wavebands of the electromagnetic radiation

CE59700: Chapter 3

Basic Optics

Overview

- Introduction & objectives
- Basic camera components
- Reflection and refraction
- Lens system: Definitions
- Lens equation, aberrations, and distortions
- Diffraction
- Resolving power of imaging systems

Photo. Input: Image Coordinate Measurements

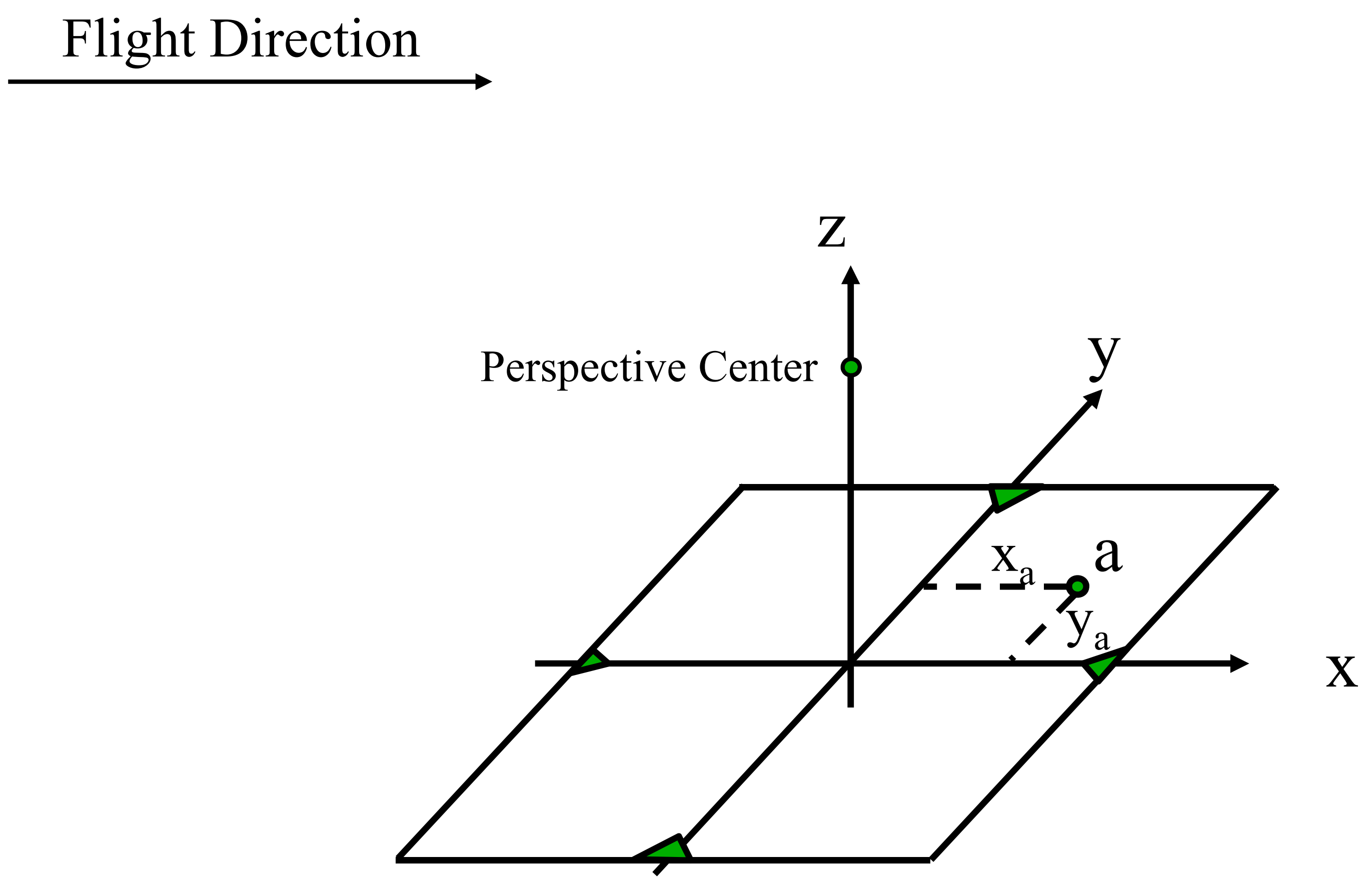
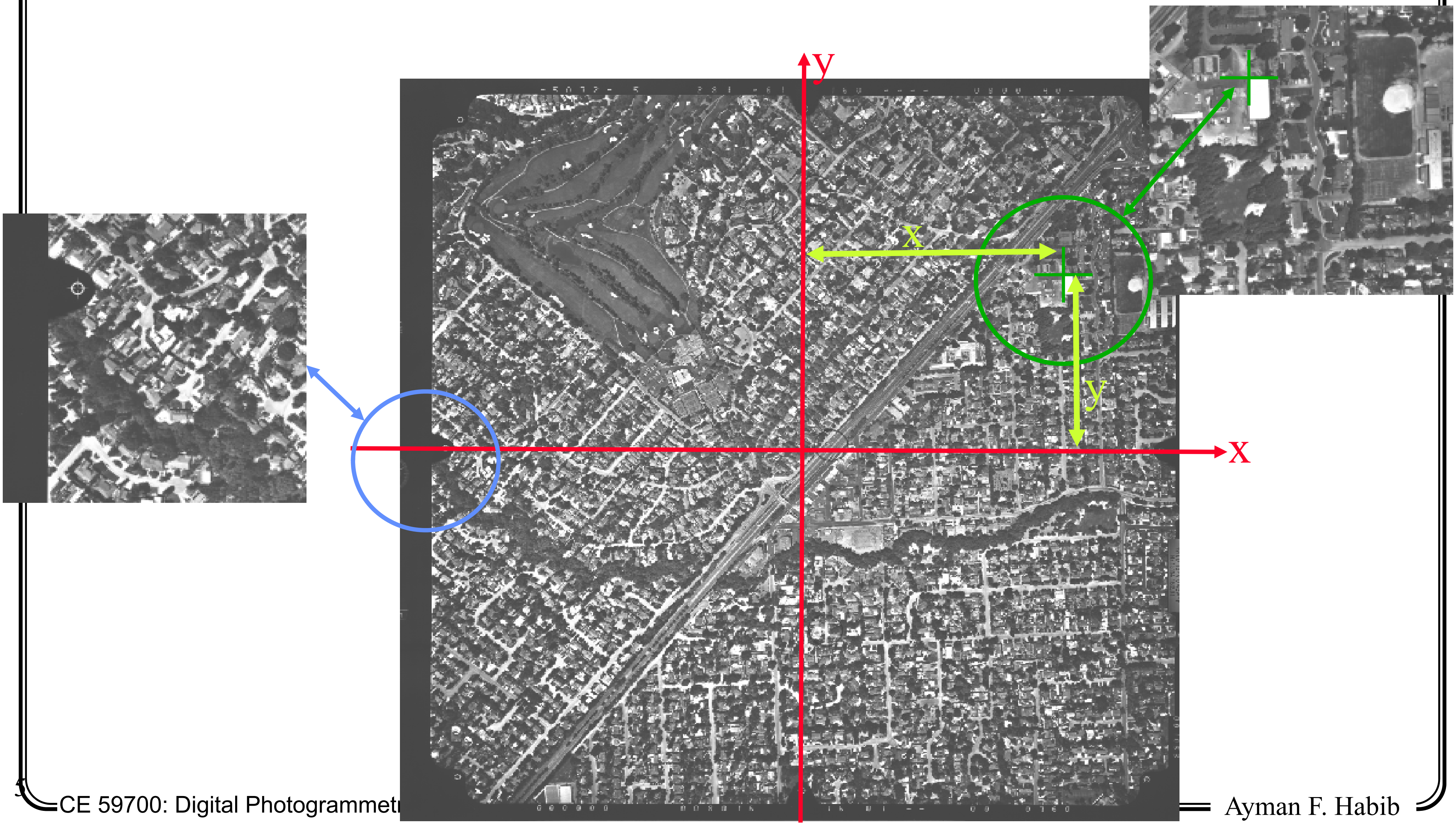
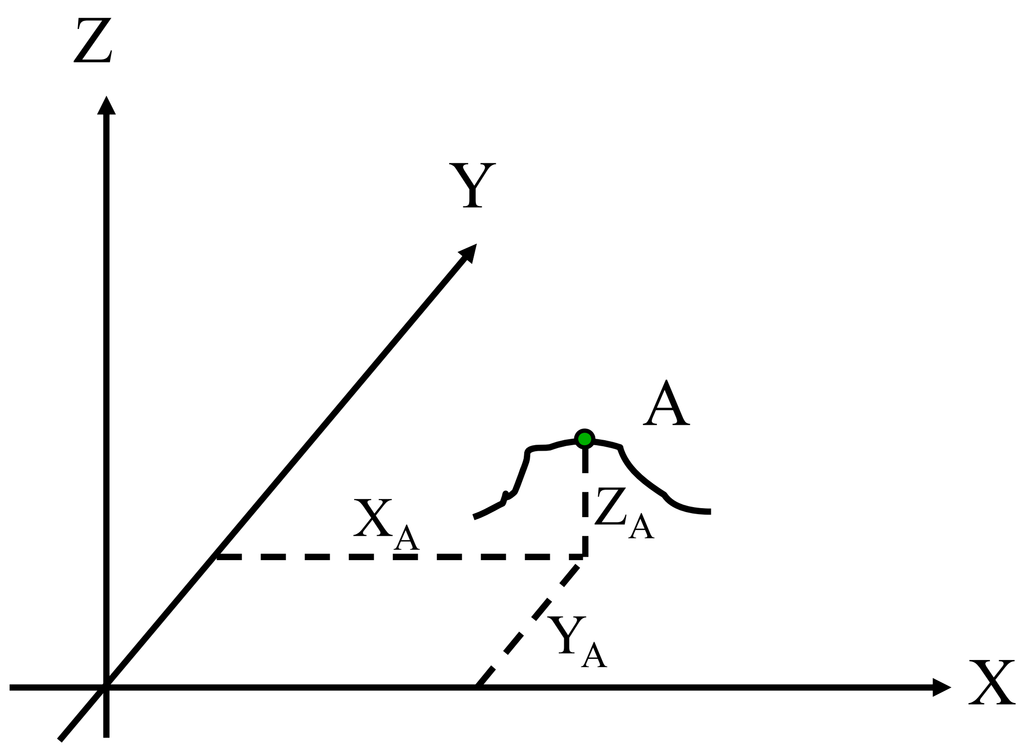


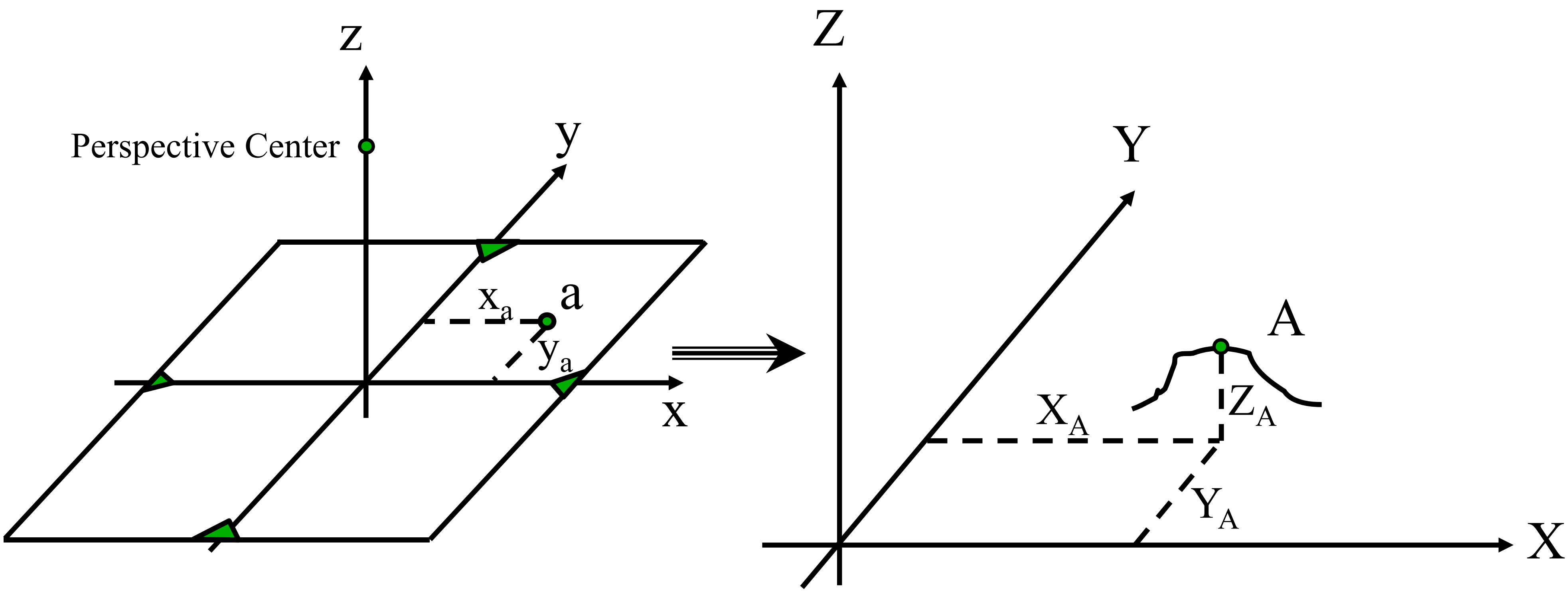
Photo. Input: Image Coordinate Measurements



Photogrammetric Output: Ground Coordinates



Photogrammetric Mathematical Model



$$x_a = f_x(X_A, Y_A, Z_A, \ldots\ldots\ldots)$$

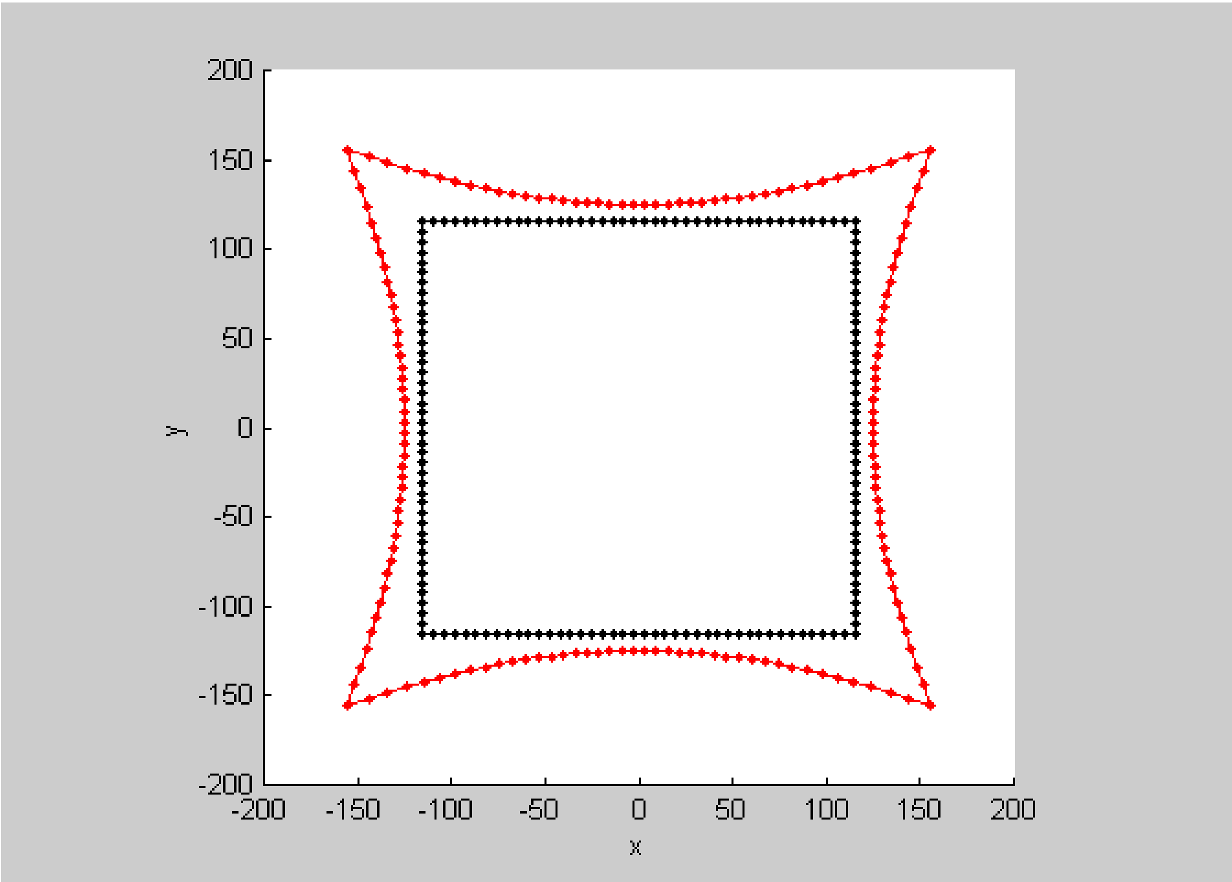
$$y_a = f_y(X_A, Y_A, Z_A, \ldots\ldots\ldots)$$

Objectives

- Investigate various factors that might affect:
  - Our ability to precisely identify features of interest in the acquired imagery
    - Aberrations
    - Diffraction
    - Depth of field
    - Depth of focus
    - Motion blur
  - The accuracy with which we measure the image coordinates of these features
    - Distortions (radial and de-centering lens distortions)

