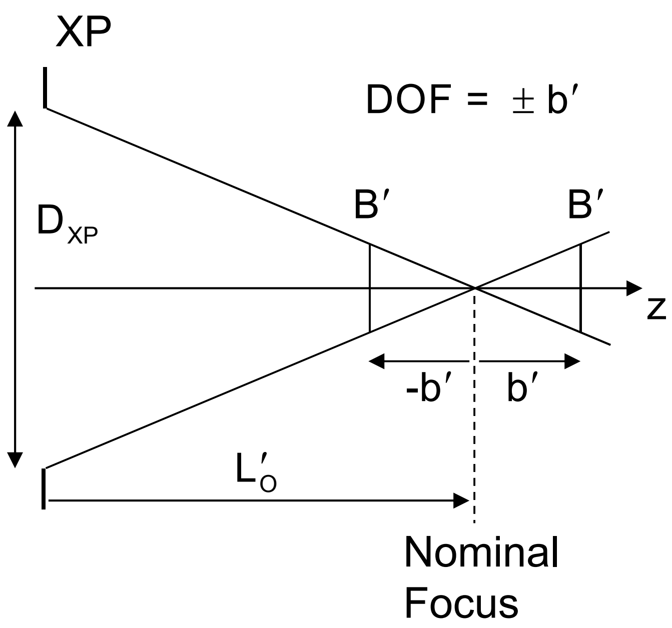
# Section 17

# Camera Systems

## Depth of Focus and Depth of Field

There is often some allowable image blur that defines the performance requirement of an optical system. This maximum acceptable blur may result from the detector resolution or just the overall system or display resolution requirement. This blur requirement results in a first-order geometrical tolerance for the longitudinal position of the object or the image plane. No diffraction or aberrations are included.

The depth of focus DOF describes the amount the detector can be shifted from the nominal image position for a given position before the resulting blur exceeds the blur diameter criterion B'.




$$b' = \frac{B'L'_O}{D_{XP}} \approx \frac{B'z'}{D_{EP}}$$

$$DOF = \pm b' \approx \pm B' \; f/\#_W$$

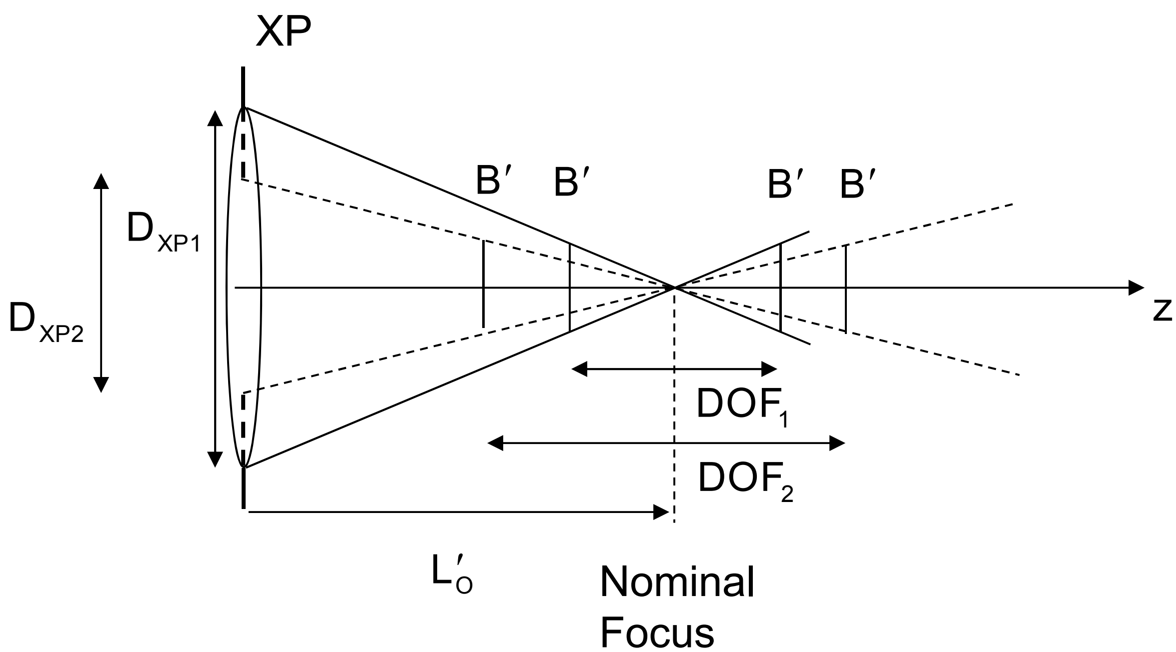
$$DOF \approx \pm \frac{B'}{2\,NA}$$

Depth of Focus and F/#

The depth of focus is directly proportional to the f/# of the lens:

$$DOF \approx \pm B' \, f/\#_W$$

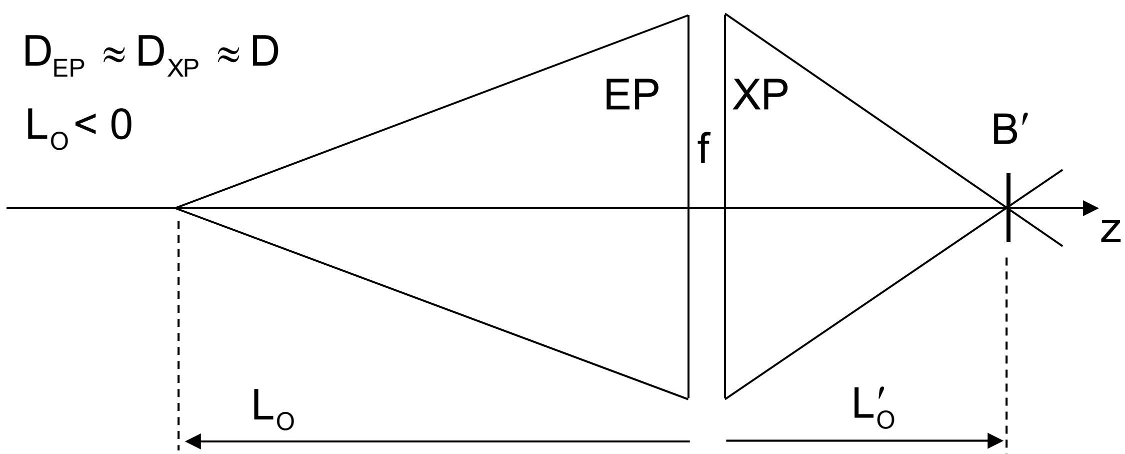
As a result, as a lens of a given focal length is stopped down (its f/# is increased), an increased depth of focus results.



# Depth of Field

When a camera is focused at a particular object distance $L_O$, there is some range of object positions $L_{FAR}$ to $L_{NEAR}$, the depth of field, that will appear in focus for a given detector or image plane position. The image plane blur criterion B' is met for these object positions.

Consider the nominal object location:

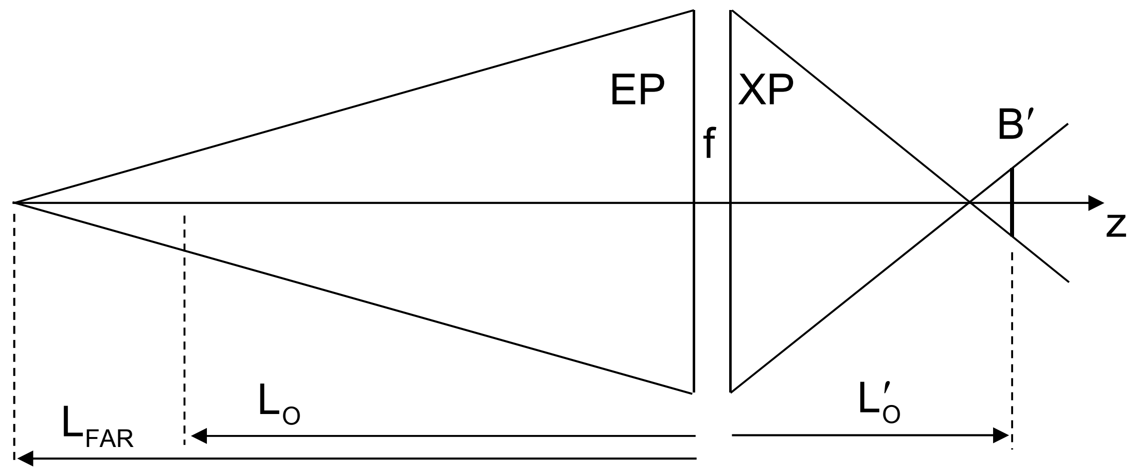



$L_O$ is the object plane where the camera is focused, and $L'_O$ is the corresponding image plane where an in-focus image is produced. The detector is located at this position.

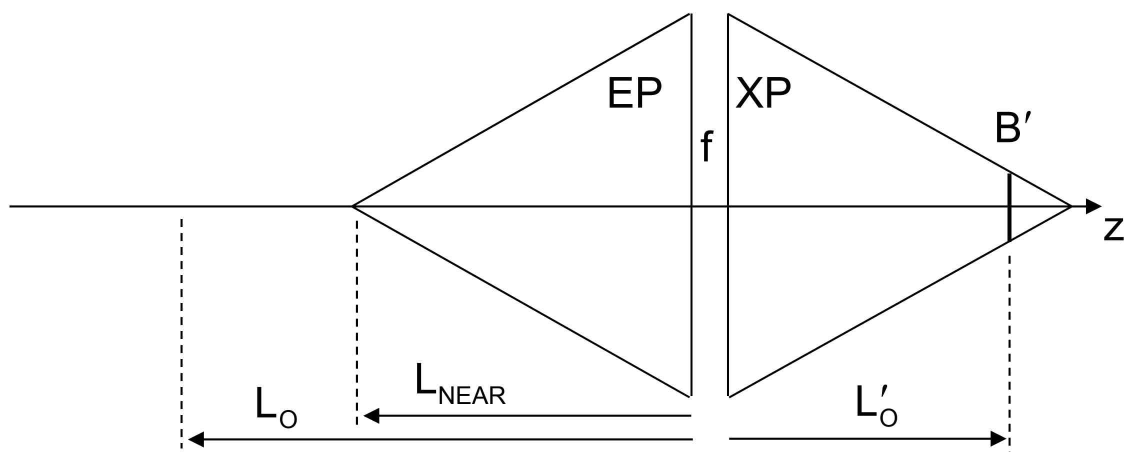
These results assume a thin lens with the stop at the lens.

Depth of Field

The same image plane/detector location is maintained. When an object is at a distance greater than $L_O$, the resulting image will move closer to the lens. A blur will form and be seen on the detector. At $L_{FAR}$, this blur equals the blur criteria B'.

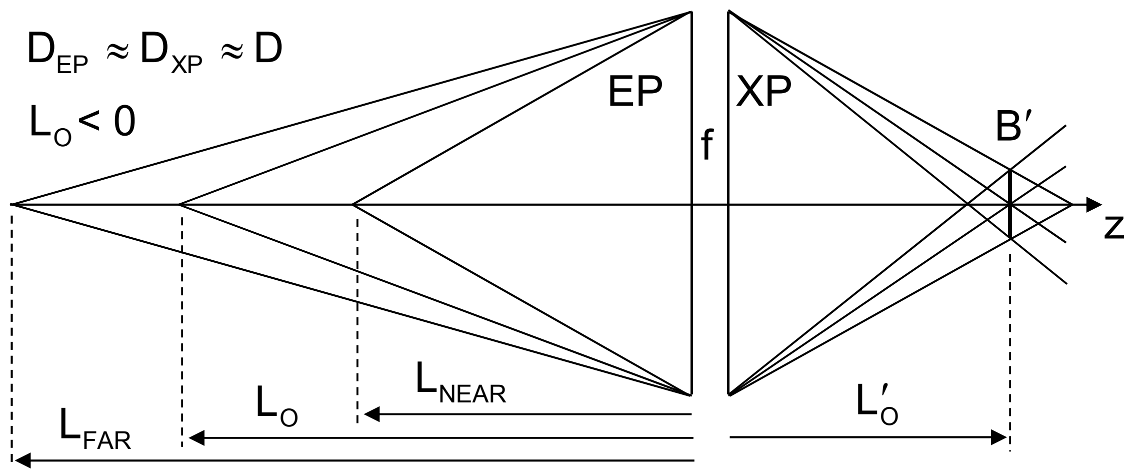



The similar scenario exists for an object at a distance less than $L_O$. At $L_{NEAR}$, this blur equals the blur criteria B'.



# Depth of Field

All object positions between $L_{FAR}$ to $L_{NEAR}$ will meet the blur criteria and appear to be in focus.




$$L_{FAR} \approx \frac{L_O fD}{fD + L_O B'} \qquad L_{NEAR} \approx \frac{L_O fD}{fD - L_O B'}$$

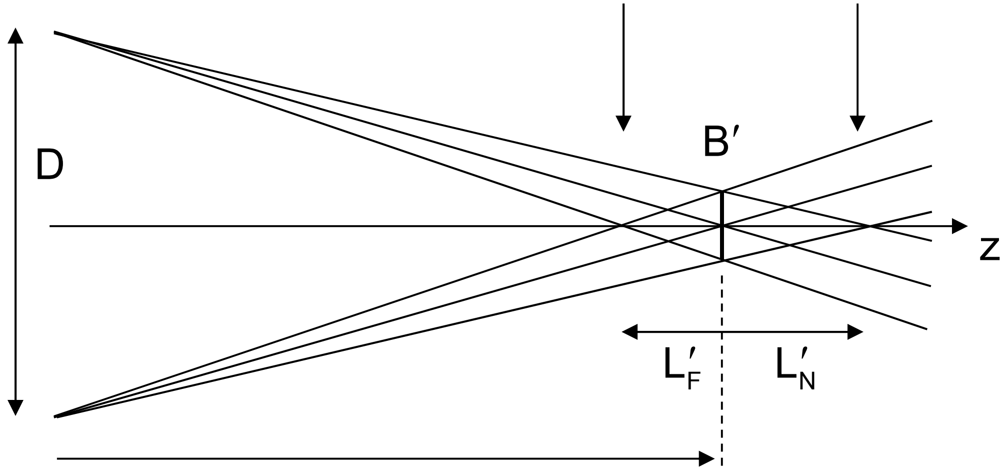
$L_O$ is the object plane where the camera is focused – this nominal object plane is conjugate to the detector. All objects positioned between $L_{FAR}$ and $L_{NEAR}$ will produce images on the detector that have geometrical blurs less than the blur criterion B'.

This linear blur condition is called the photographic depth of focus as it constrains the blur on a print or film to be smaller than a certain diameter. Historically, this was probably related to the grain size in the film.

These results assume a thin lens with the stop at the lens.

Depth of Field – Derivation

Consider the image side:




$$\frac{L'_O + L'_N}{D} = \frac{L'_N}{B'}$$

$$\frac{L'_O + L'_F}{D} = -\frac{L'_F}{B'}$$

$$L'_N\left(\frac{1}{D} - \frac{1}{B'}\right) = -\frac{L'_O}{D}$$

$$L'_F\left(\frac{1}{D} + \frac{1}{B'}\right) = -\frac{L'_O}{D}$$

$$B' << D \qquad \frac{1}{B'} >> \frac{1}{D}$$

$$L'_N \approx \frac{B'L'_O}{D} \qquad L'_F \approx -\frac{B'L'_O}{D}$$

$$L' = -L'_F = L'_N = DOF = \frac{B'L'_O}{D}$$

Depth of Field – Derivation – Continued

The nominal object position $L_O$ is conjugate to $L'_O$:

$$\frac{1}{L'_O} = \frac{1}{L_O} + \frac{1}{f}$$

$$L'_O = \frac{f L_O}{f + L_O}$$

The image distances corresponding to the image limits are:

$$z' = L'_O \pm L' = L'_O \pm \frac{B' L'_O}{D}$$

Solve for the corresponding object positions $L_{FAR}$ and $L_{NEAR}$:

$$\frac{1}{z'} = \frac{1}{L'_O \pm L'} = \frac{1}{L} + \frac{1}{f}$$

$$\frac{1}{L} = \frac{f - (L'_O \pm L')}{(L'_O \pm L') f}$$

$$L = \frac{(L'_O \pm B' L'_O / D) f}{f - (L'_O \pm B' L'_O / D)}$$

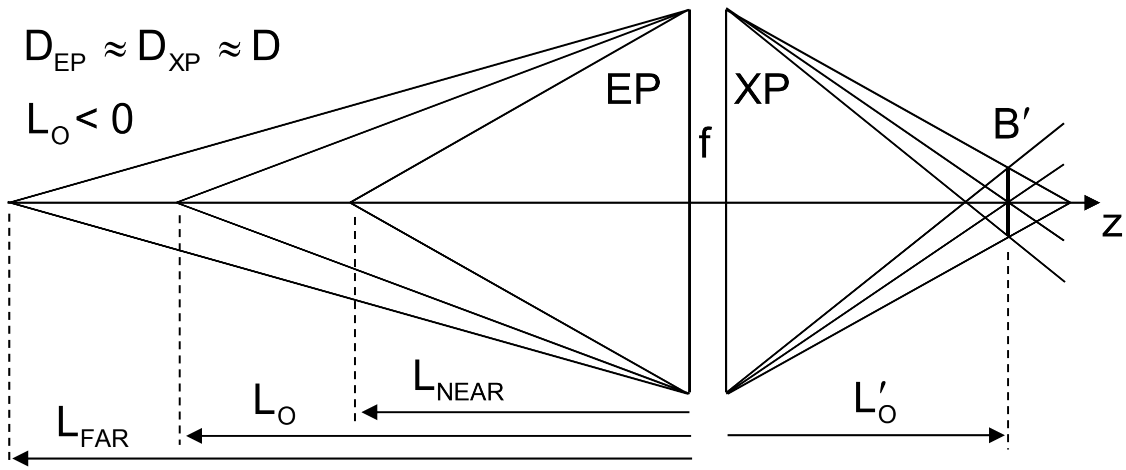
$$L = \frac{L'_O f (D \pm B')}{fD - L'_O (D \pm B')}$$

$$L = \frac{L'_O f (D \pm B')}{fD - L'_O (D \pm B')}$$

$$L = \frac{\dfrac{f^2 L_O (D \pm B')}{f + L_O}}{fD - \dfrac{f L_O (D \pm B')}{f + L_O}}$$

$$L = \frac{L_O f \left(D \pm B'\right)}{fD \mp L_O B'}$$

Depth of Field – Derivation – Continued




$$L = \frac{L_O f\left(D \pm B'\right)}{fD \mp L_O B'}$$

$$L_{FAR} = \frac{L_O f\left(D - B'\right)}{fD + L_O B'} \approx \frac{L_O fD}{fD + L_O B'} \qquad z' = L'_O - L'$$

$$L_{NEAR} = \frac{L_O f\left(D + B'\right)}{fD - L_O B'} \approx \frac{L_O fD}{fD - L_O B'} \qquad z' = L'_O + L'$$

## Hyperfocal Distance

An important condition occurs when the far point of the depth of field $L_{FAR}$ extends to infinity. The optical system is focused at the hyperfocal distance $L_H$, and all objects from $L_{NEAR}$ to infinity meet the image plane blur criterion and are in focus.

$$L_{FAR} = \infty = \frac{L_O f\left(D - B'\right)}{fD + L_O B'} = \frac{L_H f\left(D - B'\right)}{fD + L_H B'} \qquad L_O = L_H$$

$$fD + L_H B' = 0$$

$$L_H = -\frac{fD}{B'} = -\frac{f^2}{\left(f/\#\right)B'}$$

Hyperfocal Focus Position

$$f/\# = \frac{f}{D}$$

Where is $L_{NEAR}$ when the system is focused at $L_H$?

$$L_{NEAR} = \frac{L_O f\left(D + B'\right)}{fD - L_O B'} \approx \frac{L_O fD}{fD - L_O B'}$$

$$L_O = L_H = -\frac{fD}{B'}$$

$$L_{NEAR} \approx \frac{-f^2 D^2 / B'}{fD + fD}$$

$$L_{NEAR} \approx -\frac{fD}{2B'} = \frac{L_H}{2}$$

The near focus object limit is approximately half the hyperfocal object distance.