Aberrations

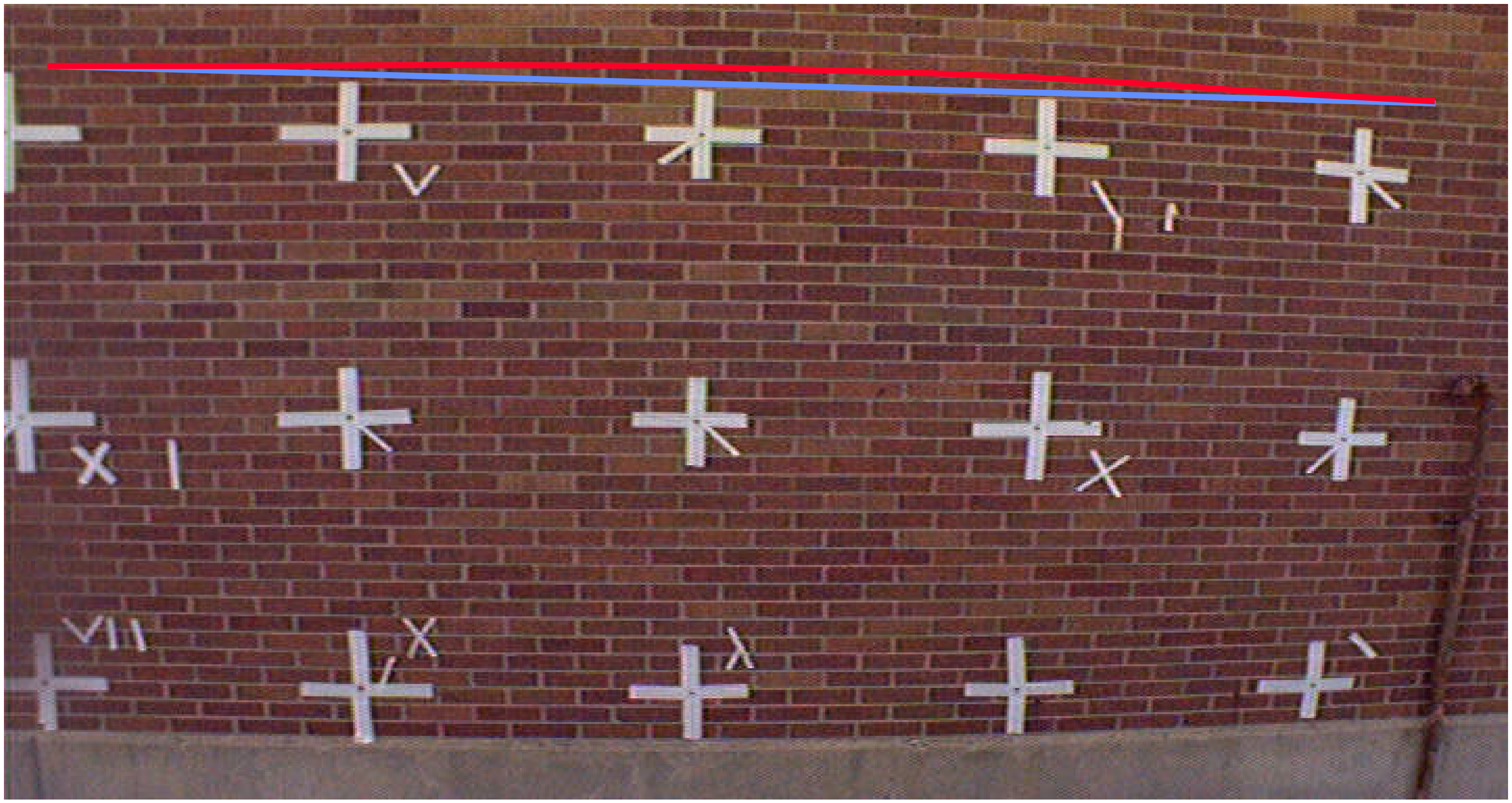
Distortions



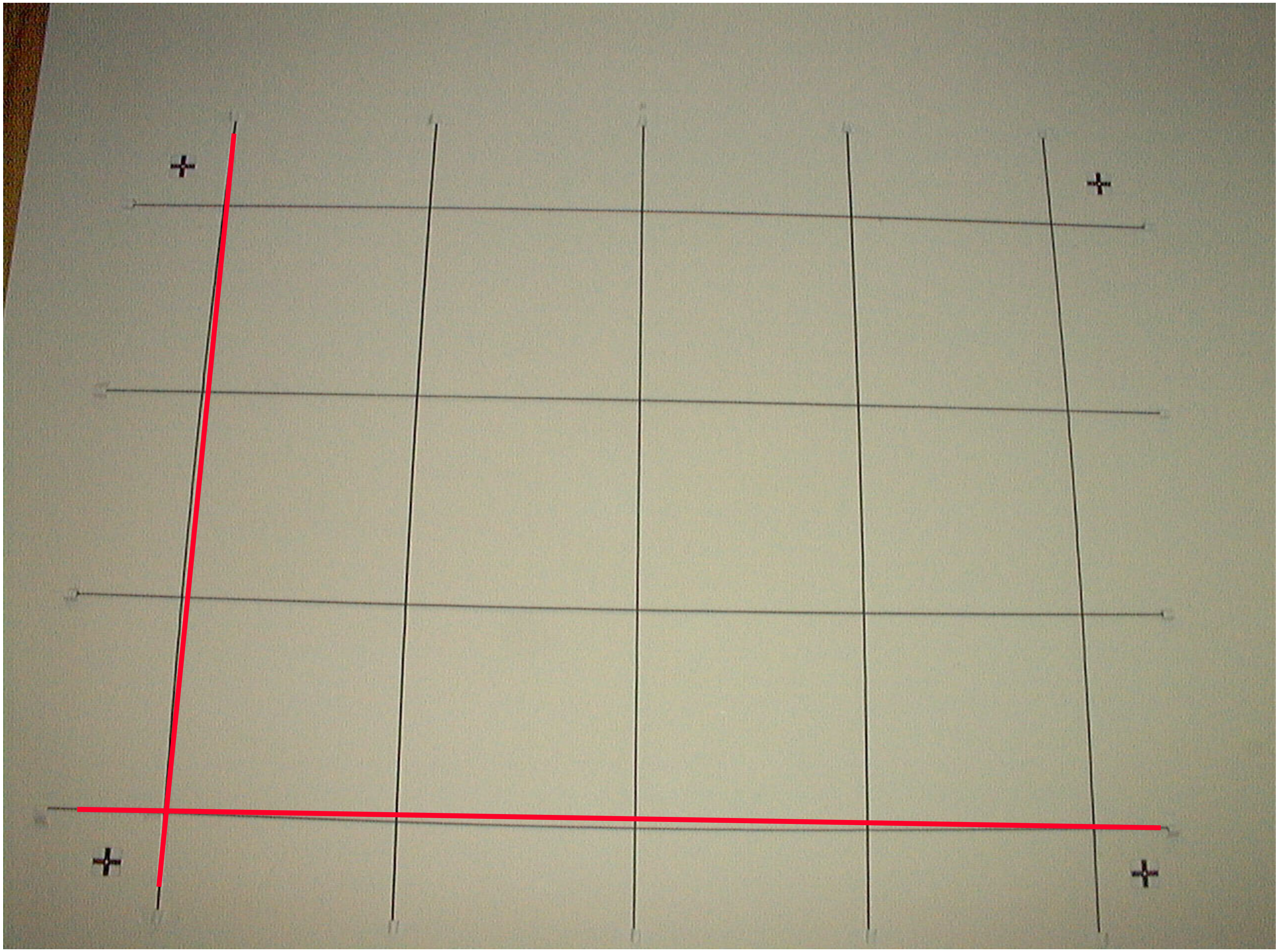
Without distortions

With distortions

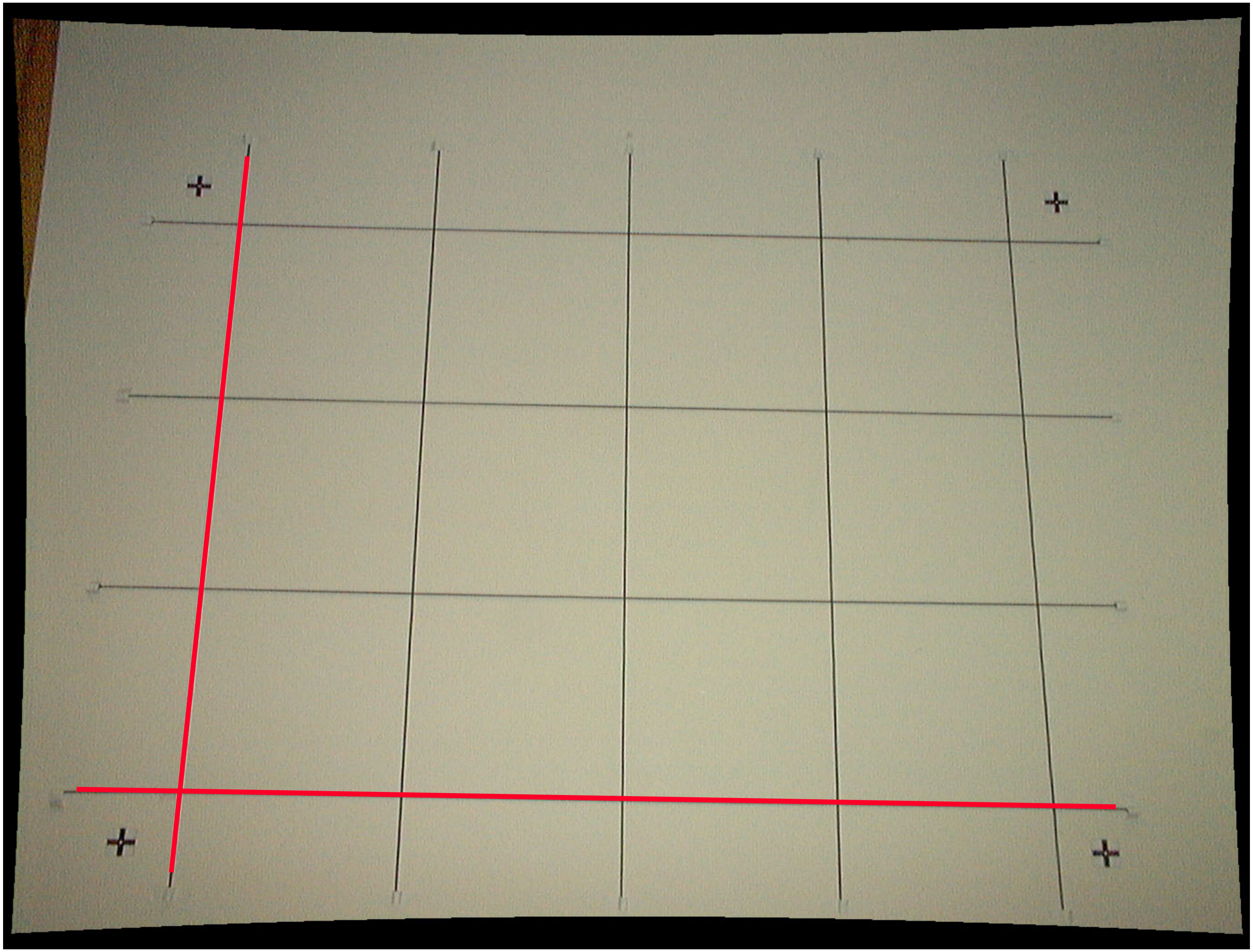
Distortions



Before Distortion Removal

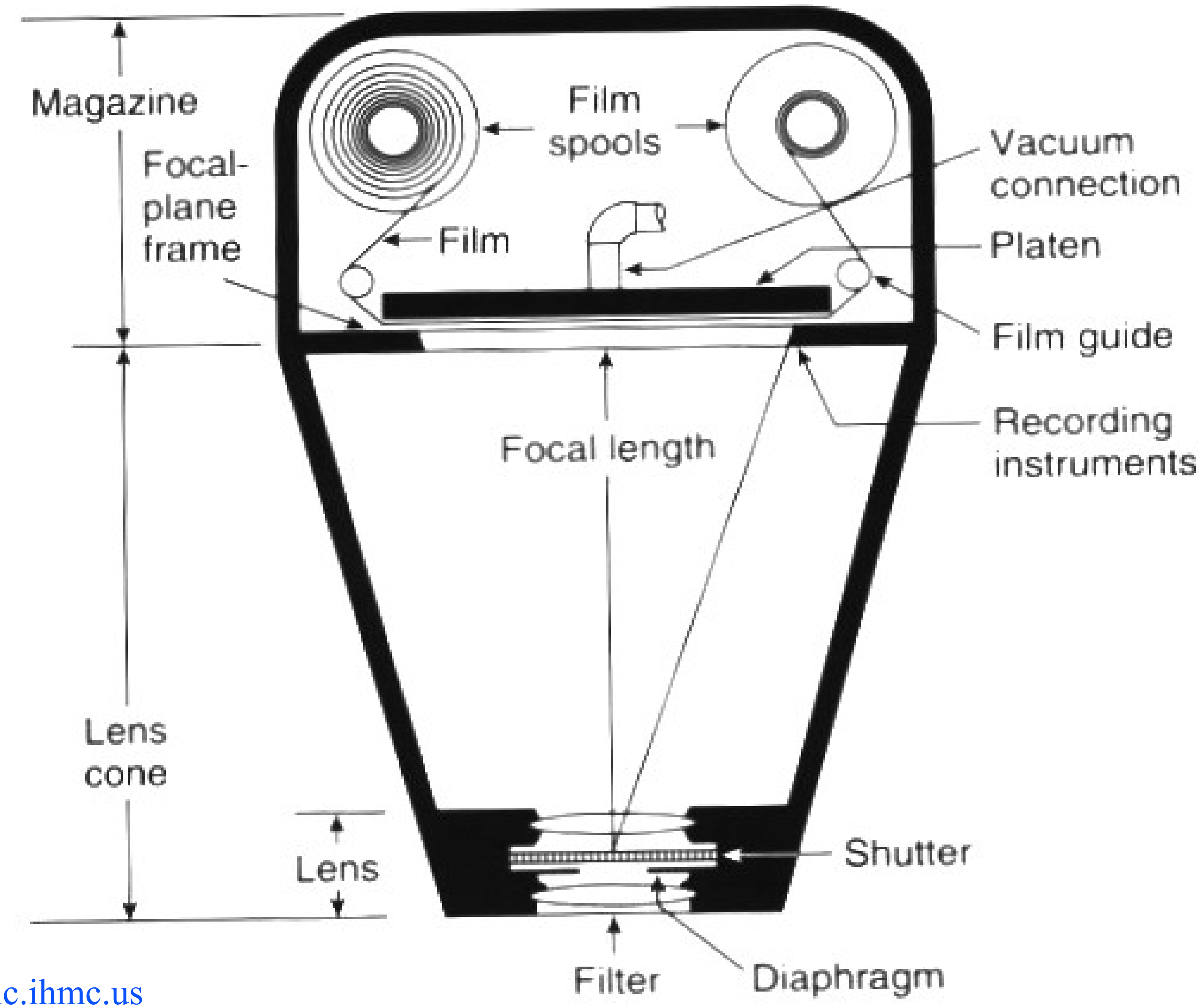


After Distortion Removal



Photogrammetric Cameras

Analog Photogrammetric Cameras

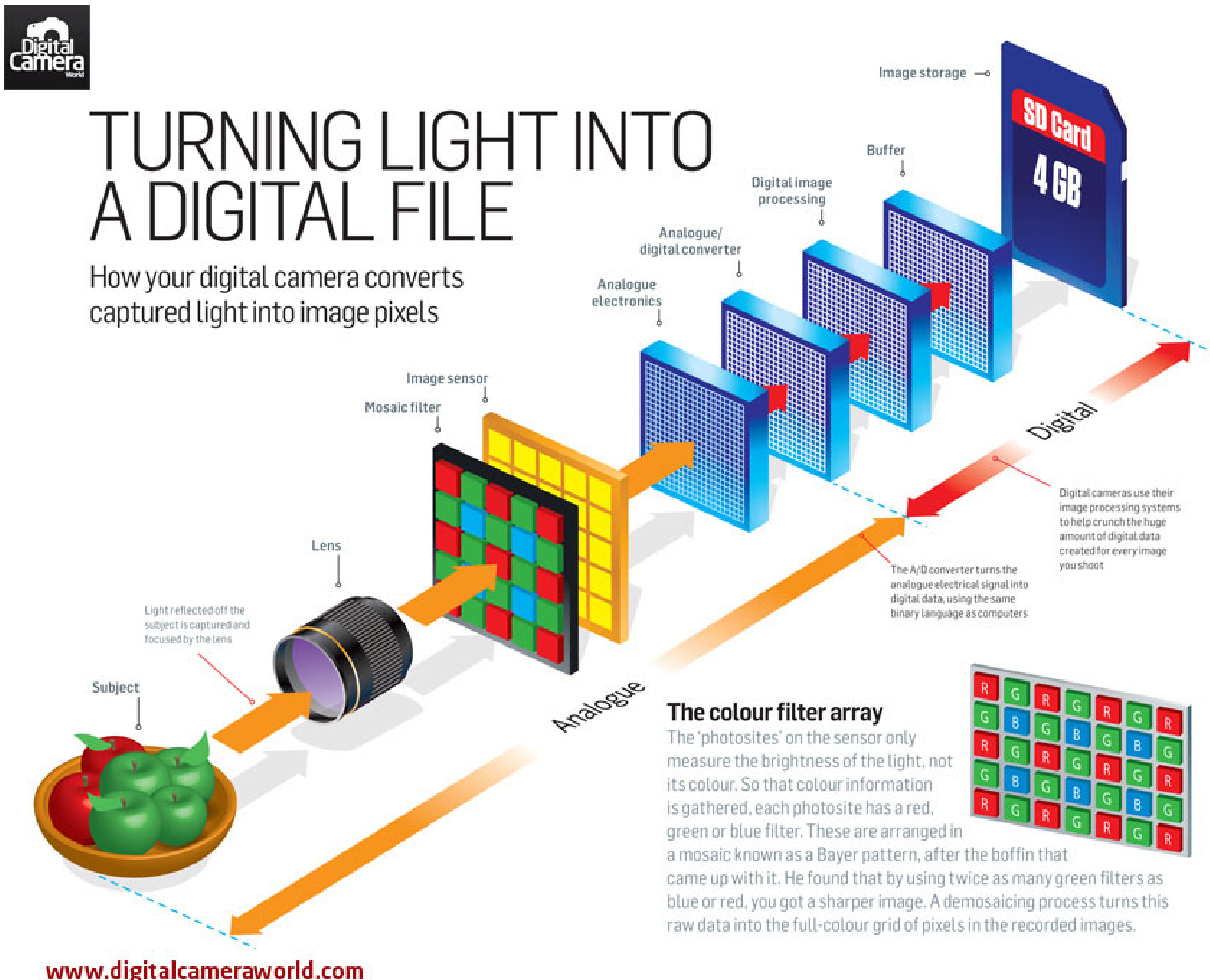


http://cmapspublic.ihmc.us

Analog Aerial Camera: RC30

http://www.leica-geosystems.com

Digital Cameras



Block Diagram of a Digital Camera

Digital Aerial Camera: DMC™

http://www.ziimaging.com

Basic Components of a Camera

- Lens: collects light and brings it to focus at the image plane
- Aperture: opening that controls the amount of light entering the camera
- Shutter: determines the time period during which the film/digital sensor will be exposed to light
- Film/digital sensor: light-sensitive media
- Body: light proof housing of the camera mechanism

Basic Optics

- Optics is the science of controlling and manipulating light.
- Optics is divided into two main branches:
  - Geometric optics, and
  - Physical optics.
- In geometric optics, light is considered as groups or bundles of rays traveling in straight lines.
  - These groups or bundles might be parallel to each other, converge toward each other, or diverge from one another.
  - If all the rays are traveling parallel to each other, the light is said to be *collimated*.