<u>Hyperfocal Distance and Depth of Focus</u>

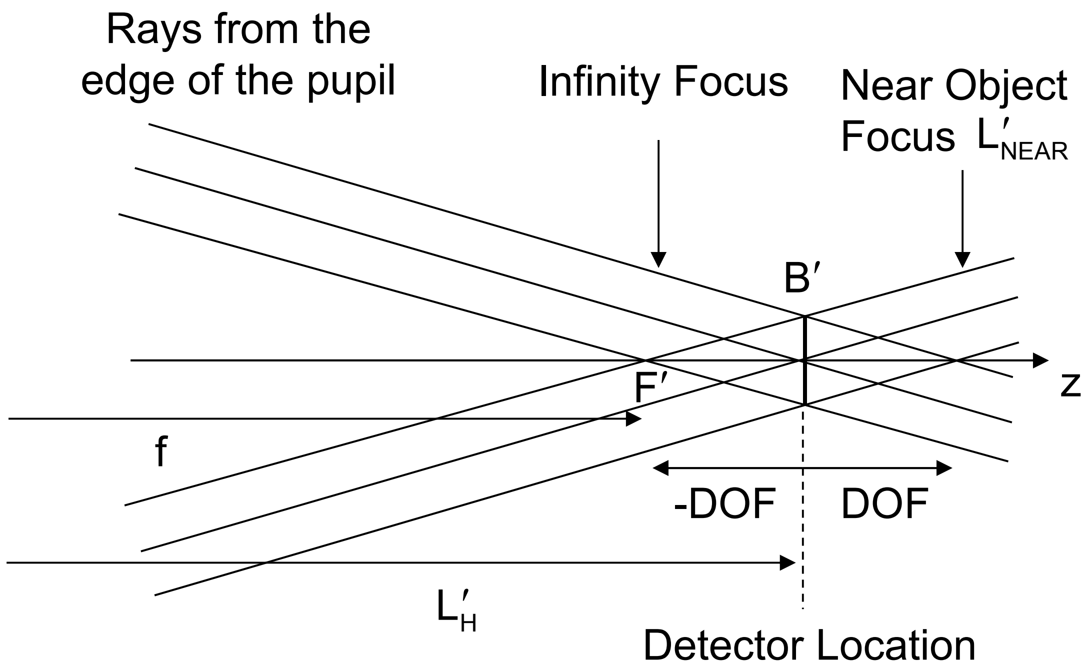
The detector is placed at the conjugate to the hyperfocal distance:

$$\frac{1}{L'_H} = \frac{1}{L_H} + \frac{1}{f} = -\frac{B'}{fD} + \frac{1}{f}$$

$$\frac{1}{L'_H} = \frac{1 - B'/D}{f}$$

$$L'_H = \frac{f}{1 - B'/D} \approx f + \frac{fB'}{D}$$

$$L'_H \approx f + B'f/\# = f + DOF$$




$$DOF \approx B'f/\#$$

$$DOF \ll L'_H$$

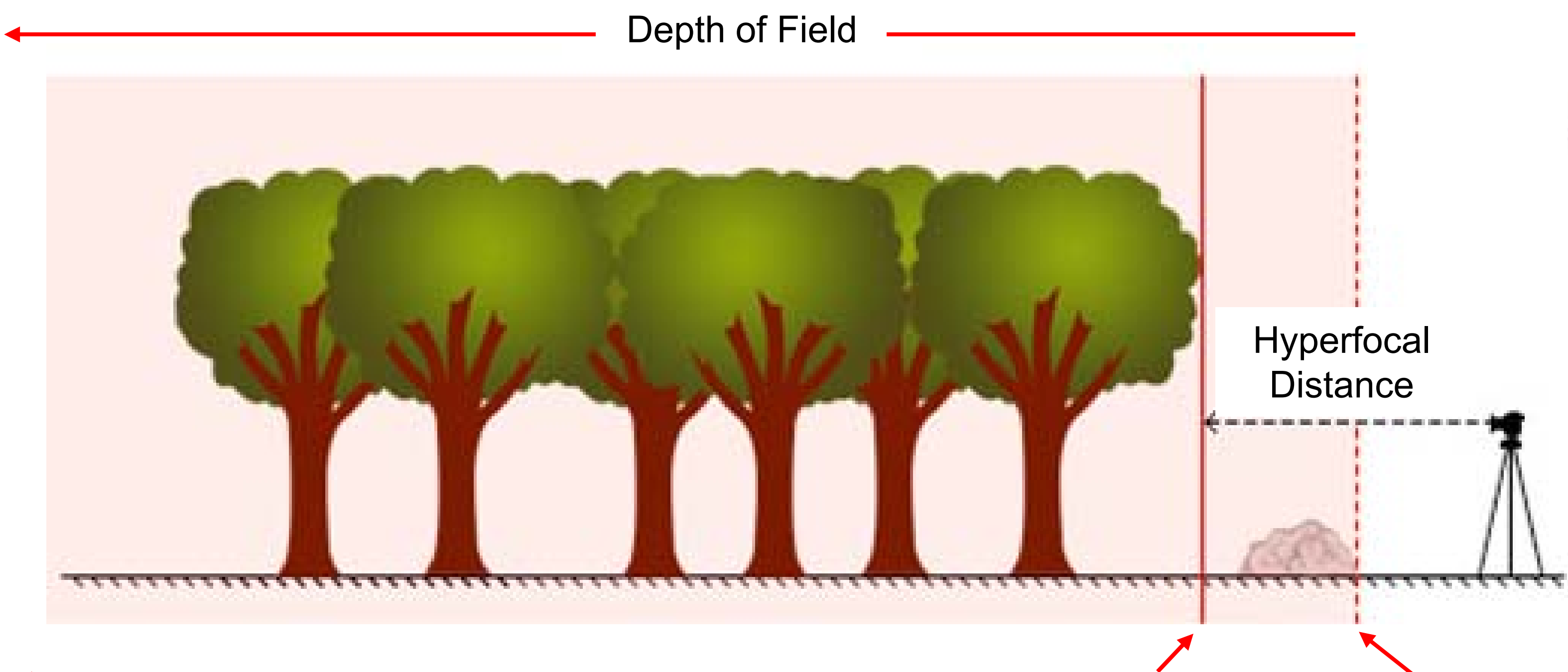
Of course, objects at infinity will focus at the rear focal point of the lens, but produce an acceptable blur on the detector.

The separation between the sensor and the rear focal point is given by the Depth of Focus.

Objects at the Near Point will focus a Depth of Focus behind the sensor, and will also produce an acceptable blur on the detector.

$$\frac{1}{1-x} \approx 1 + x$$

## Hyperfocal Distance




$L_{FAR} = \infty$

$$L_O = L_H = -\frac{fD}{B'}$$

$L_O = L_H$

$L_{NEAR} = L_H/2$

If the camera were focused at infinity, the depth of field actually extends beyond infinity. Focusing at the hyperfocal distance maximizes the use of the available depth of field that includes infinity.

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## Hyperfocal Distance and Depth of Focus and Field

There are many assumptions in these Depth of Focus/Field calculations. The two most important are that there is no diffraction (Airy disc) and that there are no aberrations. Once again, a thin lens with the stop at the lens is assumed.

However, these results are very important as the limitations to system performance are often these first-order geometrical considerations:

| | |
|---|---|
| Depth of Focus | - Film plane flatness |
| Depth of Field | - Focus precision |
| | - Number of autofocus zones |
| | - Artistic considerations |
| Hyperfocal Distance | - Why fixed-focus cameras work |

Number of autofocus zones:

- The most distant zone will be from infinity to half the hyperfocal distance.
- The second zone extends from half the hyperfocal distance to its near point.
- The next zone starts at this near point, etc.

- There can be overlap between the zones.
- The object position only needs to be determined within a zone.
- The zones get shorter as the object distance get closer.

## Example – The Fixed-Focus Camera

System specification: 35 mm film (24 x 36 mm)
4R Print (4 x 6 inch or 100 x 150 mm)
Maximum blur on the print is 0.006” (0.15 mm)
Near focus is 4 ft (1200 mm)
Focal length = 38 mm (sets angular FOV with film)

Print Magnification ≈ 4X

$$B' = \frac{.006''}{4} = \frac{.15\,mm}{4} = .038\ mm$$

$$L_H = 2L_{NEAR} = -8\,ft = -2438\,mm$$

$$L_H = -\frac{fD}{B'} \qquad f = 38\,mm$$

$$D = 2.44\,mm$$

$$f/\# = f/D = f/15.5$$

The exposure is set by the shutter speed and the film speed (ISO).

Dividing the format size with the blur on the film provides about 632 x 947 effective “pixels.” This is approximately SVGA resolution.

## Example – The Fixed-Focus Digital Phone Camera

System specification: Sensor 1/3.2" Format (4.54 x 3.42 mm)
Number of Pixels = 3264 x 2488 (8MP)
Pixel Size = 1.4 μm
Near focus is 4 ft (1200 mm)
Focal length = 4.8 mm (35 mm equivalent = 38 mm)

Set the image blur equal to twice the pixel size.