Basic Optics: Physical Optics

- In physical optics, light is treated as a group of electromagnetic waves in which the light propagation is considered as a progression of these waves.
- Each of these waves has its own amplitude, frequency, and phase.
- If the waves propagate along parallel lines, the light is said to be collimated.
- If the waves propagate along converging or diverging lines, the light is considered to be convergent or divergent, respectively.

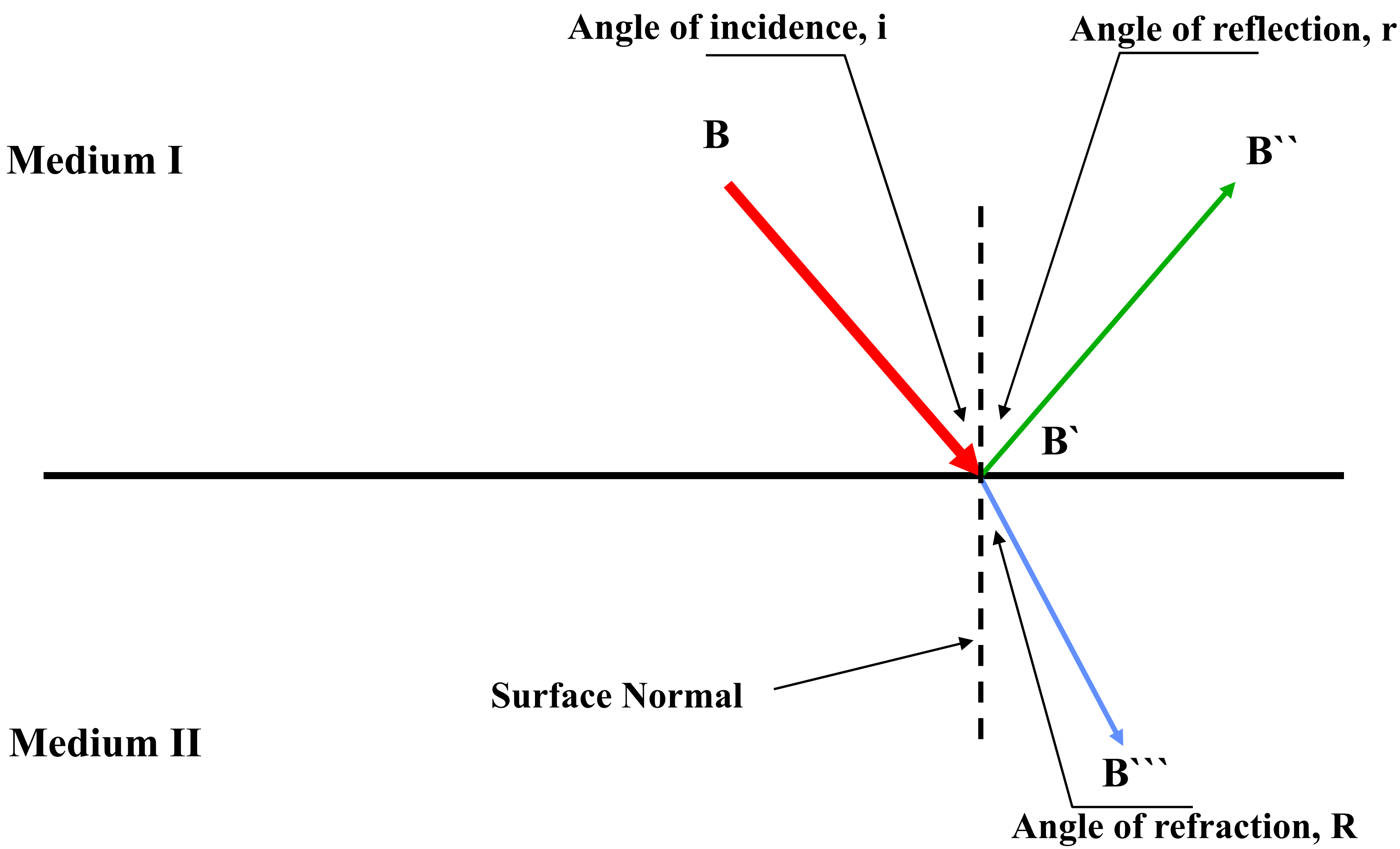
Reflection & Refraction

- When a light ray strikes the surface of an object:
  - Part of the light may be transmitted through the object material,
  - Part of it may be reflected, and
  - Part of it may be absorbed.
- Light passing from one transparent material to another of different composition, as from air to glass, will undergo a change in velocity.
- The velocity in each medium depends on the refractive index of that medium.

Reflection & Refraction

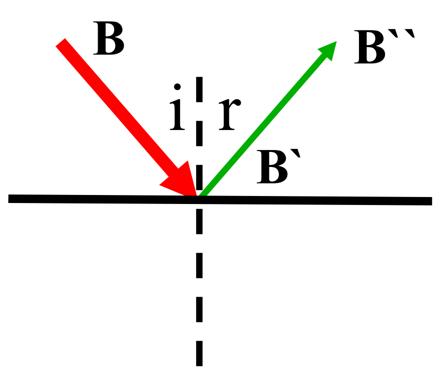
- The refractive index of a medium (n) is defined as:
  - $n = c/v$
  - where:
    - c is the velocity of light in vacuum ($3 * 10^8$ m/sec).
    - v is the velocity of light in the medium under consideration.

Reflection & Refraction



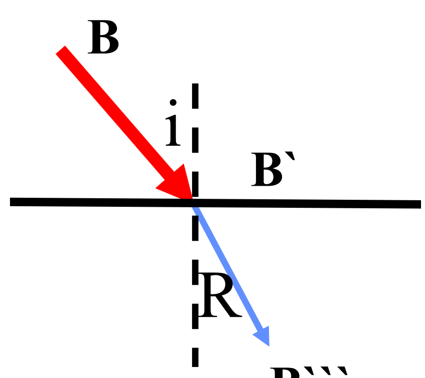
Law of reflection

- The reflection law controls the path (BB`B``).
- The reflection law states that:
  - The incident ray, the surface normal, and the reflected ray lie in the same plane.
  - The incident angle (i) = the reflection angle (r)

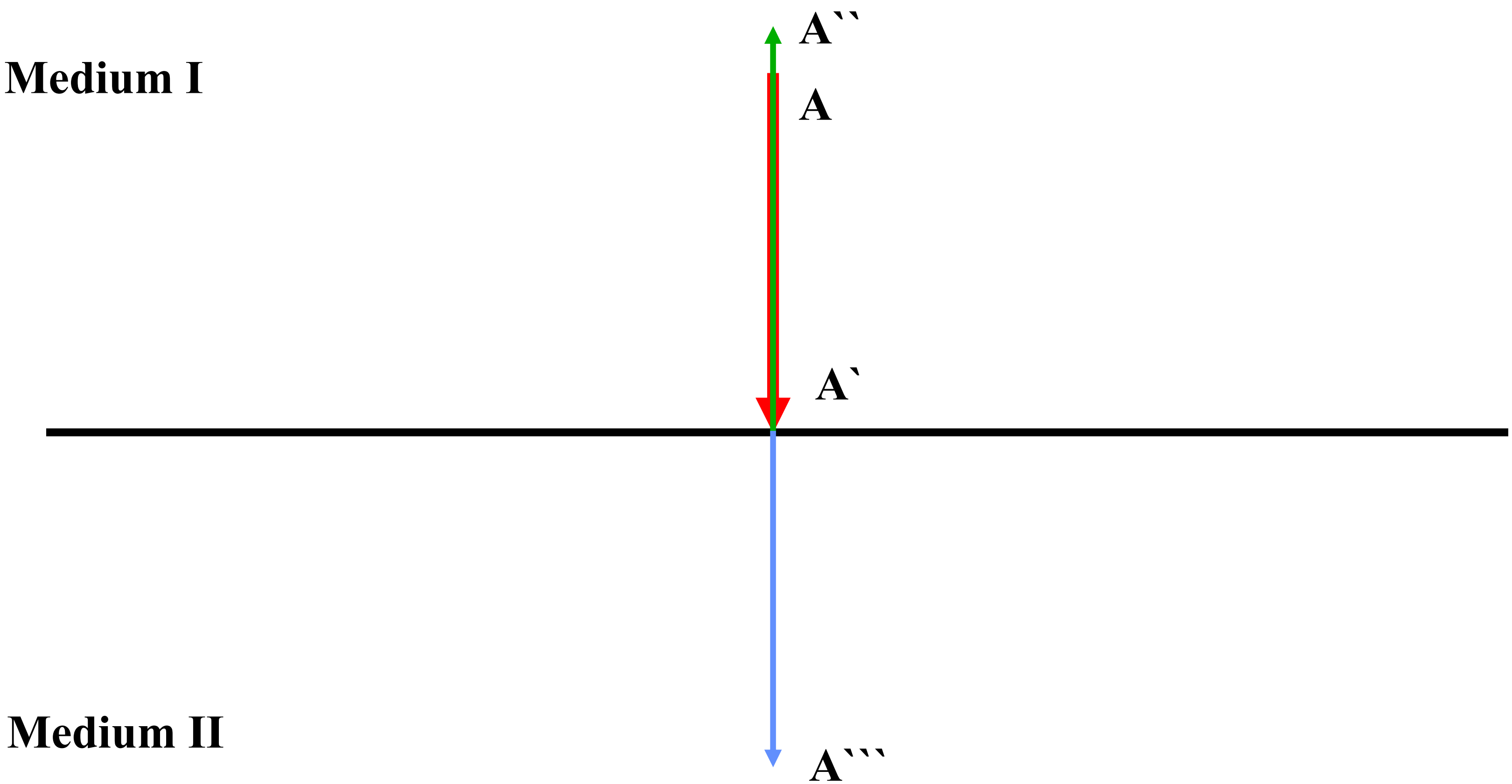


Law of Refraction (Snell's Law)

- The refraction law controls the path (BB`B```).
- Snell's Law states that:
  - The incident ray, the surface normal, and the refracted ray lie in one plane.
  - $n_i \sin(i) = n_R \sin(R)$
  - where:
    - n_i is the refractive index of the medium containing the incident ray.
    - n_R is the refractive index of the medium containing the refracted ray.



Reflection and Refraction: Special Case



- If a light ray is directed from one transparent medium to another normal to the surface separating the two media, part of it will be reflected back on itself.
- The other part continues in the same direction in the second medium.

Reflection & Refraction

- Examining Snell's Law, we can see that the refracted ray will be bent toward the surface normal if this medium has higher refractive index.
- If the light ray is directed from a medium of higher refractive index to one of lower refractive index, the ray will be bent away from the surface normal in the second medium.
  - As the incidence angle increases, the refraction angle also increases with a greater rate until it reaches (90°).
  - Beyond this point, the ray is totally reflected.

Critical Angle

- The incident angle, i_c, which causes a (90°) angle of refraction is called the *critical angle* for the two media.
- This angle can be determined from the law of refraction as follows:

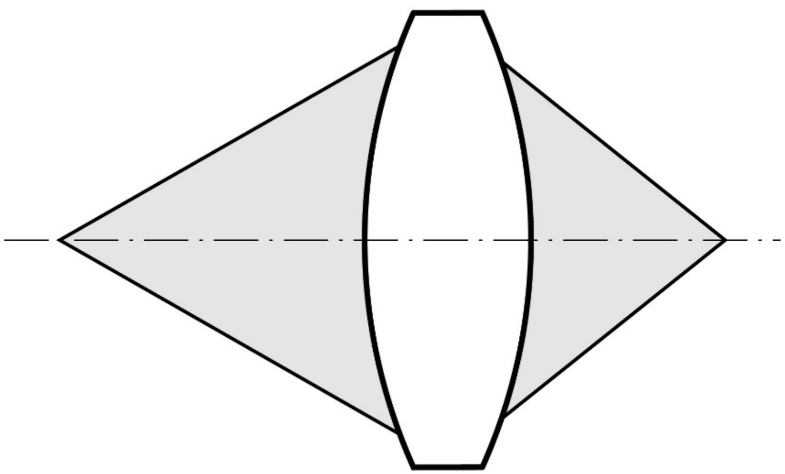
$$\sin(i_c) = {n_R}/{n_i}$$

Lens System

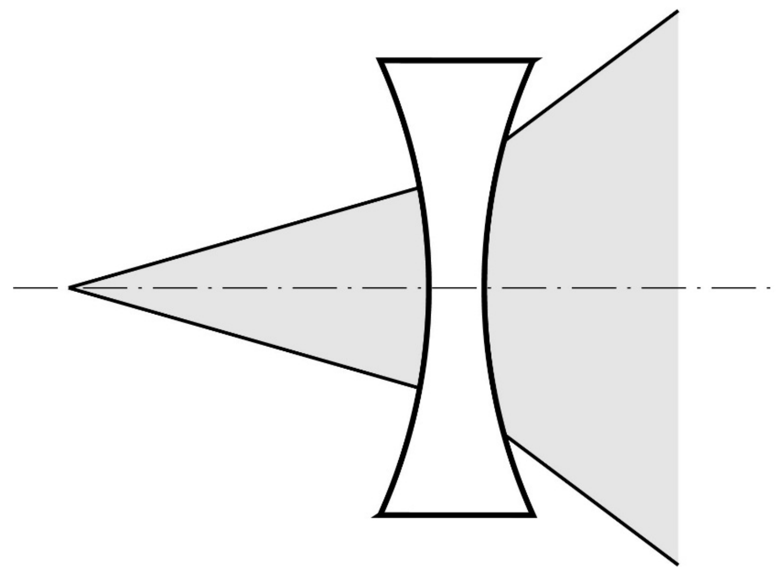
- The function of a lens in photogrammetry is to gather light rays and bring them into focus at a point.
- A positive lens changes a divergent light bundle, originating from a point source, to a convergent bundle.
- A negative lens makes the bundle more divergent.

Lens System

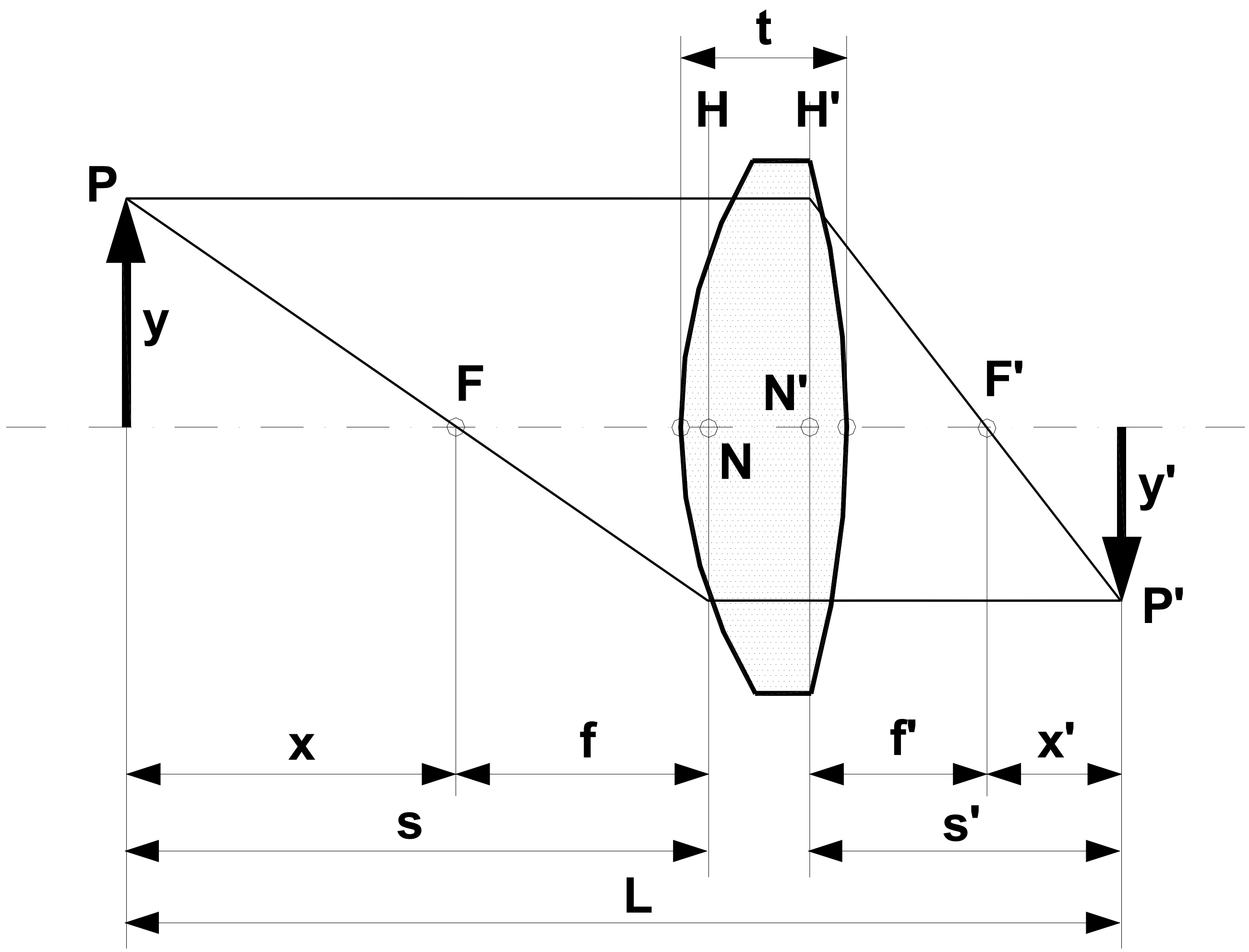
Positive Lens



Negative Lens



Basic Definitions



Basic Definitions

- Optical System:
  - any device that operates on light to produce a specific and desired effect
- Optical Axis:
  - the rotational axis of the optical system that passes through the centers of curvature of surfaces comprising the lens system
- Principal Planes (H, H`):
  - are perpendicular to the optical axis and located in such a way that the lateral magnification at their location is unity and positive
- Lateral Magnification:
  - the ratio between the image and object size

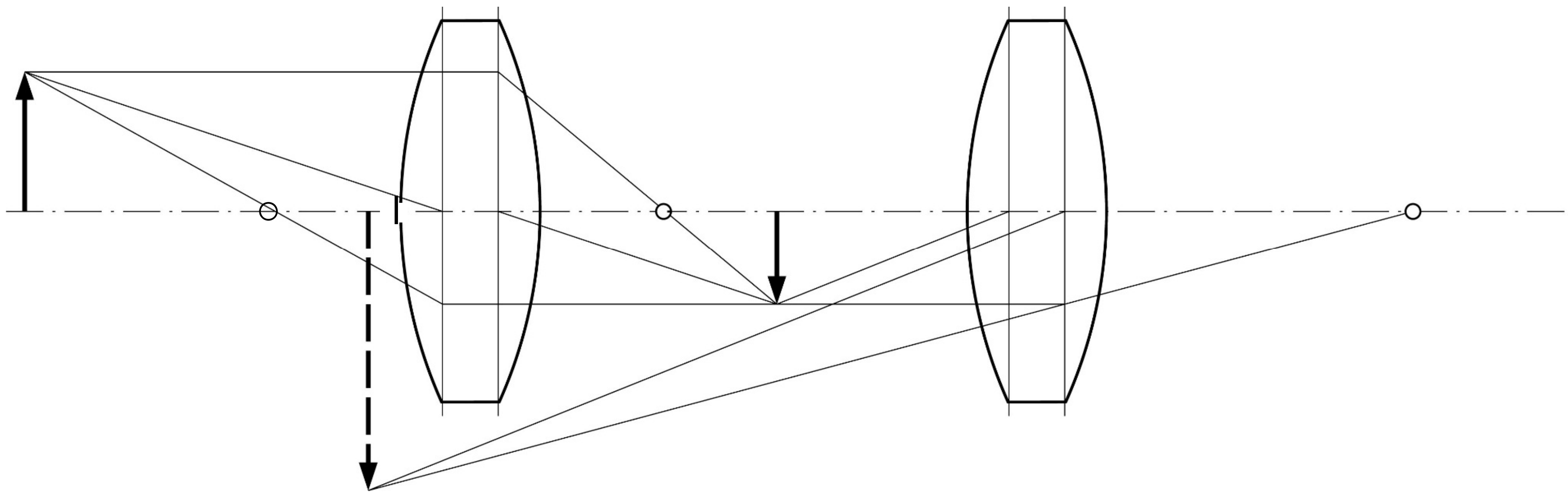
Basic Definitions

- Nodal Points (N, N`):
  - are the intersection of the principal planes with the optical axis.
  - a ray passing through the first nodal point will emerge from the rear nodal point parallel to the incident ray.
- Focal Points (F, F`):
  - are the axial points where the images of axial objects at infinity are located.
- Focal Length (f, f`):
  - is the distance between the focal point and the corresponding nodal point.

Lens Equation

- The lens equation relates the focal length (f`), the image distance (s`), and the object distance (s).
  - $1/f` = 1/s + 1/s`$
- Notes:
  - When $s \rightarrow \infty$ then $s` \rightarrow f`$
  - A ray parallel to the optical axis will be refracted in such a way that it passes through the rear focal point.
  - A ray through the front nodal point will emerge from the rear nodal point without changing its direction.
  - These simple rules allow for graphic construction of images.
  - From now on, we will assume that f is equal to f`.

Image Formation from Geometric Optics



Lens Equation for Aerial Cameras

- The object distance (*s*) is defined by the flying height above the ground (H - *h*).
- The image distance (s\`) is usually labeled as the camera constant or principal distance (*c*).
- The object distance (*s*) is very large when compared to the focal length (*f*).
  - $s \approx \infty$
  - Therefore, the image distance (s\`) is set to the focal length (*f*).
  - $c = f$

Paraxial Region

- Assumptions made in geometric optics for image formation lead to inaccuracies, which are proportional to the angle between a light ray and the optical axis (off-axial angle).
- The lens formula is only valid for very small off-axial angles where:
  - $Sin\ (\theta) = \theta$ in radians, and
  - $tan\ (\theta) = \theta$ in radians.
- That is, it is only valid for objects close to the optical axis.
  - This area is called the paraxial region.

Lens Aberrations

- Assumption: An object point will be imaged as a point.
- Actually: An object point will be imaged as a blur.
- Reason: Lens Aberrations
- Factors causing aberrations include:
  - Different wavelengths of the incident light,
  - Object points with large off-axial angle, and
  - Manufacturing flaws.

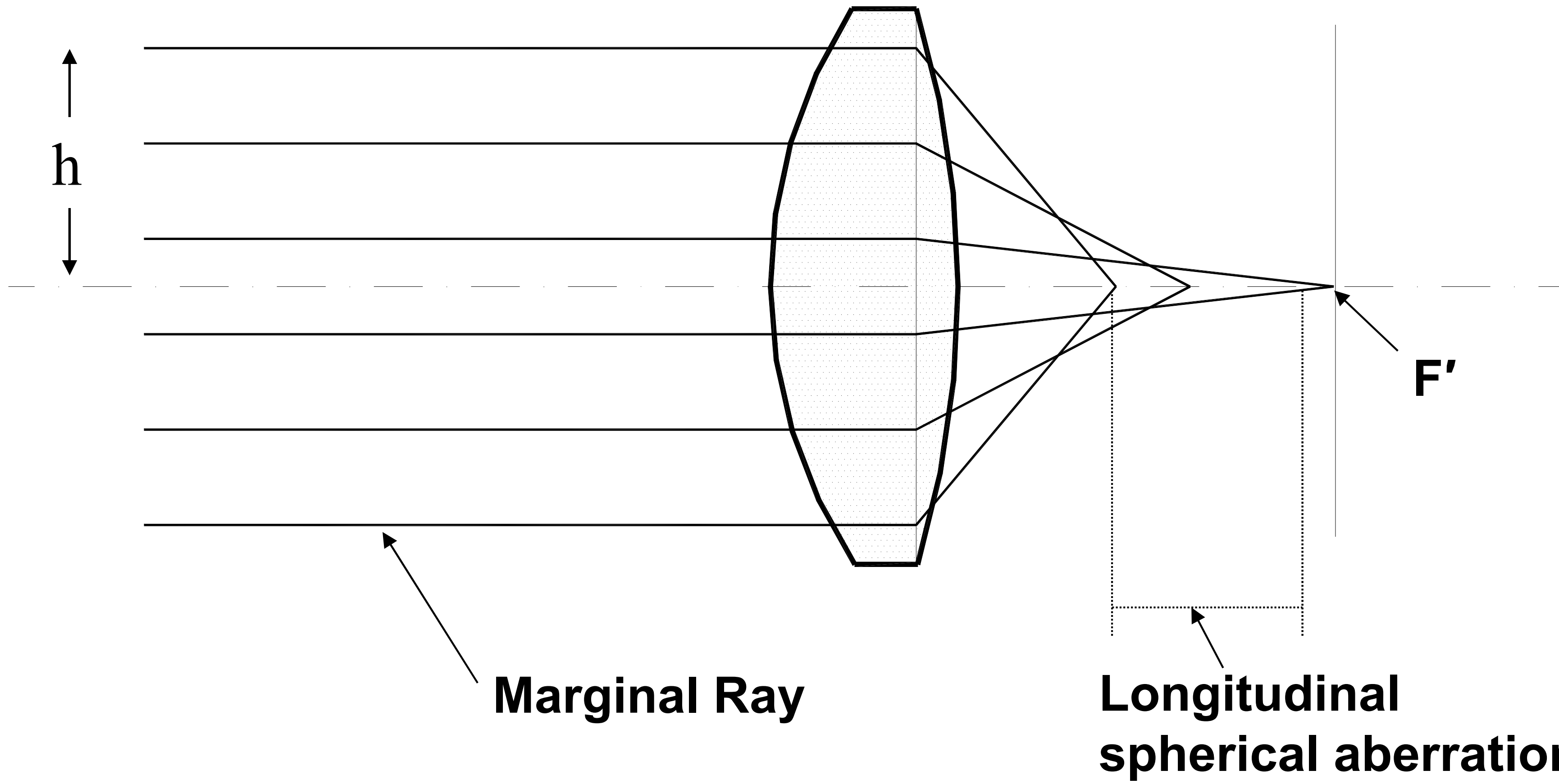
Lens Aberrations

- Aberration can be classified according to their origin as following:
  - Aberrations caused by large aperture <u>and/or</u> off-axial objects
    - Spherical aberration; Astigmatism and Curvature of field; and Coma
  - Aberrations caused by different wavelengths of the incident light
    - Chromatic aberrations
  - Aberrations caused by manufacturing flaws
    - Irregular aberrations

Aberrations Due to Axial and Off-Axial Objects

Position of object point	Small aperture angle (Narrow Bundle)	Large aperture angle (Wide Bundle)
Axial	Aberration free	Spherical aberration
Off-Axial	Astigmatism and curvature of field	Coma

Spherical Aberrations



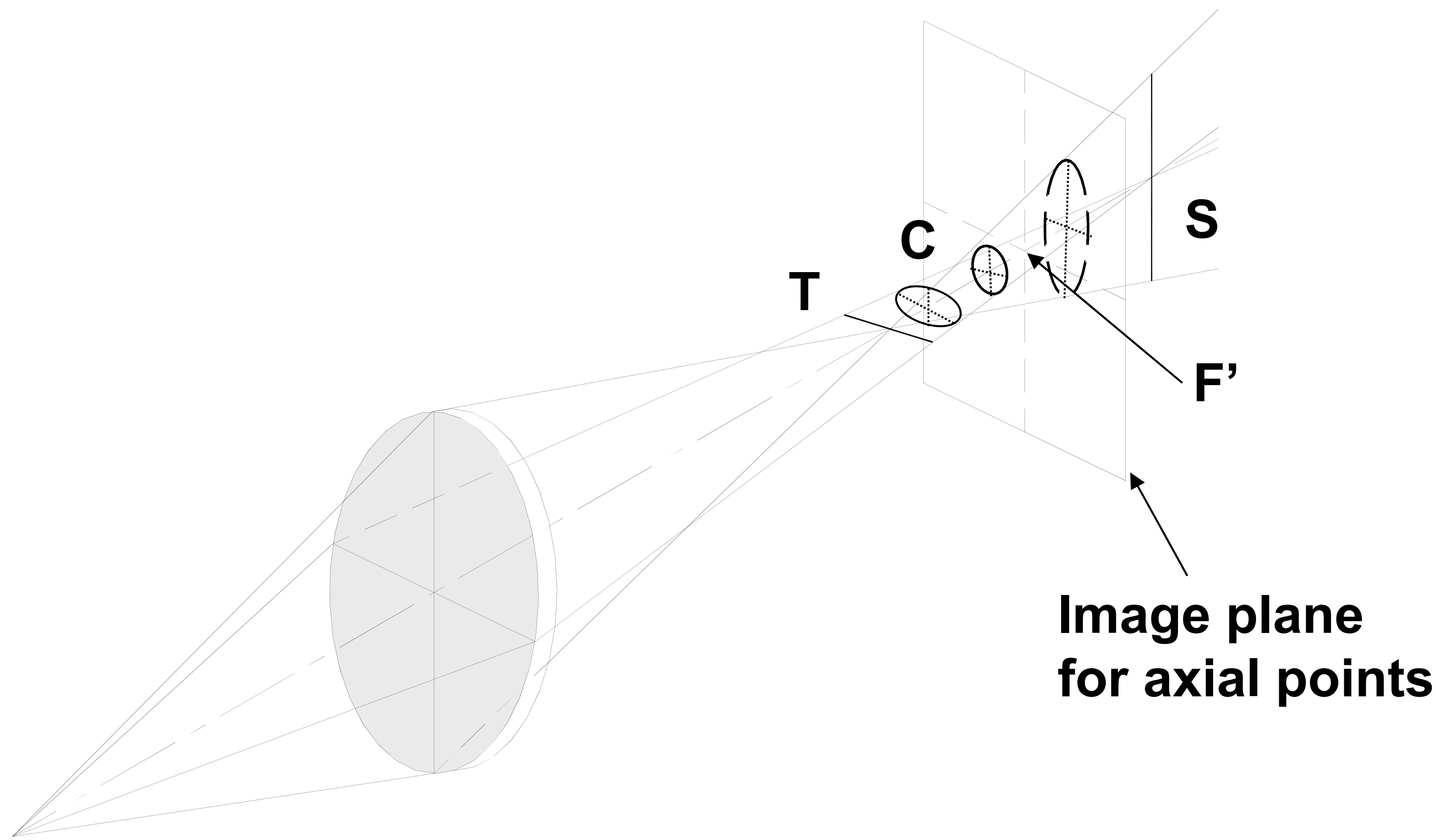
Spherical Aberrations

- Spherical aberration applies only to points lying on the optical axis.
- Regardless where the image plane is located, the resulting image of a point will be a small circle.
- The longitudinal spherical aberration depends on the height (h).
  - The distance between the marginal rays and optical axis (radius of the aperture)
- The best image quality is reached at a position between the foci of the marginal rays and the paraxial rays.
  - The cross section of the bundle of rays at this location is known as the circle of least confusion.

Spherical Aberrations

- The longitudinal aberration is proportional to h^2.
- The radius of the circle of least confusion is proportional to h^3.
- Consequently, stopping down the lens (i.e., reducing the diameter of the aperture) decreases the effect of spherical aberrations.

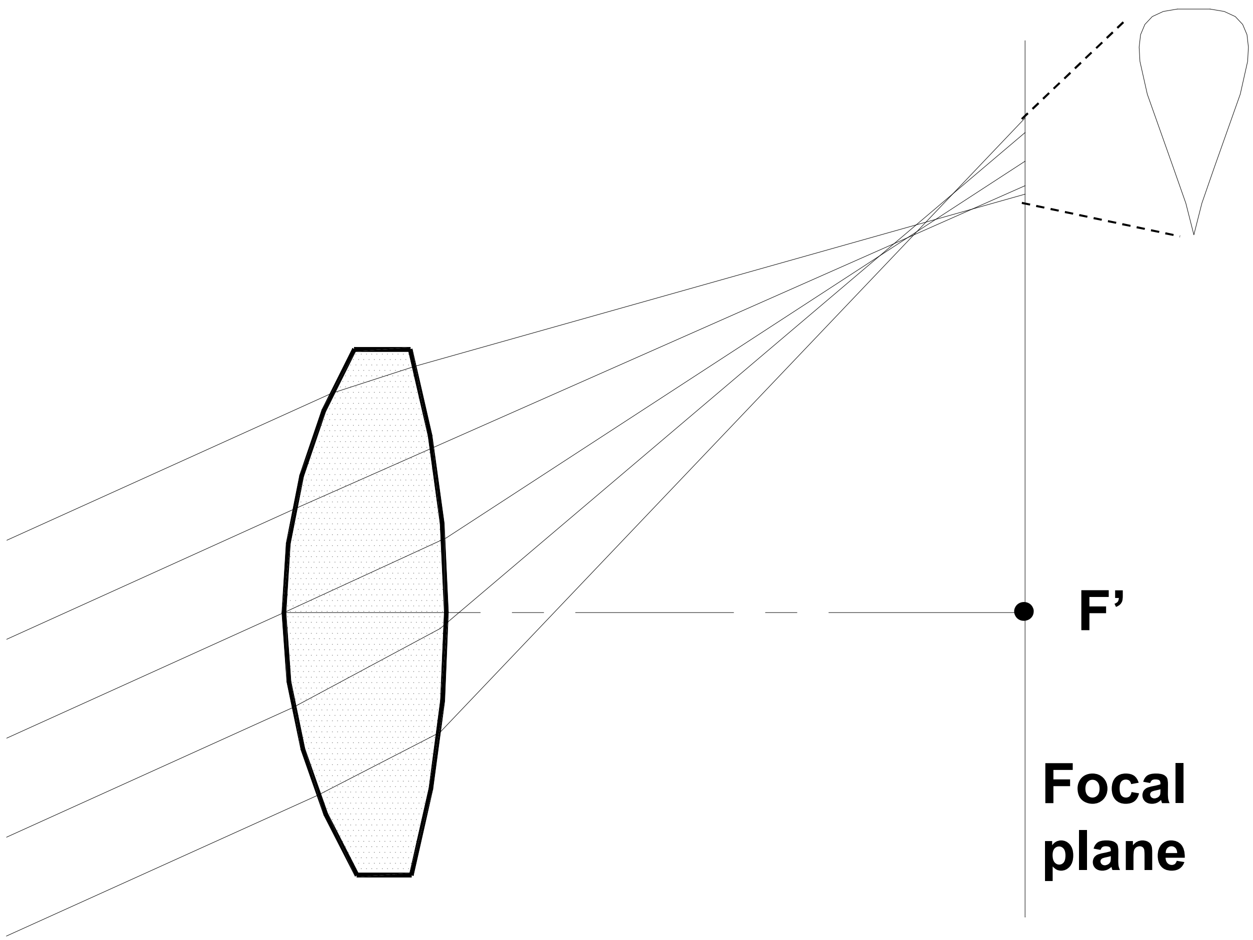
Astigmatism and Curvature of Field



Astigmatism and Curvature of Field

- A narrow but oblique bundle intercepts the lens surface non-symmetrically.
- As a result, the bundle in the image space does not precisely intersect in one point but in two short lines.
- The separation (longitudinal distance) between these lines is called astigmatism and curvature of field.