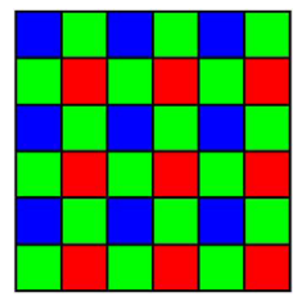
$$B' = 2.8\,\mu m = .0028\,mm$$

$$L_H = 2L_{NEAR} = -8\,ft = -2438\,mm$$

$$L_H = -\frac{fD}{B'} \qquad f = 4.8\,mm$$

$$D = 1.4\,mm$$

$$f/\# = f/D = f/2.9$$

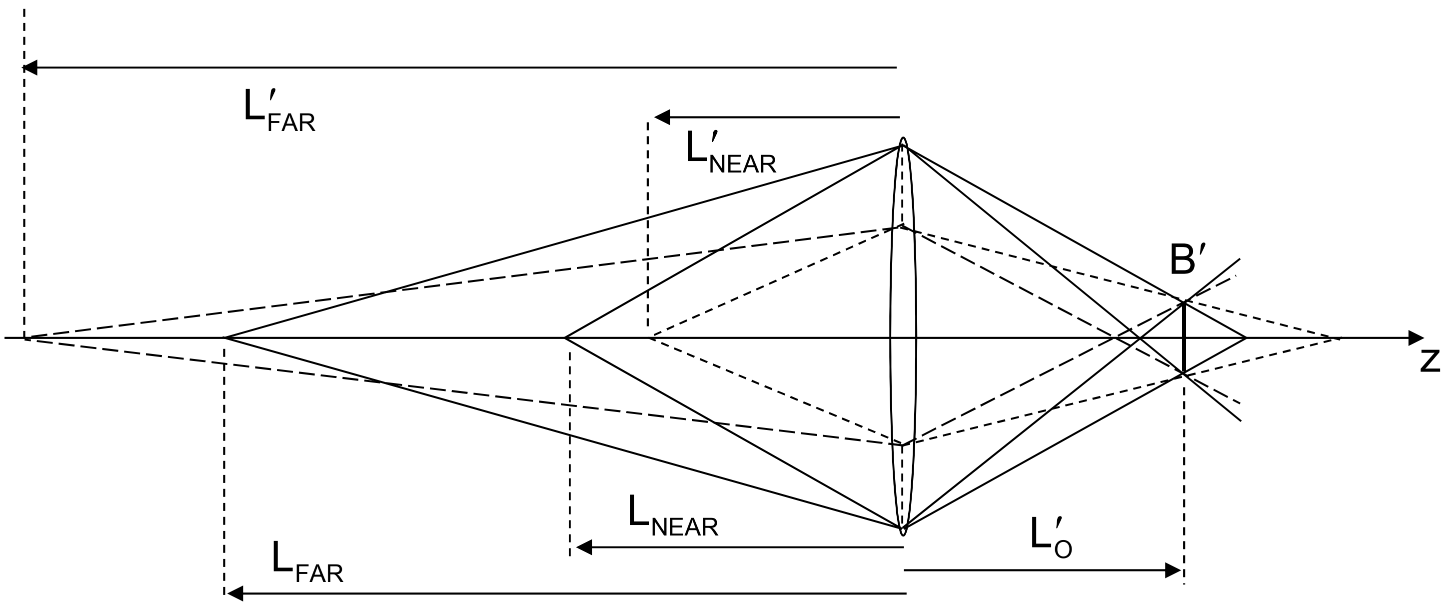


Bayer Color Filter Array

Most camera phones seem to operate at f/2.5 to f/2.2.

Depth of Field and F/#

As a lens of a given focal length is stopped down, the depth of field increases with the increased depth of focus.




As the f/# of a lens increases (the lens is stopped down), the hyperfocal distance also moves closer to the lens:

$$L_H = -\frac{fD}{B'} = -\frac{f^2}{B' f/\#} \qquad L_{NEAR} \approx \frac{L_H}{2} = -\frac{f^2}{2B' f/\#}$$

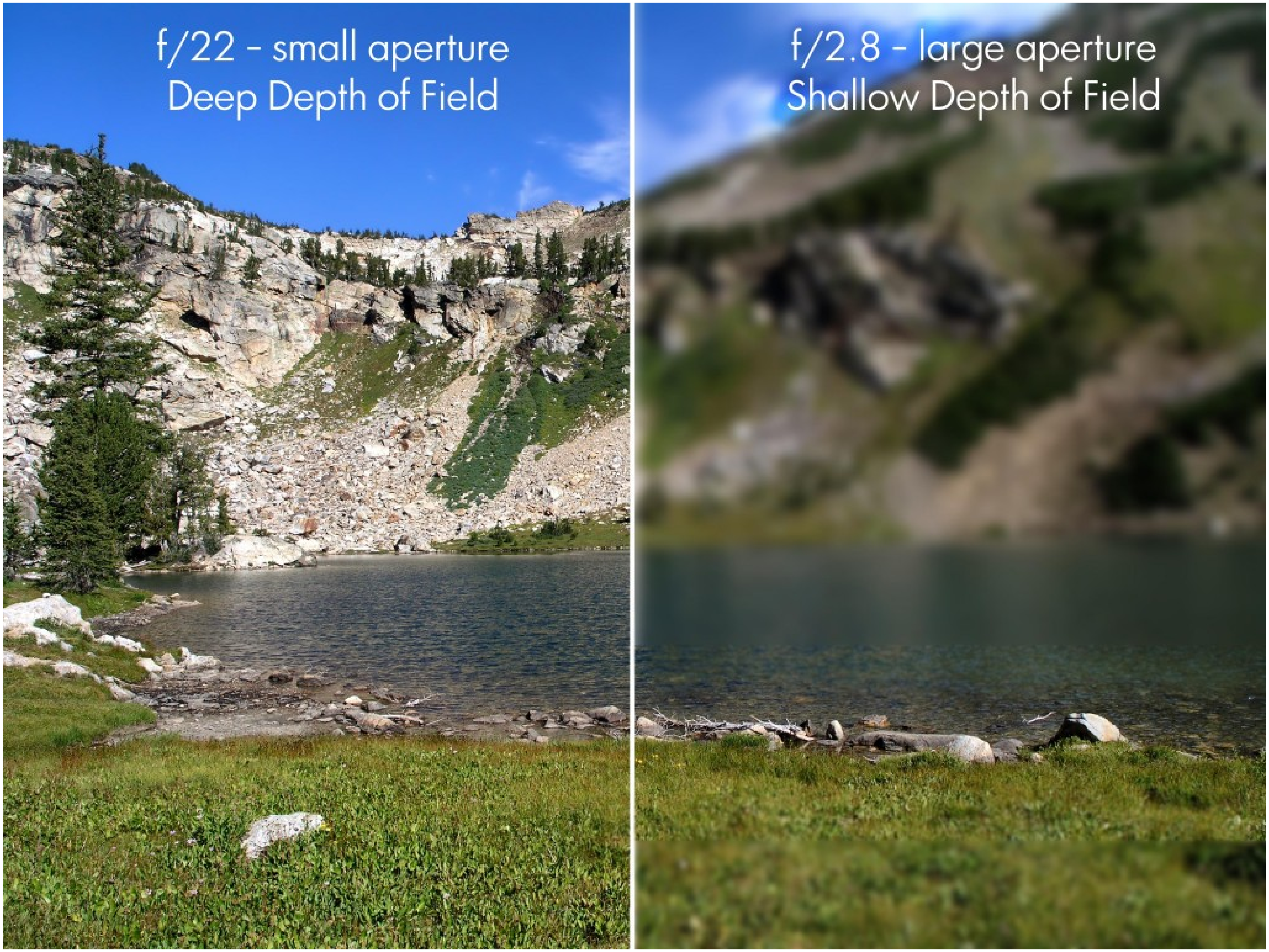
Depth of Field and F/#

f/32

f/5.6

wikipedia

Depth of Field and F/#

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Depth of Field and F/#


photographywisdom.com

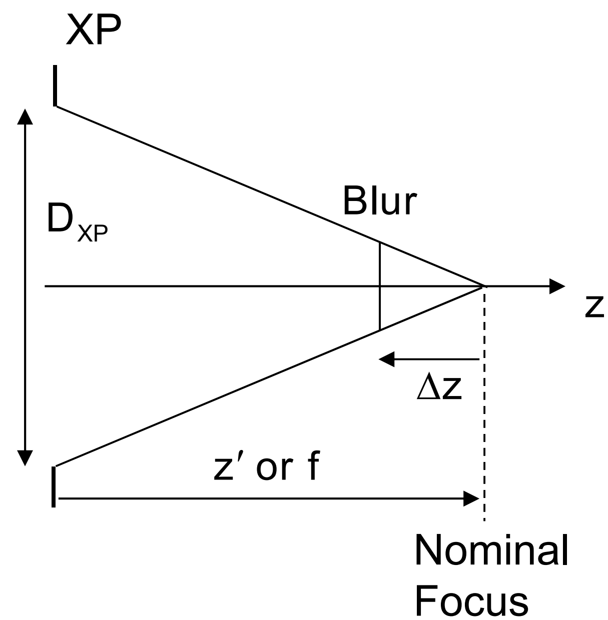
Image Quality

Various factors can affect the recorded image quality:

- Focus or defocus: A circular blur results.

$$\frac{Blur}{|\Delta z'|} = \frac{D_{XP}}{z'} \qquad \text{Assume} \quad D_{XP} \approx D_{EP}$$

$$Blur = \frac{|\Delta z'|}{f/\#_W}$$

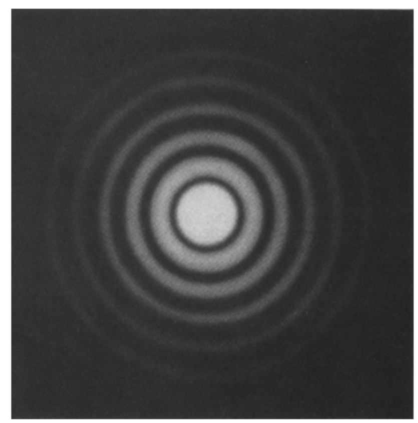



- Aberrations of the imaging system

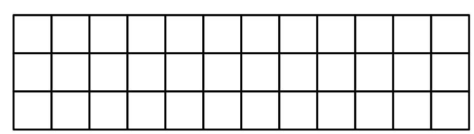
- Diffraction: The diameter of the Airy Disk is