Coma

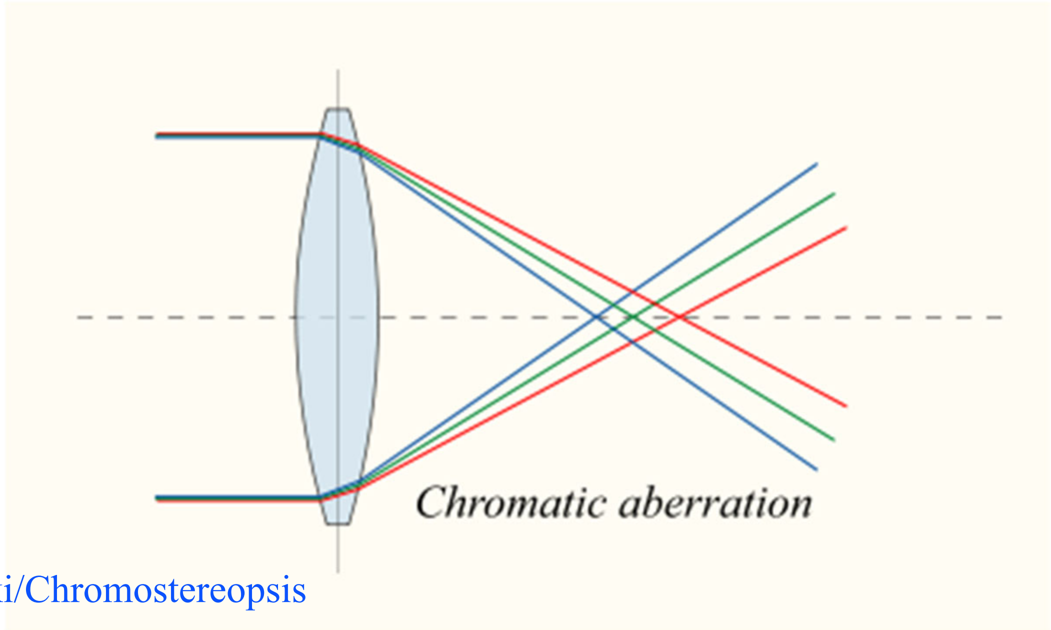


Coma

- The image of an off-axial object with a wide bundle has a comet-shape blur.
- Like astigmatism, coma is the result of the non-symmetric intercept of the oblique and wide bundle with the lens.

Chromatic Aberrations

- Chromatic aberration is caused by the fact that glass has different refractive indices for different wavelengths.
- As a result, every wavelength has its separate focus.
- This is a similar situation to the case of spherical aberration.



http://en.wikipedia.org/wiki/Chromostereopsis

Chromatic Aberrations

Image captured with a high quality lens

Image captured with a lens showing chromatic aberrations

http://en.wikipedia.org/wiki/Chromostereopsis

Diffraction

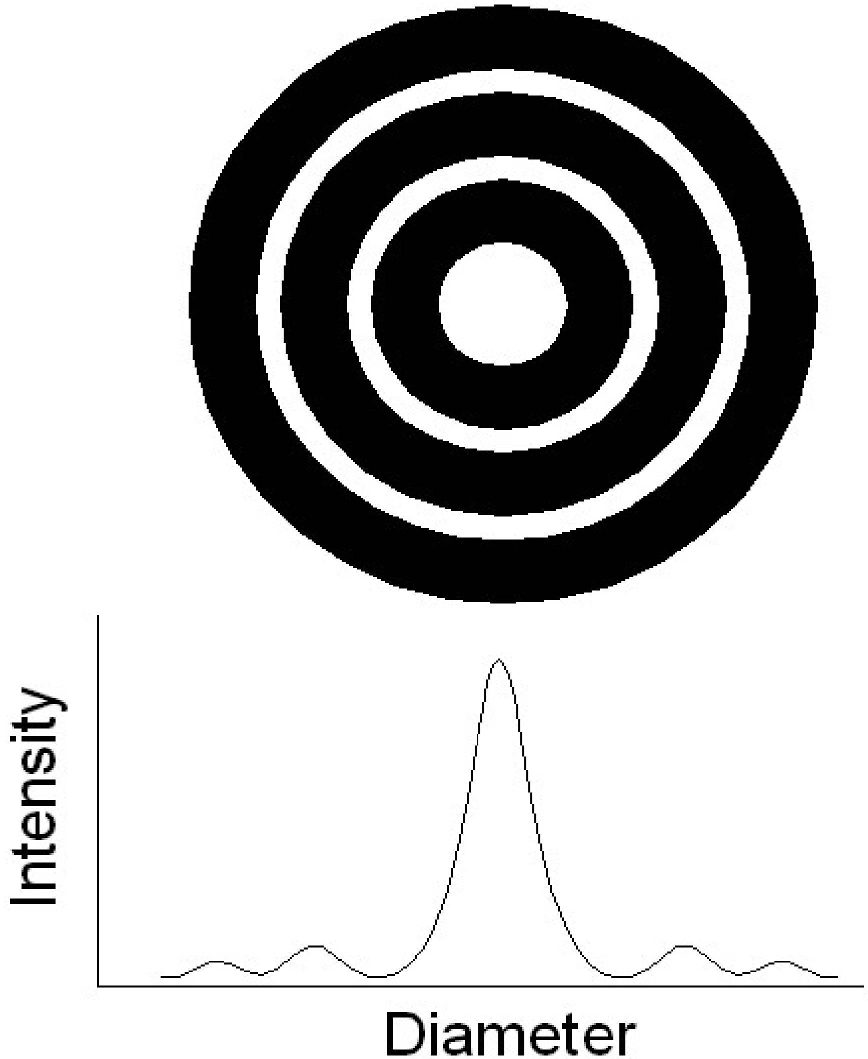
- Diffraction is caused by the interference of light waves with the aperture.
- As a result, an object point will appear as a small disc surrounded by a number of dark and bright rings.
- The radius of the central disc (r) can be computed as follows:
  - $r = 1.22\,\lambda\,(f/d)$ where:

    λ is the wavelength of the light,

    f is the focal length, and

    d is the diameter of the aperture.

Diffraction

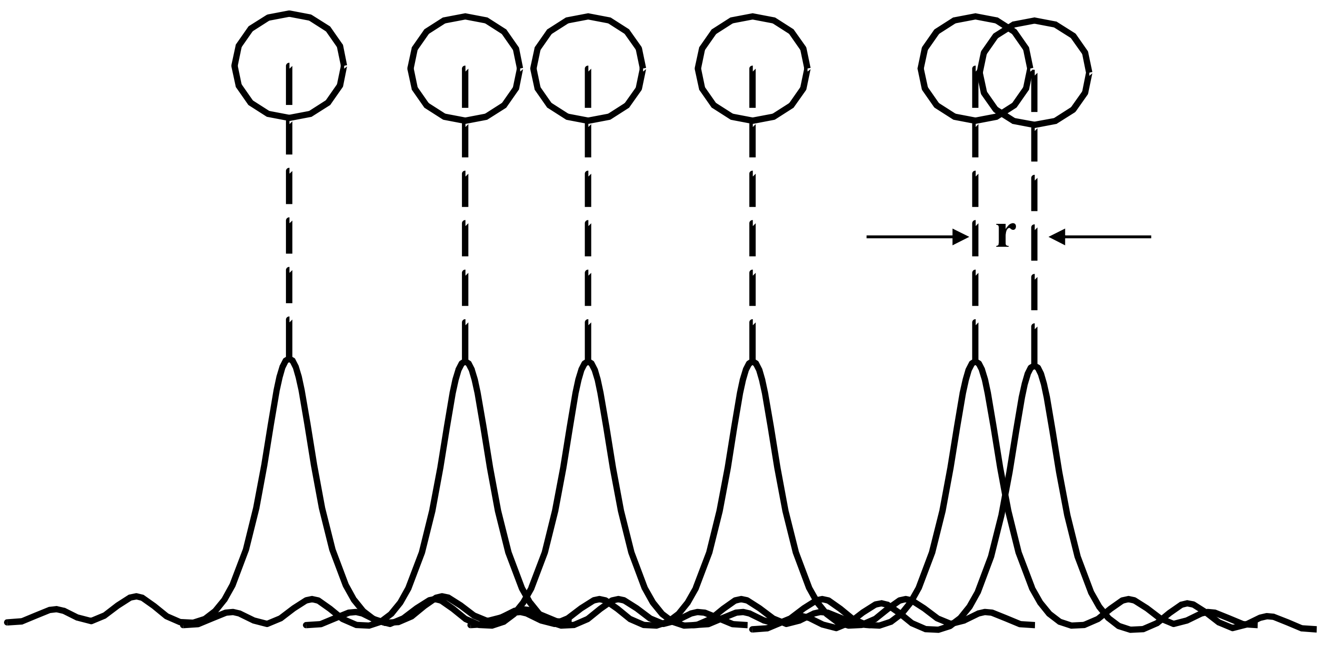


Diffraction

- If two discs are to be moved towards each other, a point will be reached at which the two discs will no longer be identified as two separate objects.
- This is the case when the two objects are separated by the radius of one disc.
- The reciprocal of the disc radius is a measure of the resolving power of the lens system (optical resolution).

$$\text{Optical Resolution} = 1/r = \frac{1}{1.22\lambda(f/d)} \; lines/mm$$

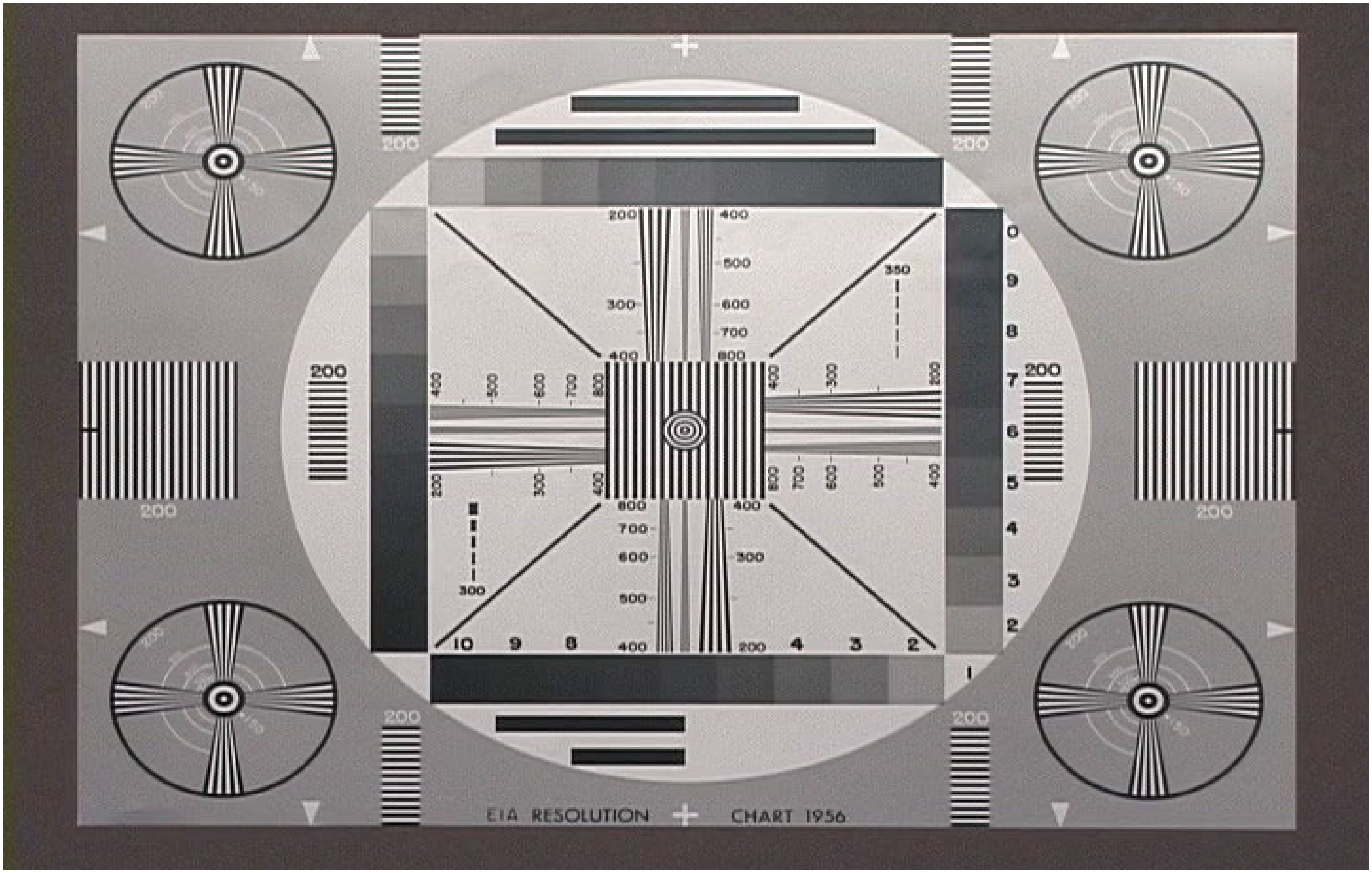
Diffraction



Resolving Power of an Imaging system

- Resolution is the ability of the system to identify nearby objects as separate entities.
- We want to establish a quantitative measure of the capability of our imaging system (camera and film) to image neighboring points or lines as separate entities.
- The resolution is measured in *line-pairs per mm* using resolution test chart.

Resolution Test Chart

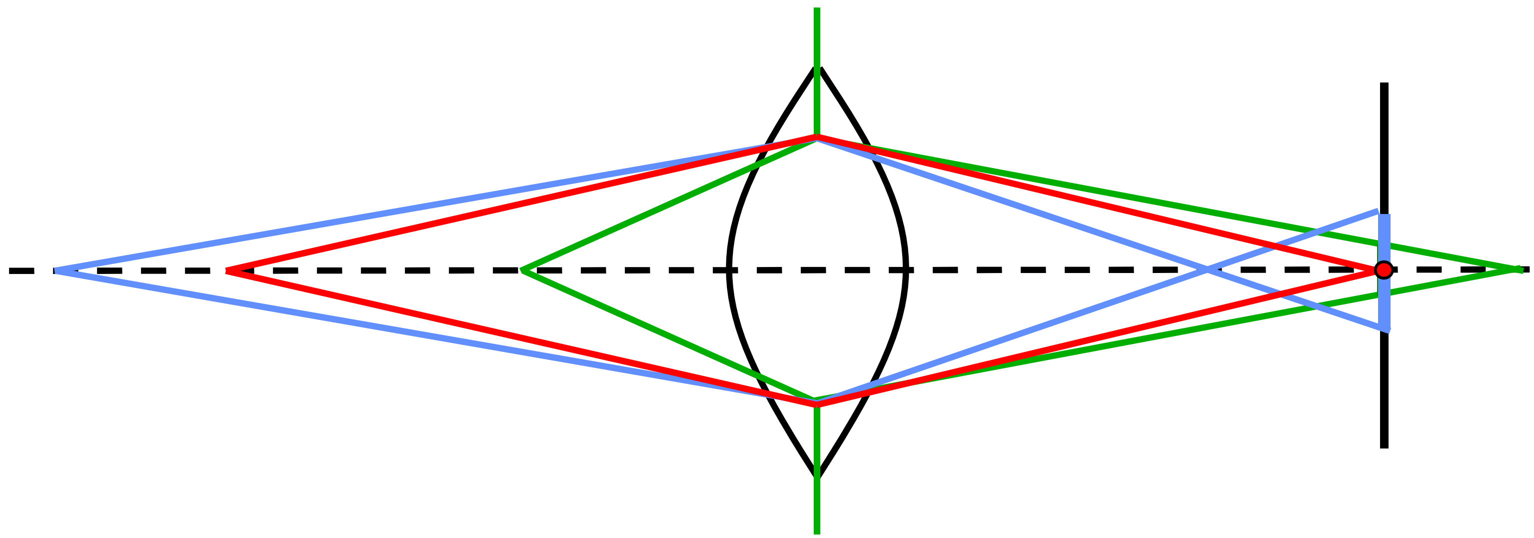


http://www.dennishollingsworth.us/archives/image/test-pattern-1-TVE.gif

Resolving Power of an Imaging system

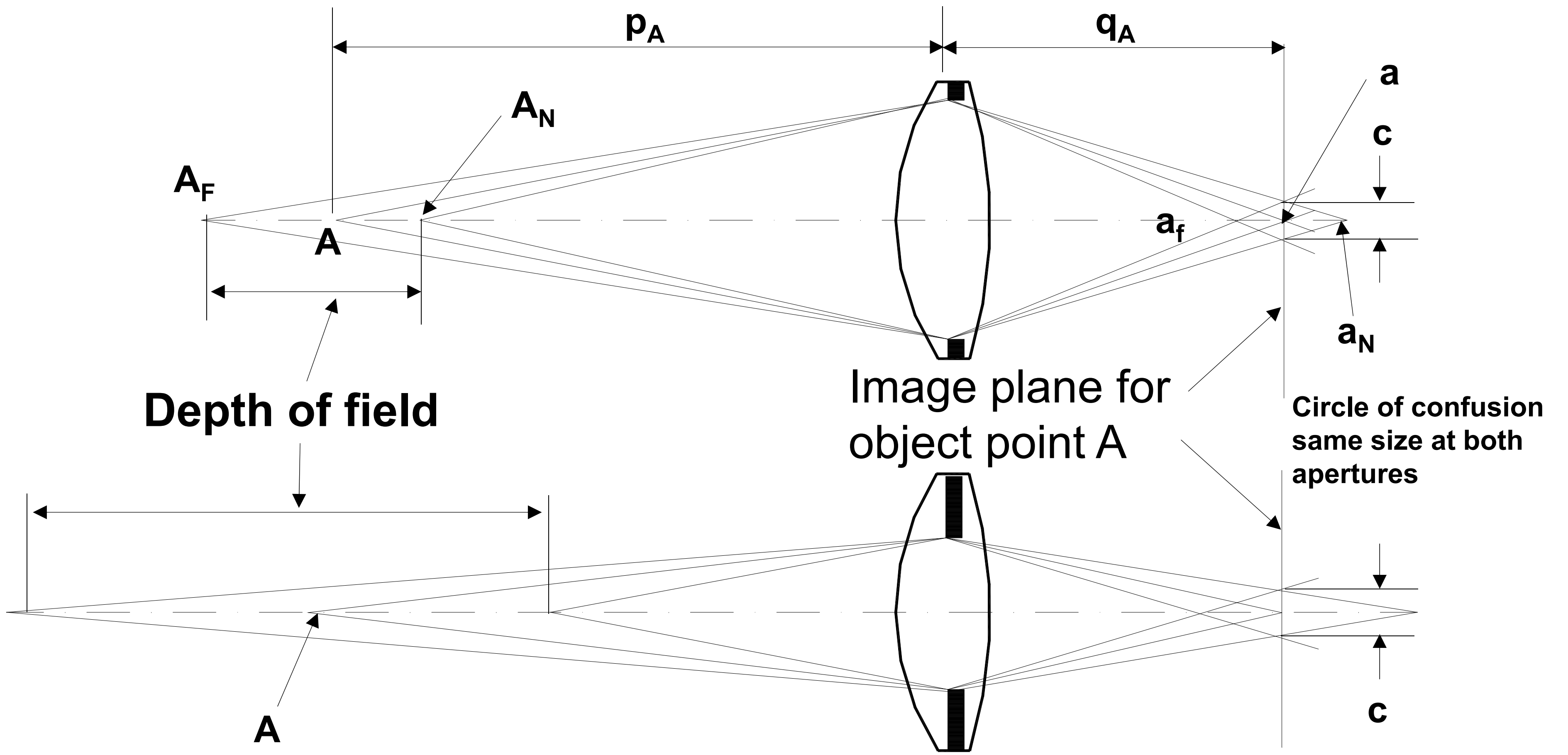
- Factors that affect the resolving power include:
  - Lens aberrations,
  - Depth of field,
  - Depth of focus,
  - Diffraction,
  - Film material or CCD/CMOS array, and
  - Motion blur.

Depth of Field

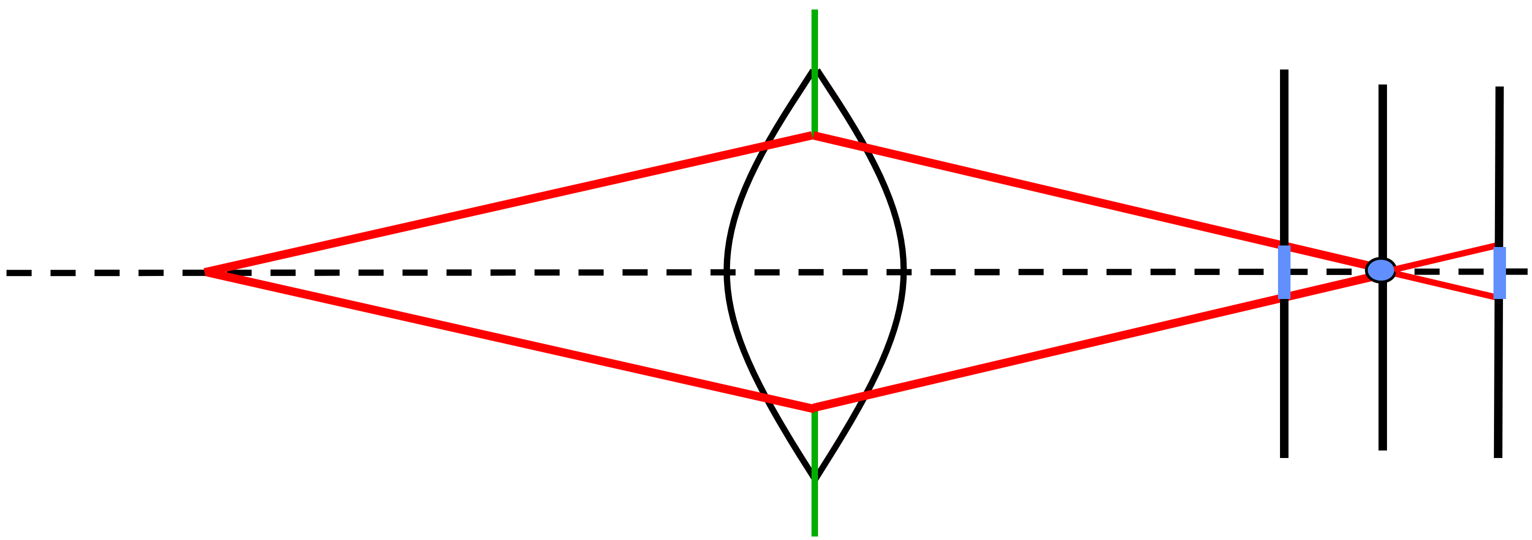


Depth of Field

- The distance in the object space within which the object point can be moved and still be in acceptable focus.

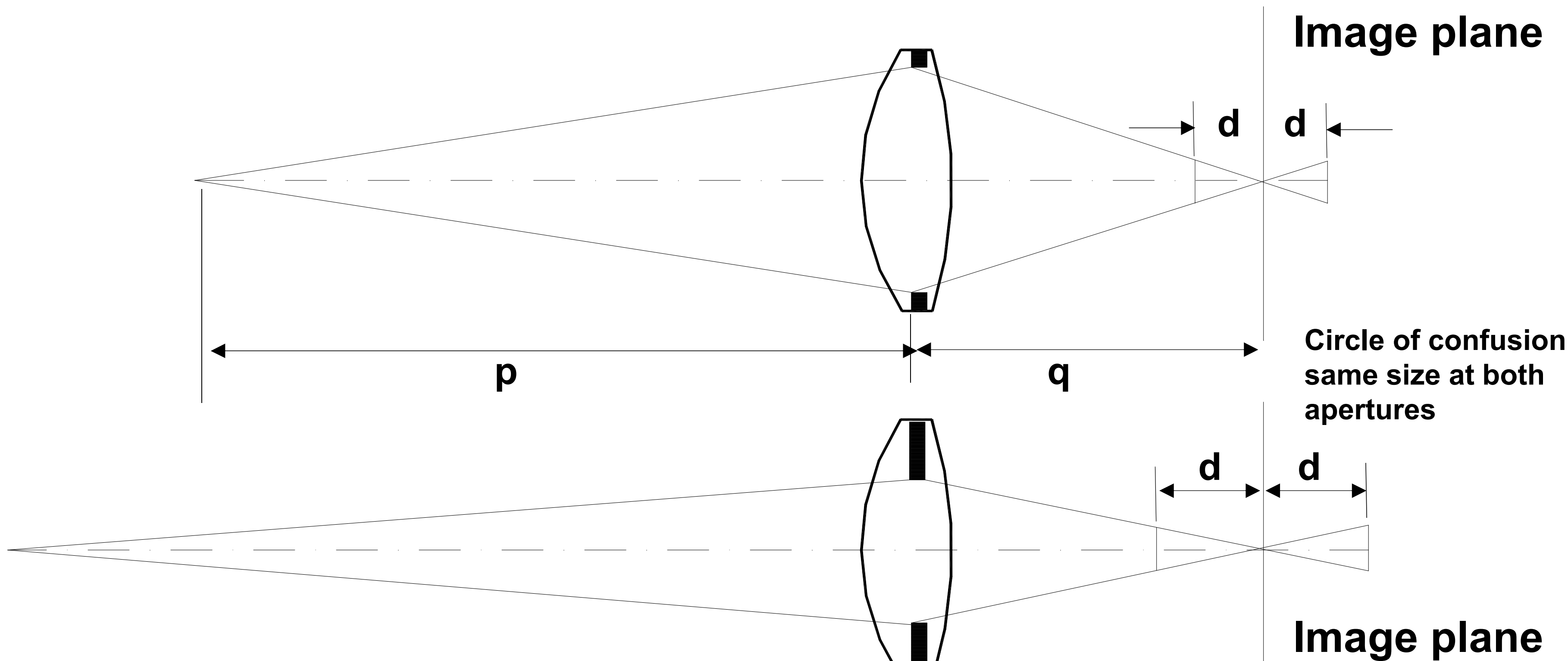


Depth of Focus



Depth of Focus

- Depth of focus is the distance in front or behind the plane of best focus for a given object distance where the image is still in acceptable focus.



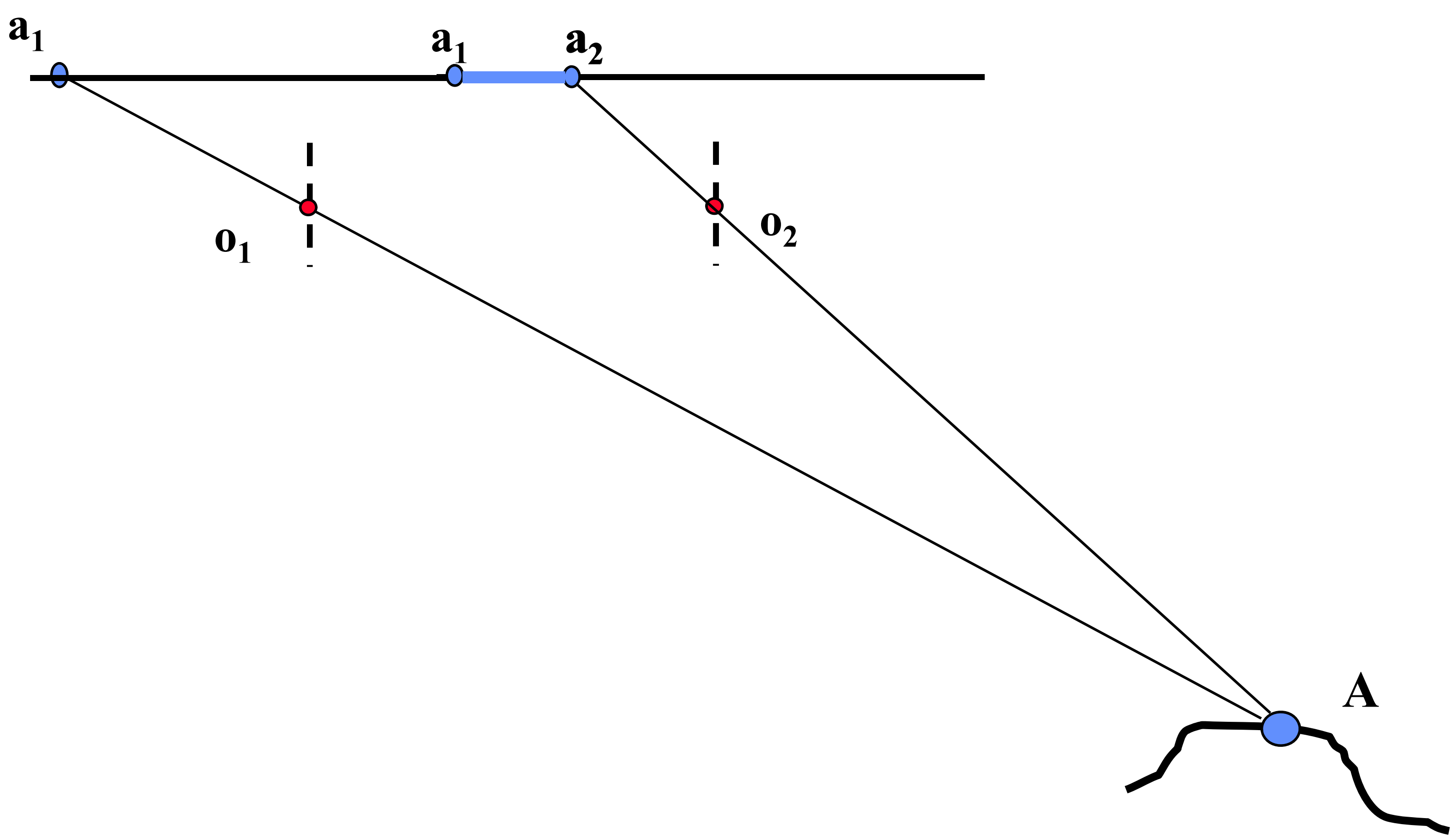
Factors Affecting Depth of Field/Depth of Focus

- The focal length
- The object distance
- The diameter of the aperture stop
  - The smaller the aperture the larger the depth of field and focus.
- The radius of the acceptable circle of confusion

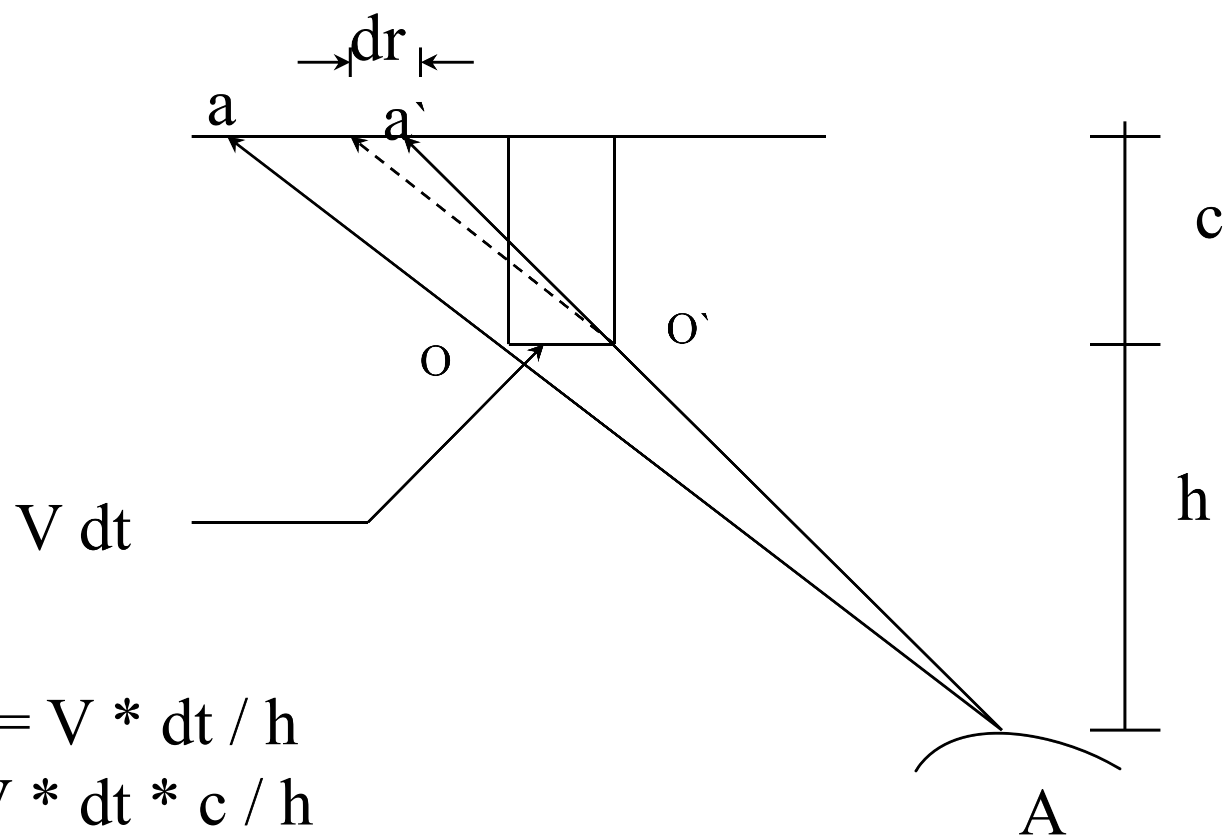
Motion Blur

- During the exposure of the photograph, the camera shutter remains open for a short time (dt) while the aircraft is still flying at a velocity (V).
  - This causes a blur (motion blur) in the captured image.
- The magnitude of the motion blur depends on:
  - The shutter opening time/shutter speed (dt),
  - The velocity of the aircraft (V),
  - The flying height (h), and
  - The camera constant – principal distance (c).

Motion Blur



Motion Blur

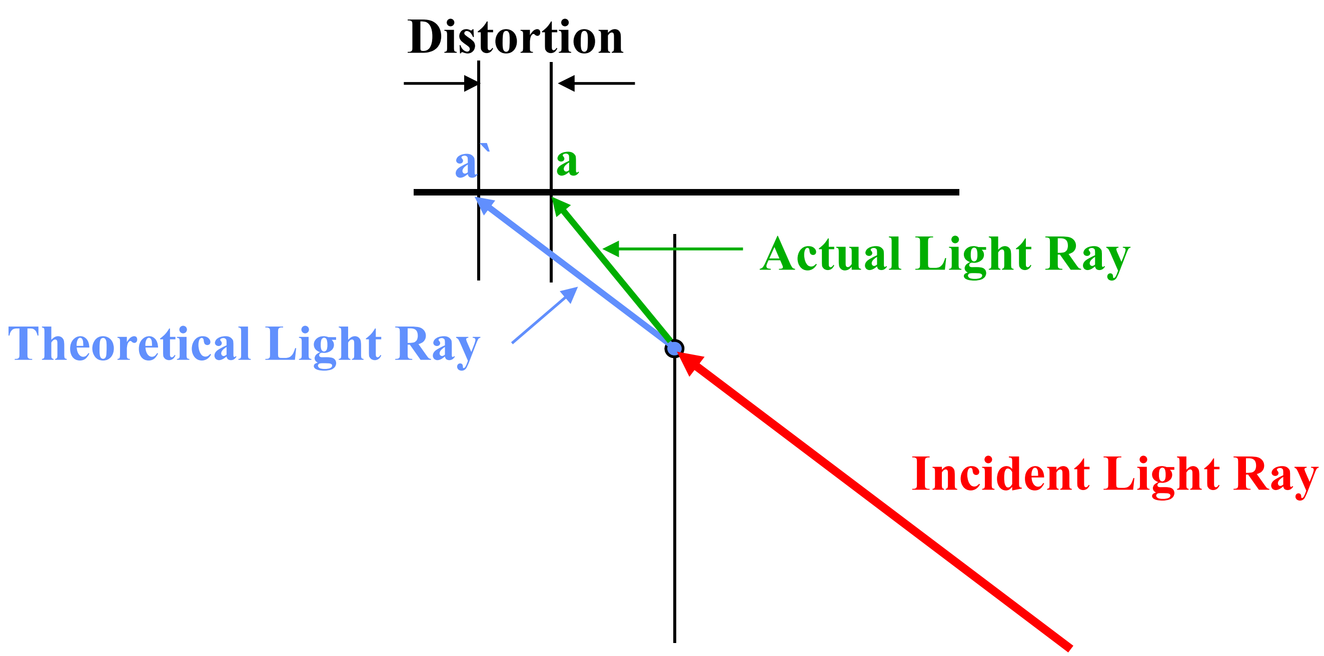


$$dr / c = V * dt / h$$
$$dr = V * dt * c / h$$

Motion Blur

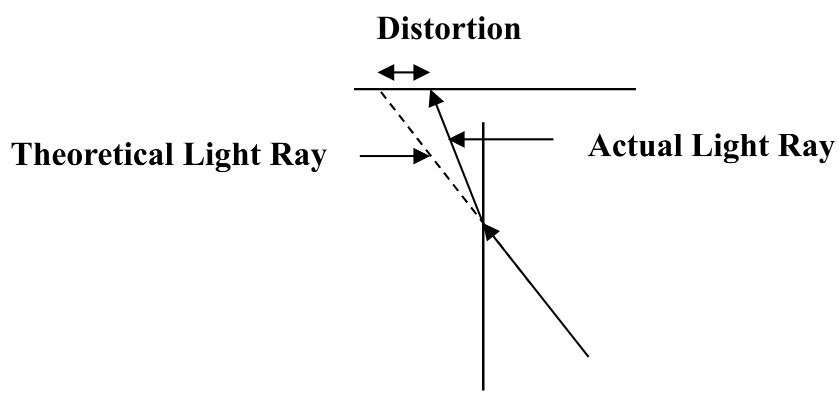
- To avoid motion blur, some photogrammetric cameras have a mechanism that causes the film to advance forward in the flight direction during the exposure time.
- The advancement magnitude should be exactly (*dr*).
- This advancement is known as the <u>*image motion compensation*</u>.