$$D = 2.44\,\lambda\, f/\#$$

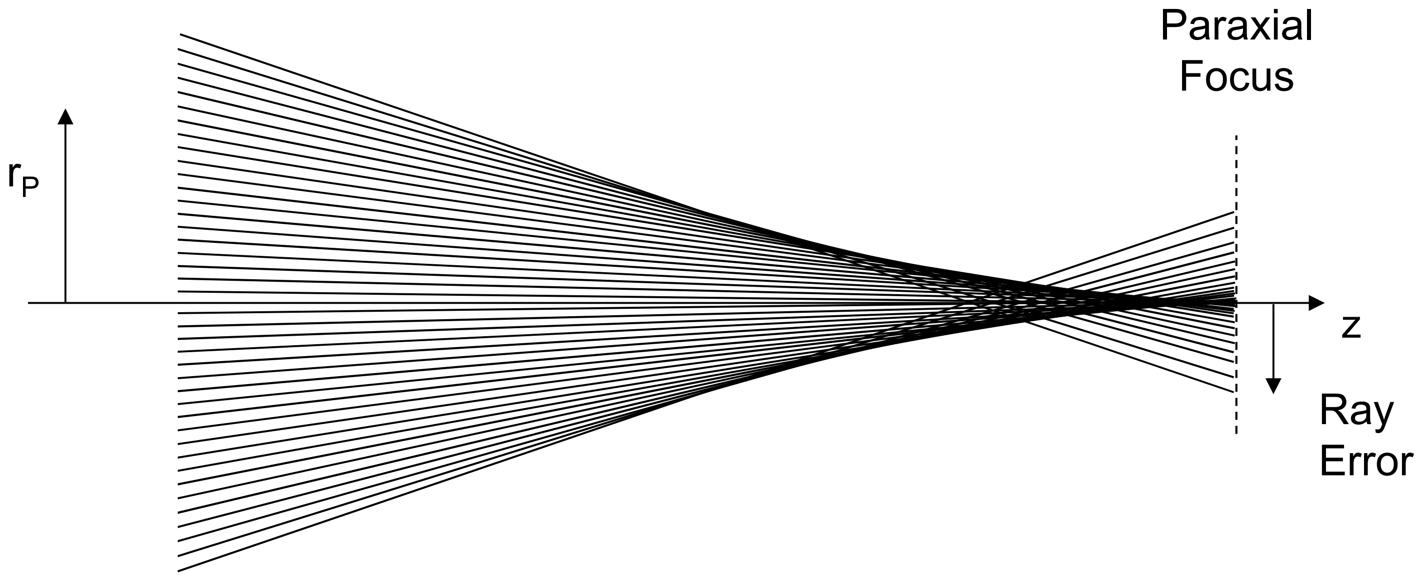
$D \approx f/\#$ in microns



- Pixel Area and Number of Pixels: The image is averaged over the active area of each pixel. Detail finer than the pixel size is lost.



## Spherical Aberration



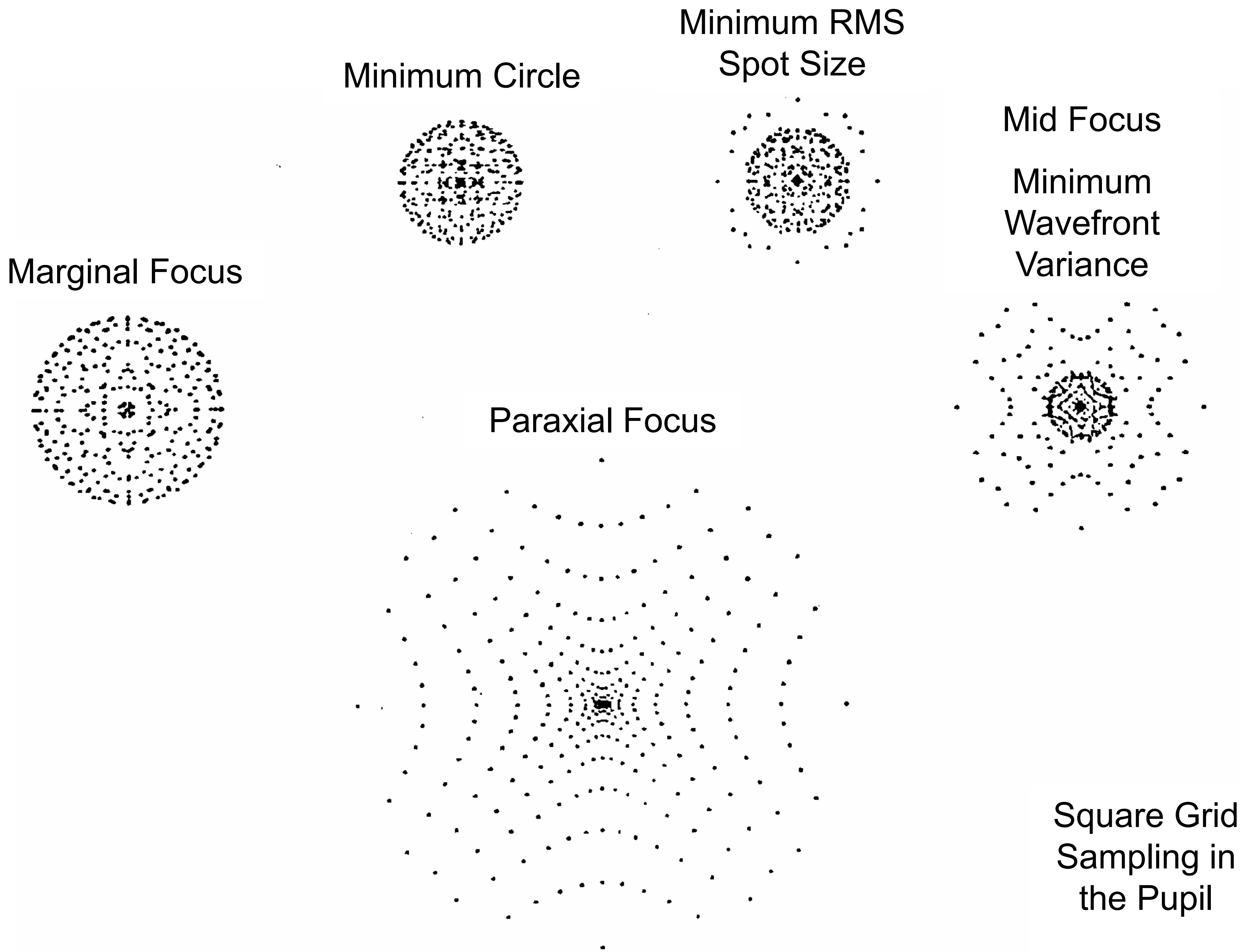

Spherical aberration is a variation of the power or focal length as a function of radial location within the pupil ($r_P$).

For a singlet (undercorrected SA), the power of the lens increases quadratically with pupil radius; the focal length decreases quadratically.

The ray error associated with SA increases as the cube of the location within the pupil. Stopping a lens down can greatly reduce the aberration blur.

$$Blur \propto \left(r_P\right)^3$$

Spherical Aberration – Spot Diagrams at Focus Positions

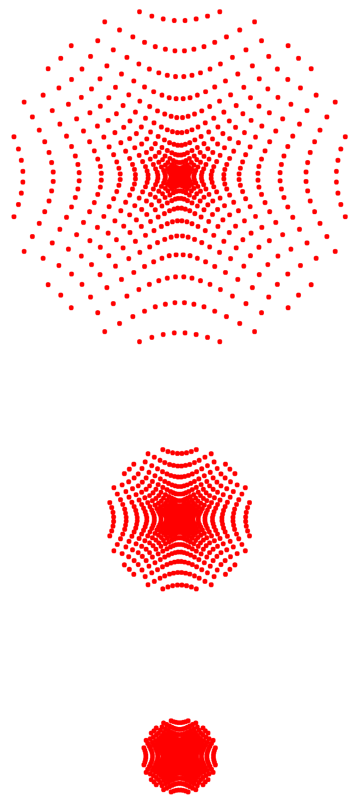


F-Number and Spherical Aberration

f/3

f/4

f/5

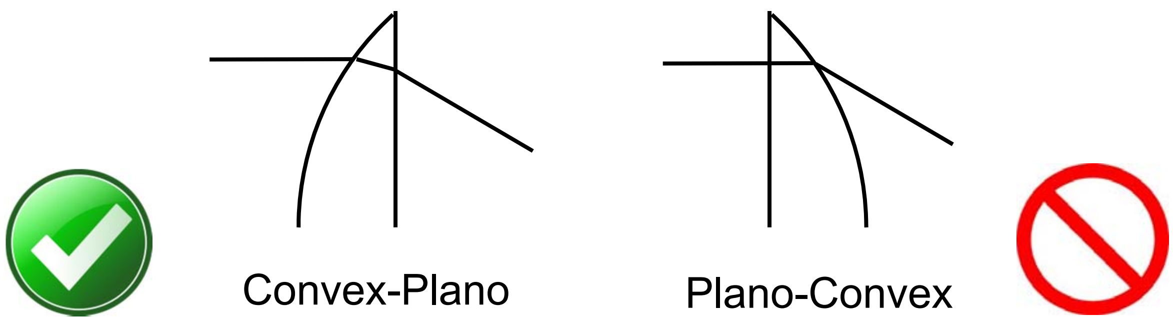


The spot size scales as the cube of the entrance pupil diameter (or the inverse cube of the f/#)

Lens Bending and Minimum Spherical Aberration

The minimum spherical aberration occurs when the light is bent the same amount at each lens surface.

Object at Infinity:




In the plano-convex configuration, all of the ray bending occurs at one surface. In the convex-plano configuration, the ray bending is split between the surfaces. This minimizes the angles of incidence at the surfaces and makes the situation as close to paraxial as possible.

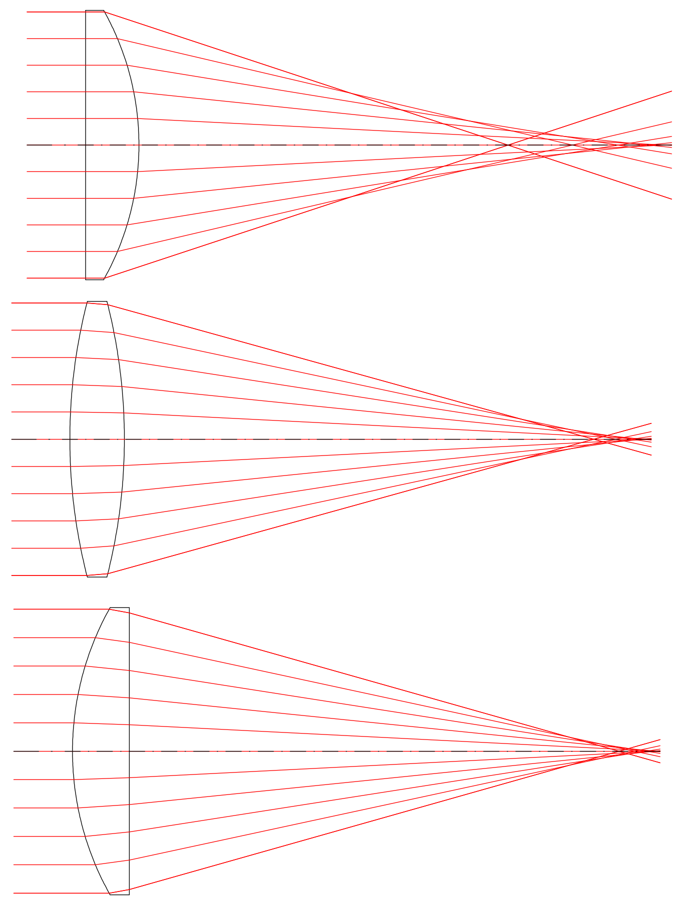
For an index of about 1.5, the convex side of the lens should always face the infinite conjugate. The plano side is oriented towards the finite conjugate.

There is no bending that completely eliminates spherical aberration. It can only be minimized. Different object/image conjugates require different bendings to minimize spherical aberration.

The optimum shape varies with index. At high index, as is often found in the IR, the best shape is a meniscus.

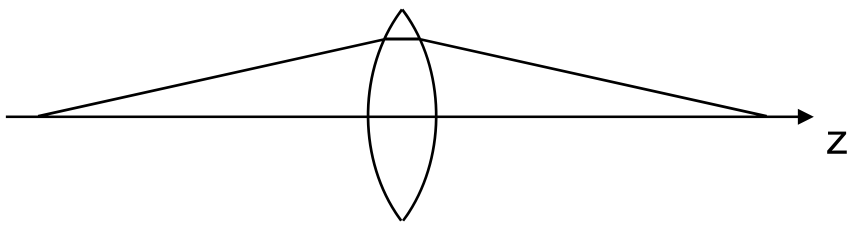
Spherical Aberration vs. Lens Shape

Spherical aberration is a function of the lens bending, or shape of the lens

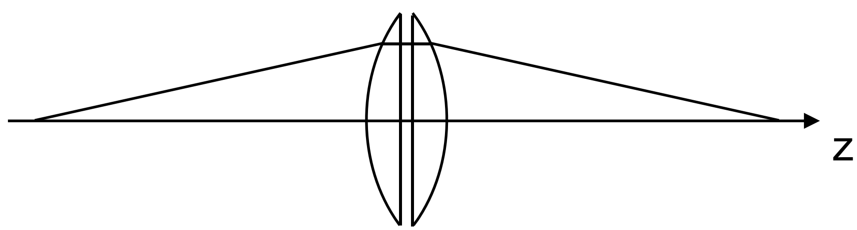


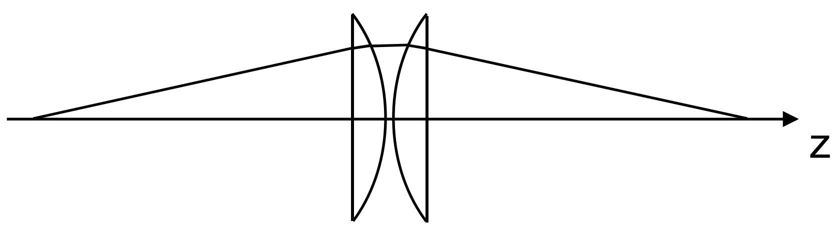
## Spherical Aberration and Finite Conjugates

At finite image conjugates, a bi-convex singlet is required to minimize spherical aberration. The particular shape depends on the magnification. At 1:1 imaging, an equiconvex lens is used.




A trick to further minimize spherical aberration is to split the biconvex lens into two plano-convex lenses and then flip each of the lenses:



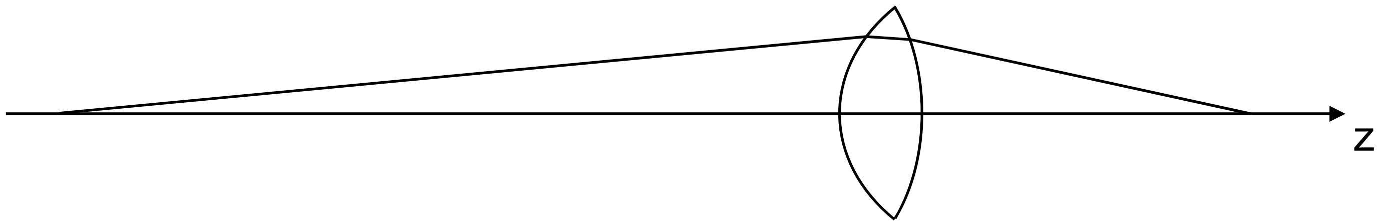




This final vertex-to-vertex arrangement uses two lenses in their infinite conjugate minimum spherical aberration configuration. Much less spherical aberration results than in the bi-convex solution. The focal lengths of the two lenses can be changed to match the object and image conjugates. This solution is also sometimes used in fast condenser lenses.

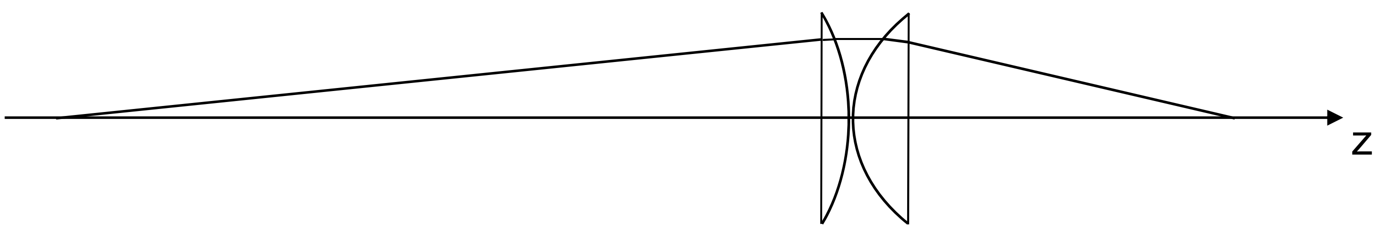
Spherical Aberration and Finite Conjugates

At non-unity conjugates, the lens is bent to obtain minimum spherical aberration.

Equal ray deviation at both surfaces is desired.

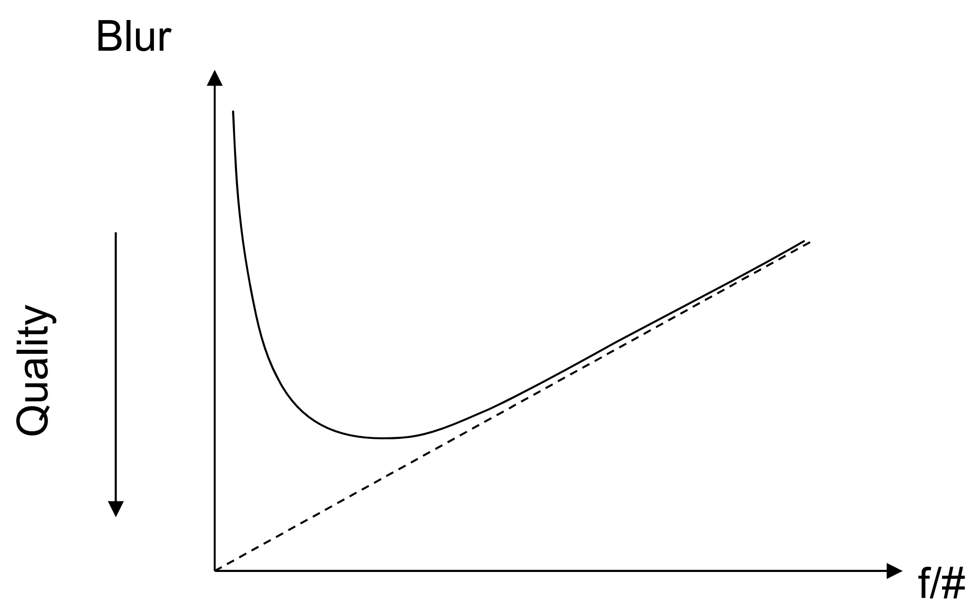



This lens can also be split into two plano-convex lenses to further minimize spherical aberration by using each element in their infinite conjugate minimum spherical aberration configuration.



Quality vs. F-Number

A qualitative plot of image blur as a function of the f/# of an objective can be drawn. With large apertures, aberrations and depth of field errors are dominant, and the blur grows quickly with faster f/#s. When the system has a small aperture, diffraction dominates, and there is a linear dependence of blur on the f/#. For many camera lenses, the minimum blur occurs at about f/5.6-8. Faster camera lenses are not produced because of the potential for reduced diffraction blur, but rather for their radiometric performance in low light level conditions or with fast shutter speeds. The best image quality is produced when the lens is stopped down several stops.



## Uses of the Stop

The diameter of the aperture stop is very important design parameter for an optical system as it controls five separate performance aspects of the system:

- The system FOV determined by vignetting.
- The radiometric or photometric speed of the system or its light collecting ability.
- The depth of focus and depth of field of the system.
- The amount of aberrations degrading image quality.
- The diffraction-based performance of the system.

While some of these aspects are interrelated, they all derive from different physical phenomena.

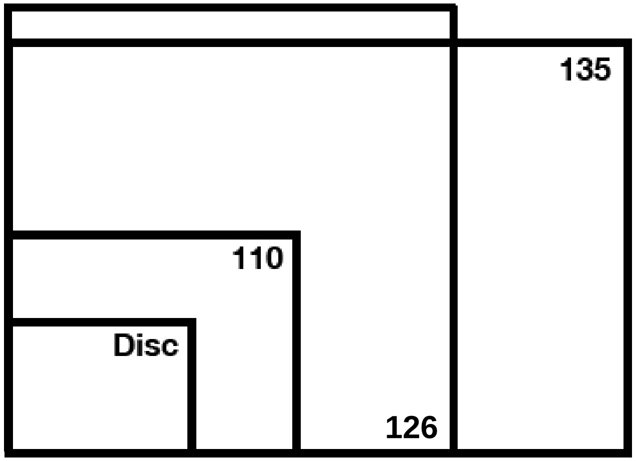
## Film Formats

| Film format | Film width (mm) | Frame size (mm x mm) | Diagonal (mm) |
|---|---|---|---|
| 120 (4:3) | 61.5 | 60 x 45 | 75.0 |
| 220 (1:1) | 61.5 | 60 x 60 | 84.9 |
| 220 (7:6) | 61.5 | 70 x 60 | 92.2 |
| 220 (3:2) | 61.5 | 90 x 60 | 108.2 |
| 126 (1:1) | 35.0 | 28 x 28 | 40.0 |
| 110 (4:3) | 16.0 | 17 x 13 | 21.4 |
| 135 (3:2) | 35.0 | 36 x 24 | 43.3 |
| Disc (4:3) | | 11 x 8 | 13.6 |
| APS Classic (3:2) | 24.0 | 25.0 x 16.7 | 30.1 |
| APS HDTV (16:9) | 24.0 | 30.2 x 16.7 | 34.5 |
| APS Panoramic (3:1) | 24.0 | 30.2 x 10.0 | 31.8 |

In photographic terms, a standard lens is one that produces an image perspective and FOV that somewhat matches human vision. A lens with a focal length equal to the diagonal of the format is usually considered standard. There is considerable variation in this definition as a standard lens for 35 mm camera (135 format) is historically 50-55 mm. Lenses that produce a larger FOV are called wide angle lenses, and lenses that produce a smaller FOV are long focus lenses.