Distortion


Distortion
a`
a
Actual Light Ray
Theoretical Light Ray
Incident Light Ray

Distortion

- Definition: Image points are displaced from their theoretical location.

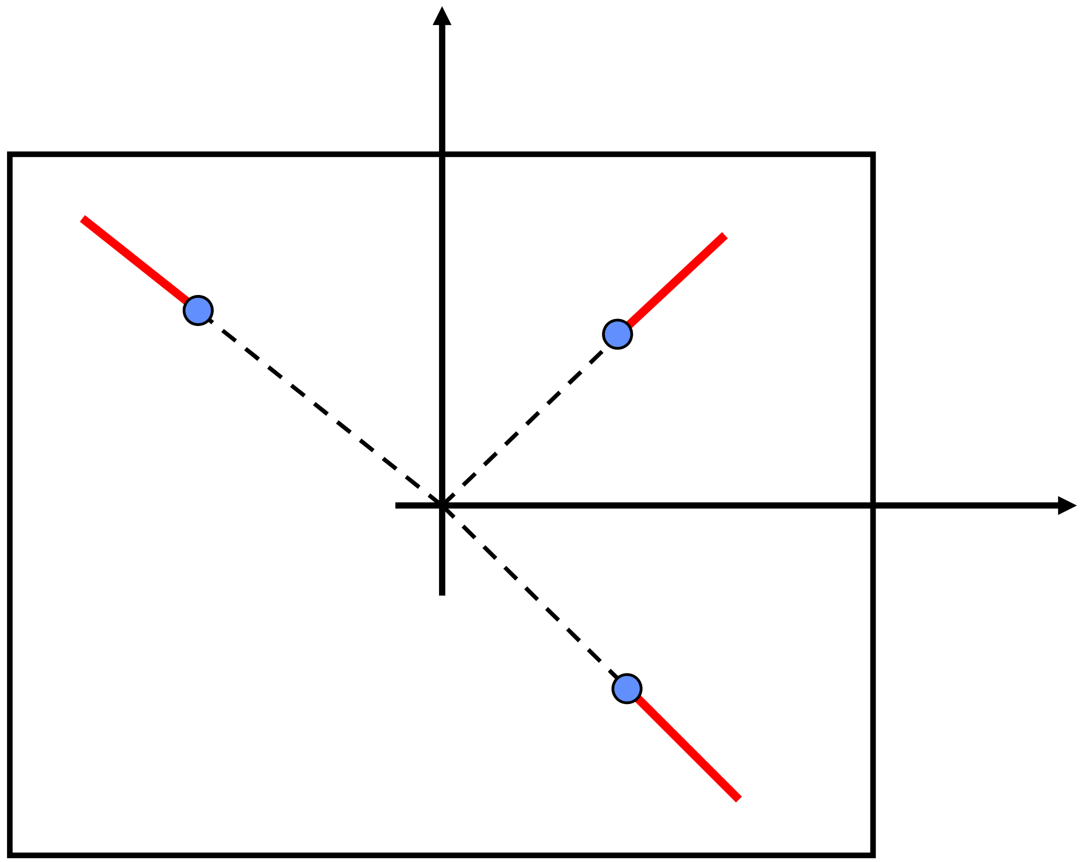


- Aberrations will affect the precision of the final image coordinate measurements.
- Distortions will affect the accuracy of the final image coordinate measurements.

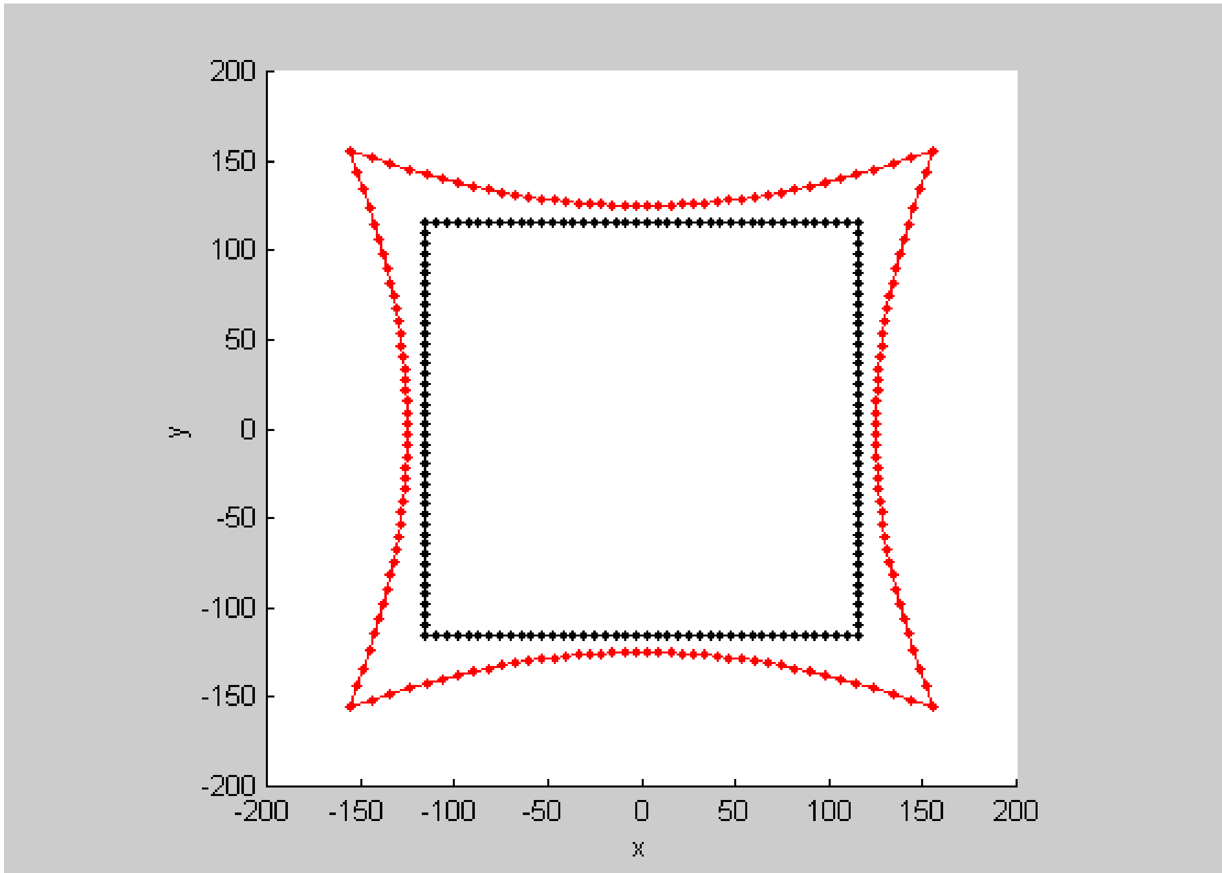
Radial Lens Distortion

- The light ray changes its direction after passing through the perspective center.
- Radial lens distortion is caused by:
  - Large off-axial angle, and
  - Lens manufacturing flaws.
- Radial lens distortion occurs along a radial direction from the <u>center of the image</u>.
- Radial lens distortion increases as we move away from the optical axis.

Radial Lens Distortion



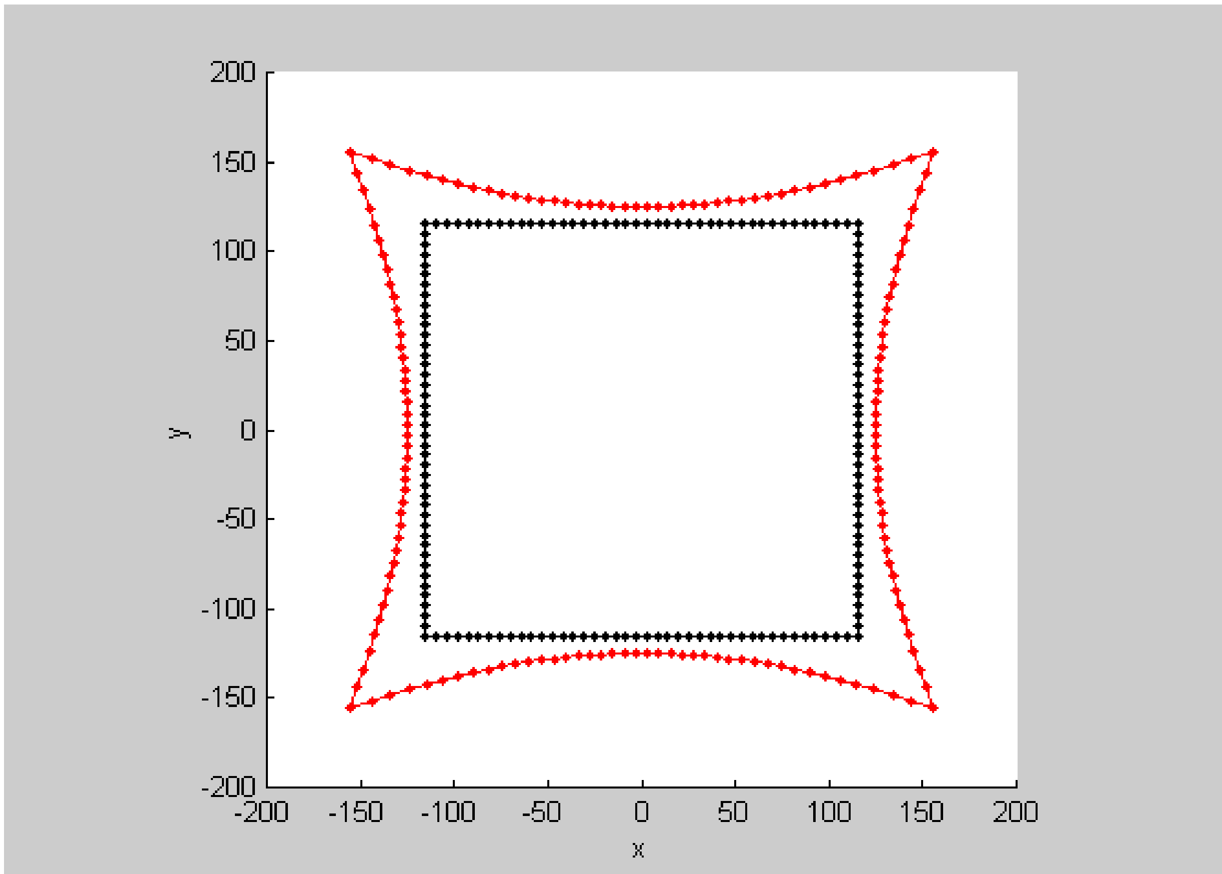
Radial Lens Distortion



Without distortions

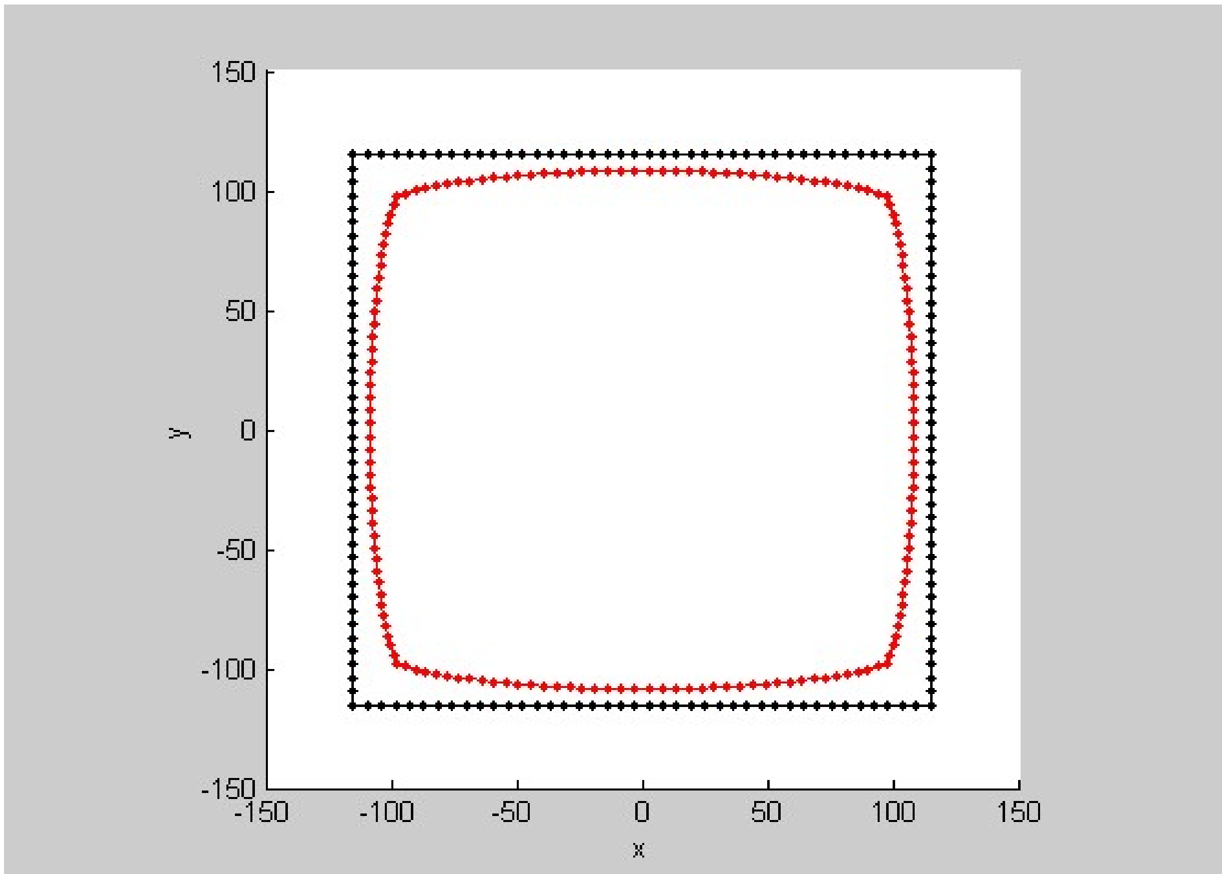
With distortions

Radial Lens Distortion



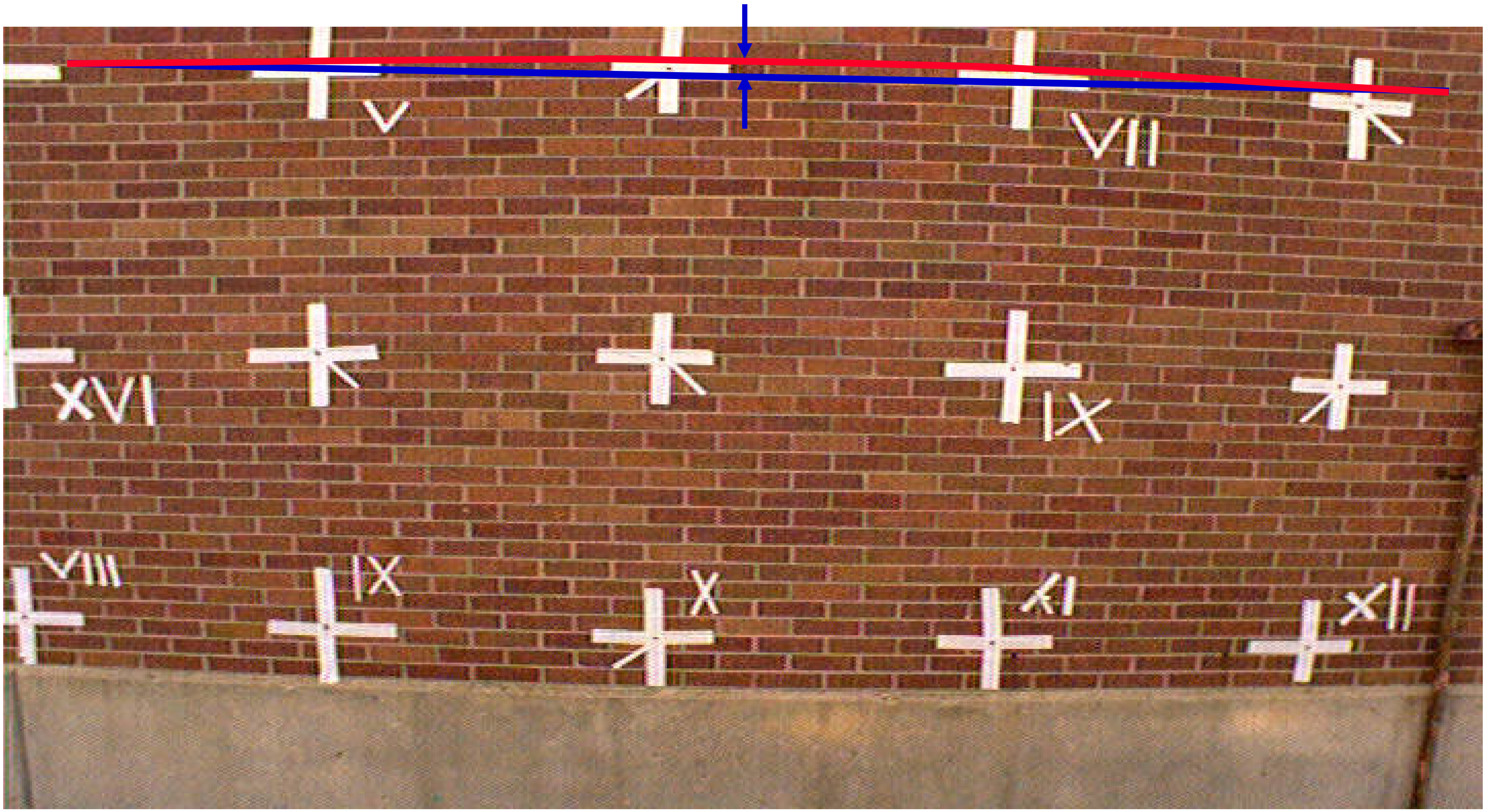
Pin Cushion Type Radial Lens Distortion

Radial Lens Distortion

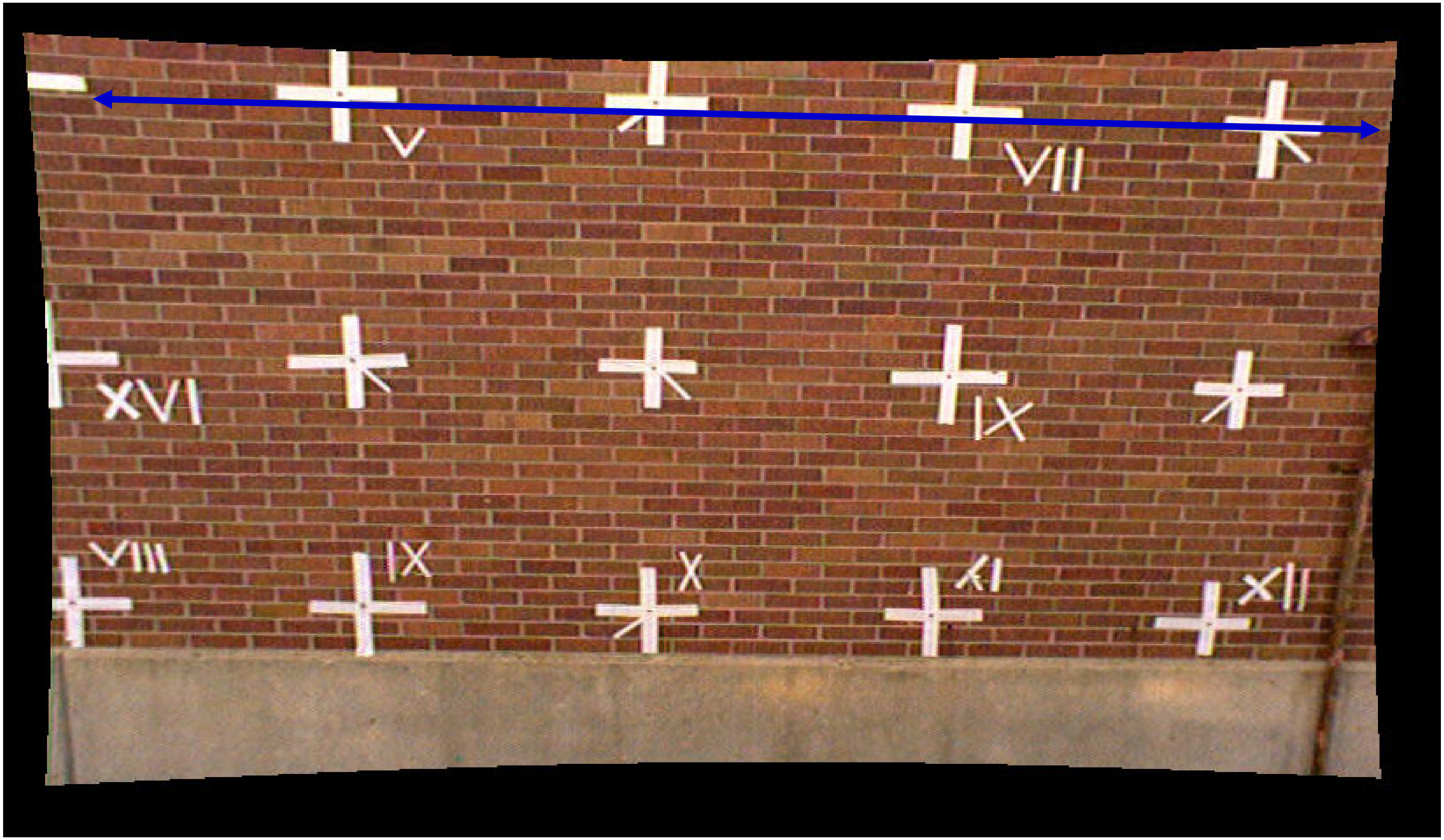


Barrel Type Radial Lens Distortion

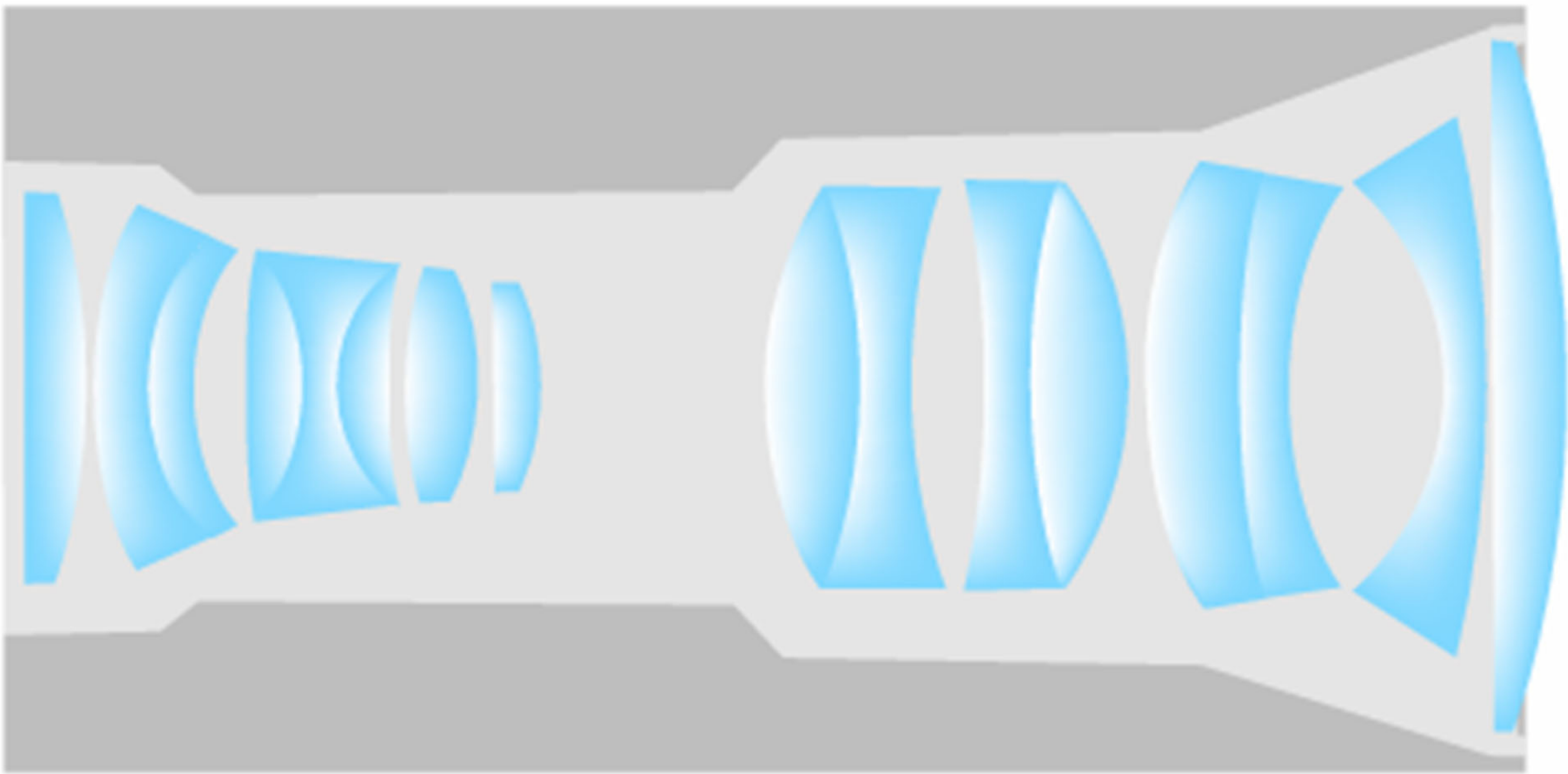
Before Distortion Removal



After Distortion Removal



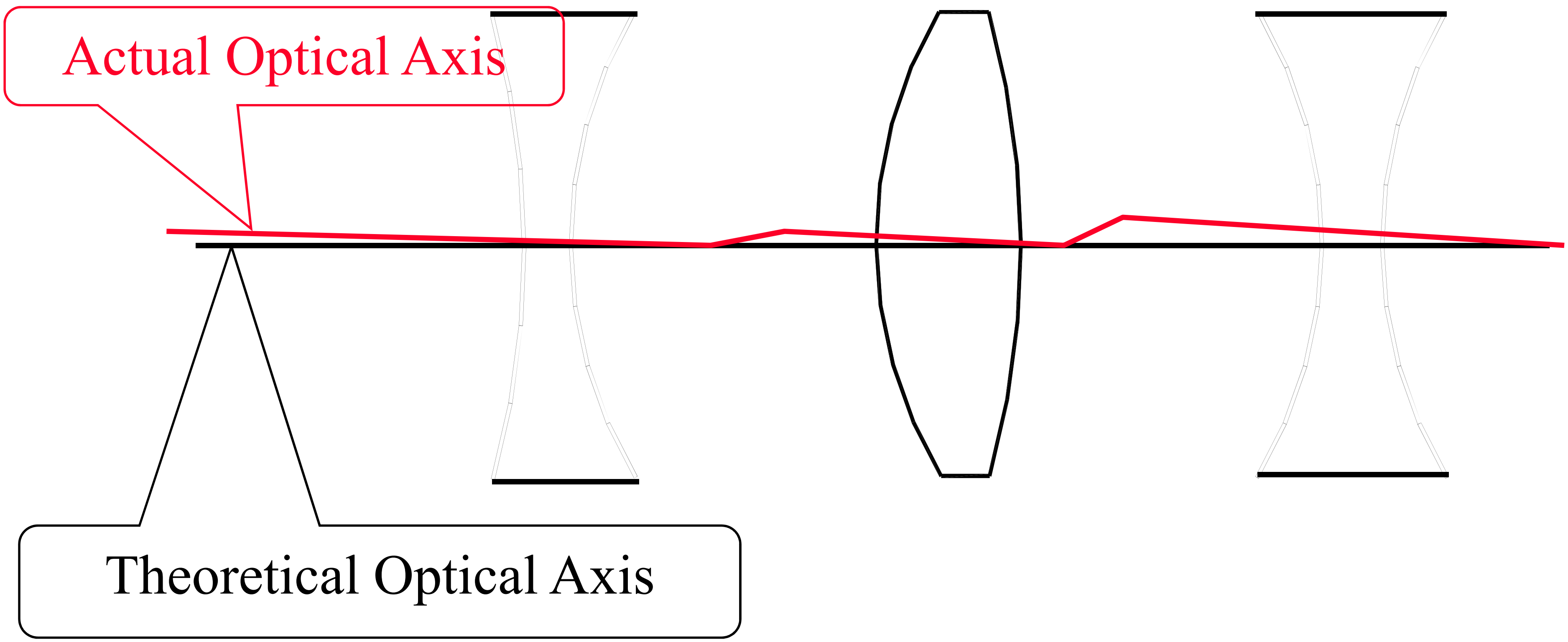
Lens Cone Assembly



Lens Cone Assembly

http://static.trustedreviews.com/94/44ca5a/dec1/4778-KonMinA2.jpg

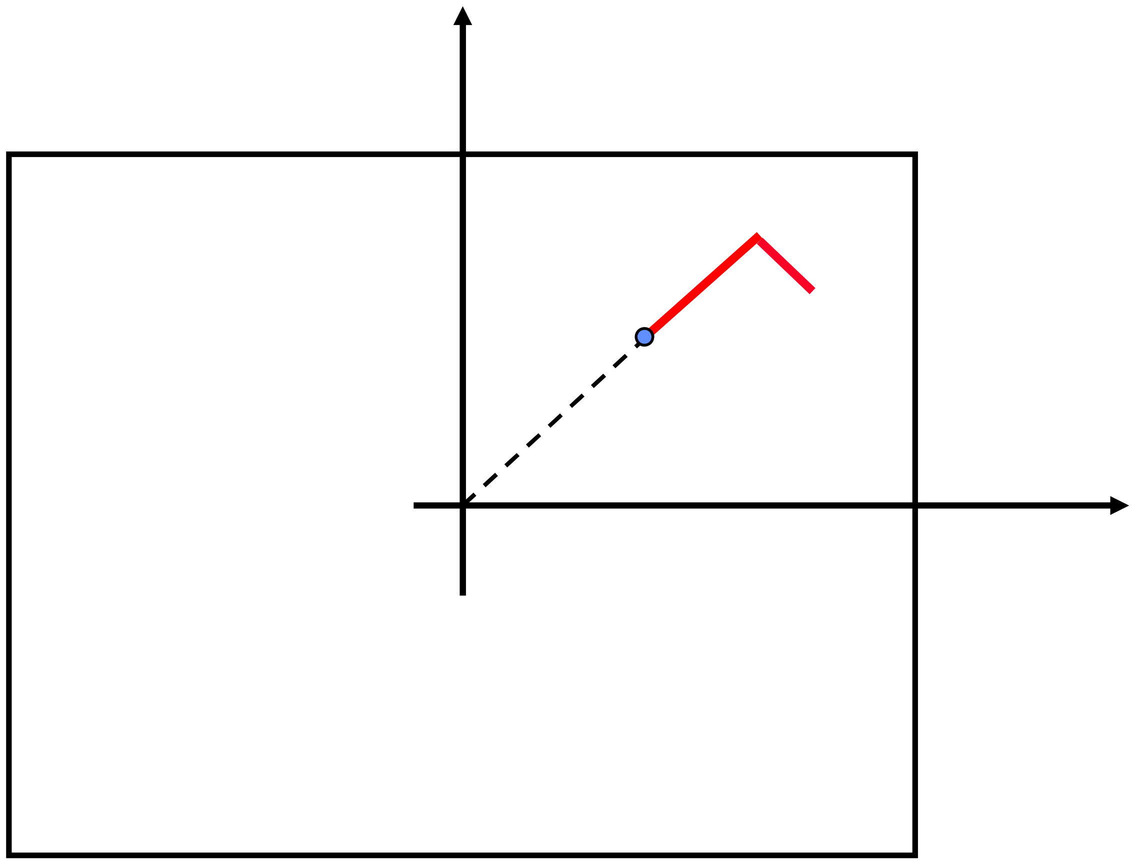
De-centering Lens Distortion



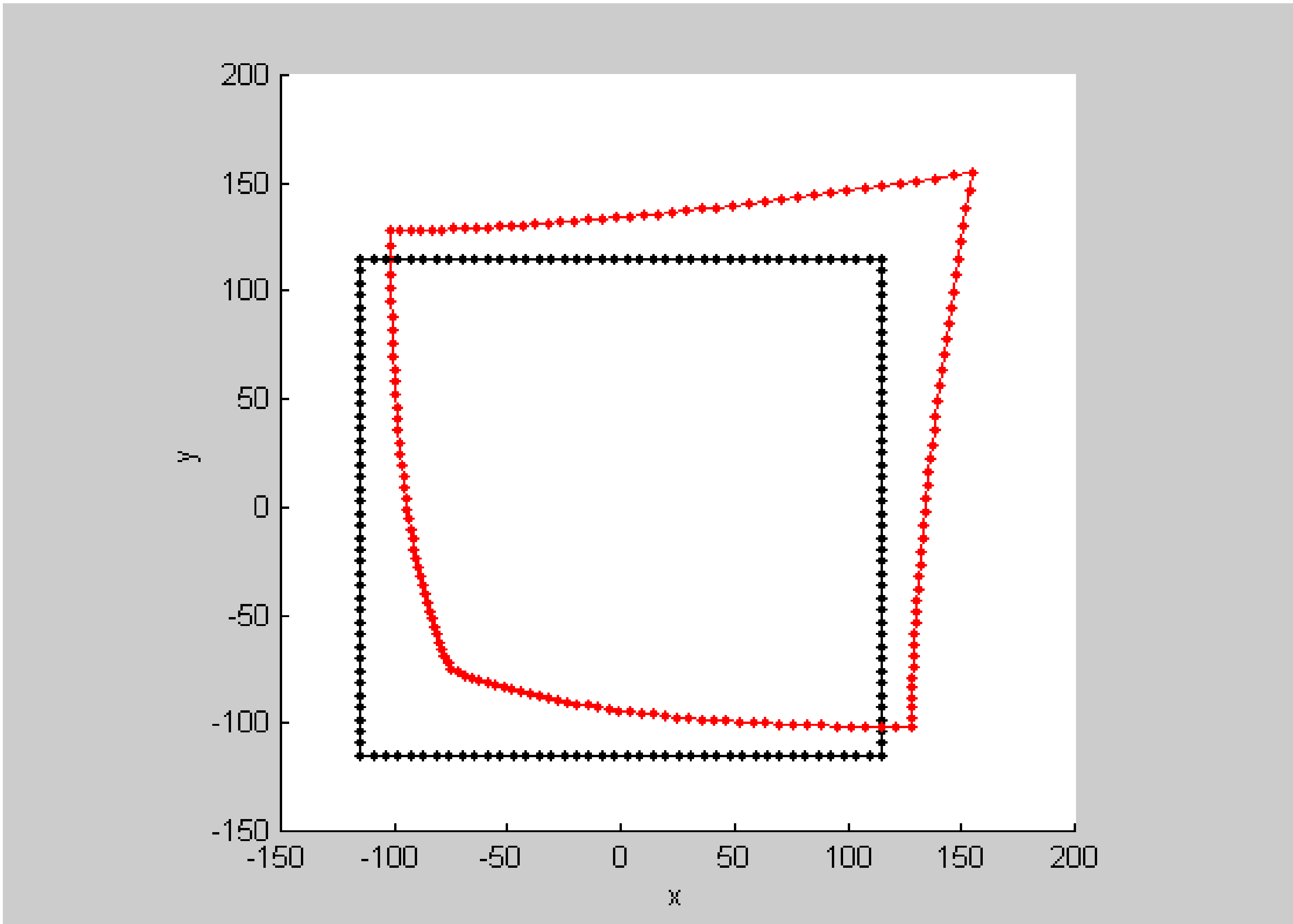
De-centering Lens Distortion

- De-centering lens distortion is caused by miss alignment of the components of the lens system.
- De-centering lens distortion has two components:
  - Radial component, and
  - Tangential component.

De-centering Lens Distortion



De-centering Lens Distortion



Without distortions

With distortions

Summary

- In this chapter, we covered the following topics:
  - Basics of geometric optics
  - Factors affecting the precision of the final image coordinate measurements:
    - Aberrations, diffraction, depth of field, depth of focus, and motion blur
    - Resolving power of the imaging system
  - Factors affecting the accuracy of the final image coordinate measurements:
    - Radial and de-centering lens distortion