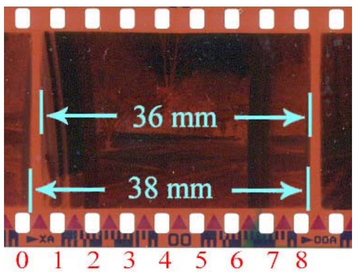
# Film Formats

Disc





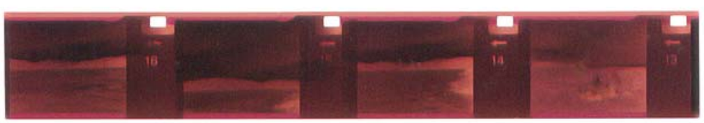
135




| | |
|---|---|
| 120: | 60 x 45 mm |
| 135: | 36 x 24 mm |
| 126: | 28(26) x 28(26) mm |
| 110: | 17 x 13 mm |
| Disc: | 11 x 8 mm |

126

110

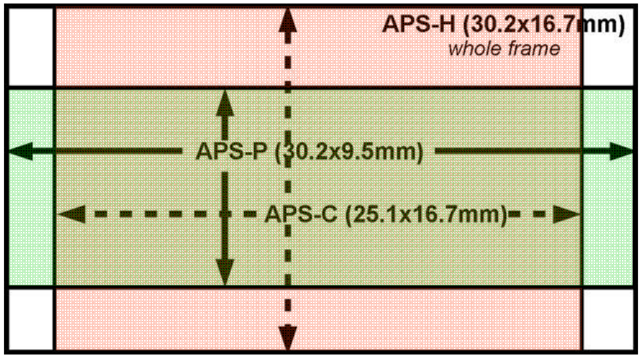


126 & 120

Wikipedia

oldfilmprocessing.com

APS Film Format

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The Advanced Photo System (APS) was introduced in 1996, and provided several advances over 35 mm film:

- Three image formats (aspect ratios)
- Magnetic and optical recording for aspect ratio, date/time, and exposure information
- Film cartridge could be removed and reinserted
- Smaller format with two perforations per frame


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| | |
|---|---|
| Classic (3:2) | 25.0 x 16.7 mm |
| HDTV (16:9) | 30.2 x 16.7 mm |
| Panoramic (3:1) | 30.2 x 10.0 mm |


The APS format never caught on due to the popularity of point-and-shoot 35 mm cameras (and the larger 35 mm film size for professionals) plus the increasing use of digital cameras. While discontinued, the classic APS format serves as the format for many digital SLRs.

## Sensor Formats

The notation for sensor formats used in electronic or digital cameras derives from video camera tubes, in particular vidicon tubes. The charge density pattern on the photoconductor detector is read by a scanning electron beam.

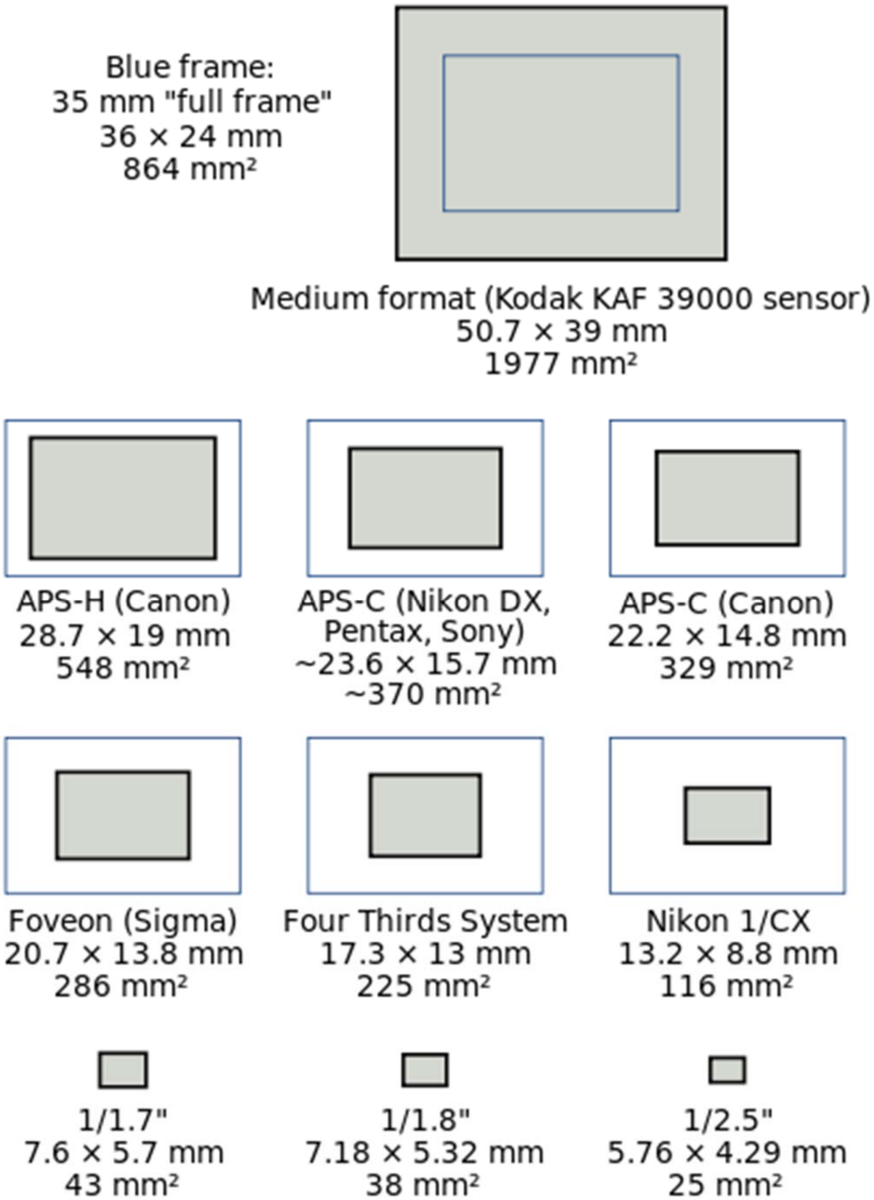

Wikipedia

| Video format | Image size (mm x mm) | Diagonal (mm) |
|---|---|---|
| 2/3 inch | 8.8 x 6.6 | 11.0 |
| 1/2 inch | 6.4 x 4.8 | 8.0 |
| 1/3 inch | 4.8 x 3.6 | 6.0 |
| 1/4 inch | 3.6 x 2.7 | 4.5 |

To match standard television/monitor format, video sensors or focal plane arrays are usually produced in a 4:3 format. Note that the format size (i.e. 2/3 inch) has little or nothing to do with the actual active area. These video formats are the outer diameter of the glass tube required for the given active area.

Modern, dedicated video cameras will likely have sensors in the HDTV aspect ratio (16:9).

## Digital Sensors




Wikipedia

A large variety of sensor formats exist for digital photography and scientific applications.

Digital single lens reflex cameras seem to be evolving into “full frame” formats, matching 35 mm film, and “APS-C format” cameras with sensors about the size of the APS Classic format (about 24 x 16 mm).

For the smaller formats, there is some variation in image size between manufacturers.

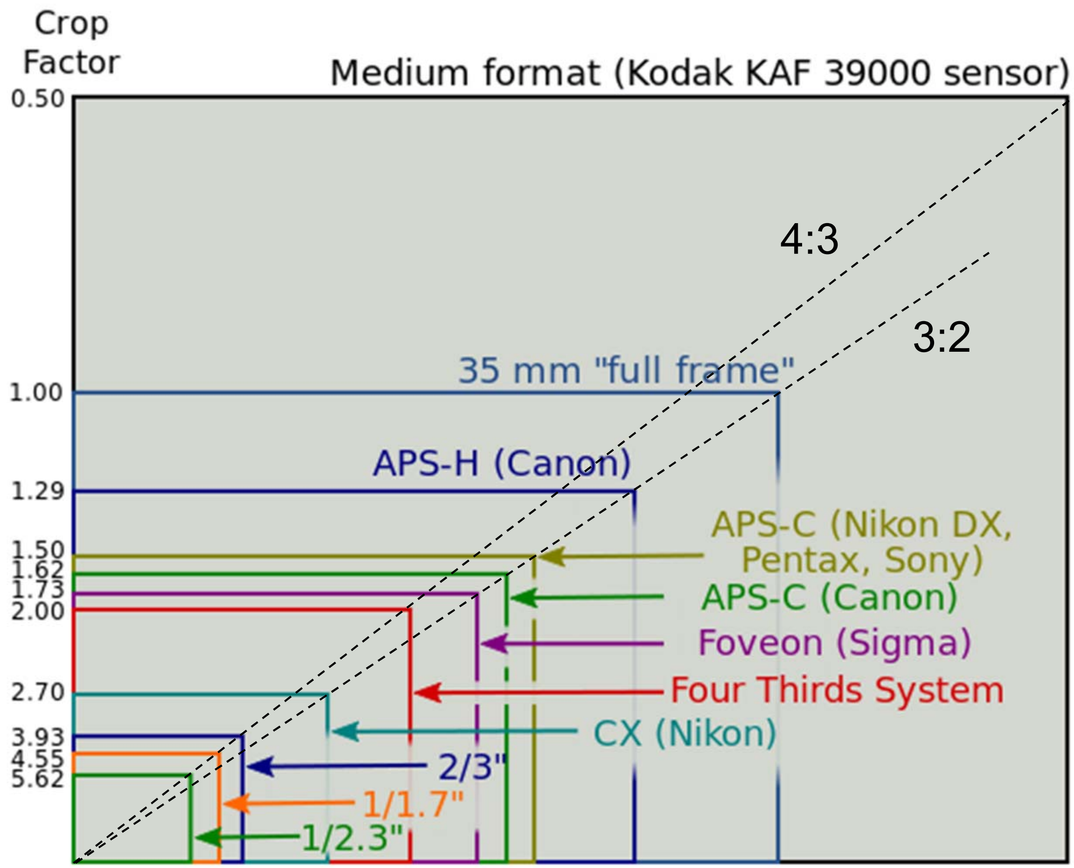
Rule of Thumb: To determine the sensor format or type, multiply the sensor diagonal by 1.5 and convert to inches.

Example: 1/2.5”

$$Diagonal = \left(5.76^2 + 4.29^2\right)^{1/2} = 7.18\ mm$$

$$Format = \frac{1.5\left(Diagonal\right)}{25.4mm\,/\,inch} = 0.42" = \left(1/2.4\right)"$$

Digital Sensors




Wikipedia

Small format cameras generally use sensors with a 4:3 or TV format. The larger-format SLR cameras use sensors with the film-based 3:2 format.

Most mobile phone cameras use tiny sensors in about the 1/3” format, with a diagonal of about 6.0 mm.

Focal Lengths and Digital Cameras

In a 35 mm camera, the fixed film format (24 x 36 mm) along with the focal length of the lens defines the FOV of the system. An experienced photographer instinctively knows what focal length to use to get a particular FOV (normal, wide angle, long focus, etc.). In fact, FOV and focal length almost become synonymous terms.

In digital cameras, there are many available sensors sizes, so the focal length means nothing without reference to the sensor size. The same focal length on two different cameras can produce very different FOVs.

$$\tan(\theta_{1/2}) = h' / f$$

Because of the familiarity of 35 mm camera focal lengths, many manufacturers are not providing the actual focal length of the lens, but rather the "35 mm equivalent" focal length. The lens covers the same FOV as the equivalent focal length on a 35 mm camera.

Other terms that are appearing, especially in digital single lens reflex cameras, are "crop factor" or "focal length multiplier". Many of these DSLRs have sensors that are smaller than the 35 mm film format and therefore cover a narrower FOV than would be expected based simply on the focal length of the lens. These terms are the multipliers that must be applied to the lens focal length to give the 35 mm equivalent focal length in terms of FOV. The crop factor for an APS-C sensor is about 1.5. This means that using a 50 mm lens produces a FOV approximately equivalent to a 75 mm lens on a full-frame camera.

Even though film is going away, the terminology of film and film-based cameras is likely to be with us for quite a while.

## Image Quality

On a small-format photographic print, a blur diameter of 75 µm (0.003 in or 3 mils) is considered excellent image quality. Note that this corresponds to the resolution of the eye (1 arc min) at the standard near point of 250 mm. Blurs larger than about 200 µm (0.008 in or 8 mils) are typically unacceptable.

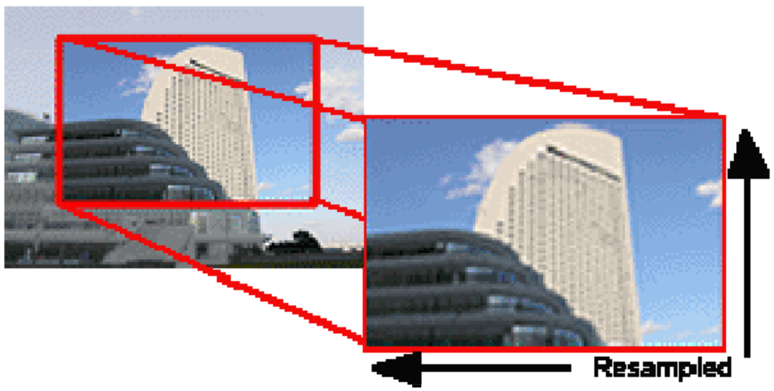
$$\alpha = \frac{75\mu\text{m}}{250\,\text{mm}} = 0.0003\,\text{rad}$$

$$\alpha = 1\,\text{arc min}$$

These blur sizes can be scaled by the enlargement ratio from the detector to determine a blur requirement for the imaging lens. For a 35 mm negative (24 x 36 mm) enlarged to a 4R print (4 x 6 in), this magnification is about 4X. A blur of 3 mils on the print corresponds to a blur of about .75 mils (19 µm) on the negative. It is easy to see that using smaller negatives places additional resolution requirements on the lens.

This analysis also leads to the required number of pixels or resolution elements across the detector. For example, a 4R print with excellent image quality (0.003 in) requires about 1300 x 2000 pixels (2.6 megapixels). Moderate quality (0.005 in) requires about 800 x 1200 pixels (1 megapixel). The method of color encoding must also factor into this analysis.

## Digital Zoom




support.nikonusa.com

Optical zoom increases the size of the image falling on the sensor. The inherent resolution of the sensor is maintained.

Digital zoom crops or uses a portion of the image recorded by the sensor and blows it up or resamples it to create the zoomed image. No additional resolution is produced.

The amount of digital zoom that can be used with good results depends on the number of recorded pixels (image resolution) and the display resolution.

Original:

Optical Zoom:

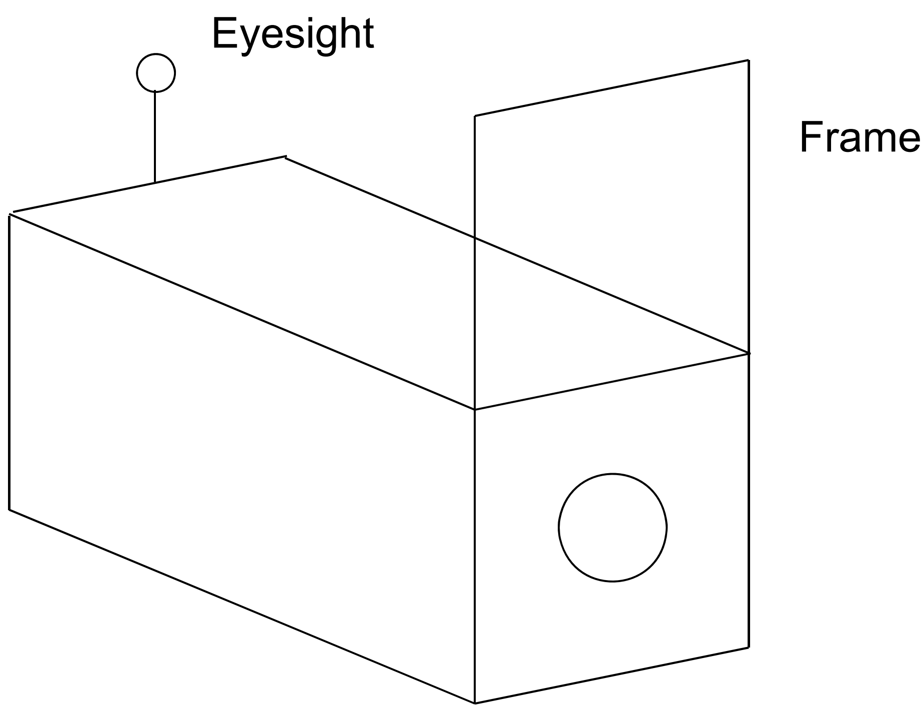
Digital Zoom:

4photos.net/blog

## Viewfinders

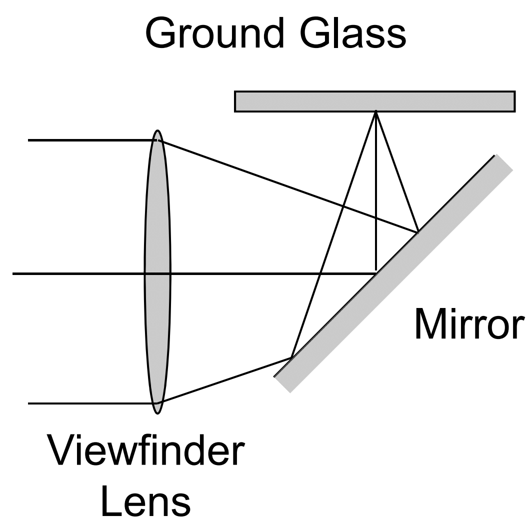
Viewfinders allow for framing the scene in camera systems. The FOV and perspective of the viewfinder should match the FOV and perspective recorded by the camera.

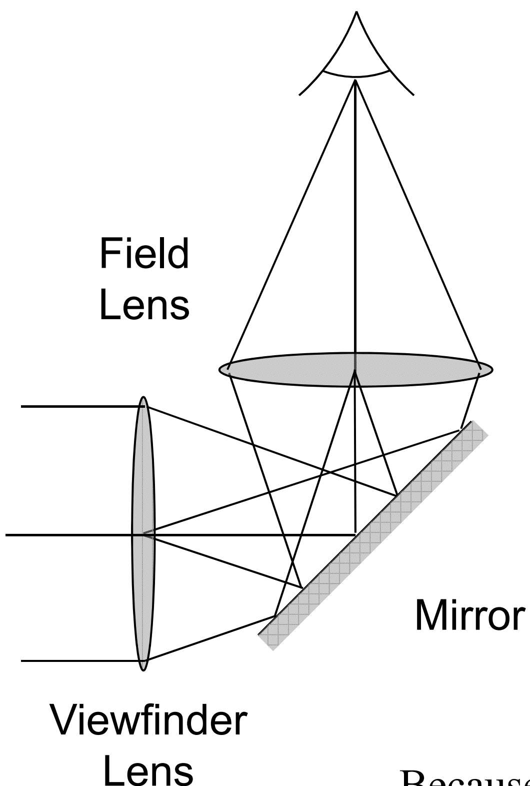
The simple open-frame viewfinder consists of a eyesight to place the eye relative to an open frame. Simple, but not very accurate. No magnification is produced.



Reflex Viewfinders

A reflex viewfinder is a waist-level viewfinder that uses an auxiliary objective on the camera. The dim image produced on a ground glass screen is erect but reverted.



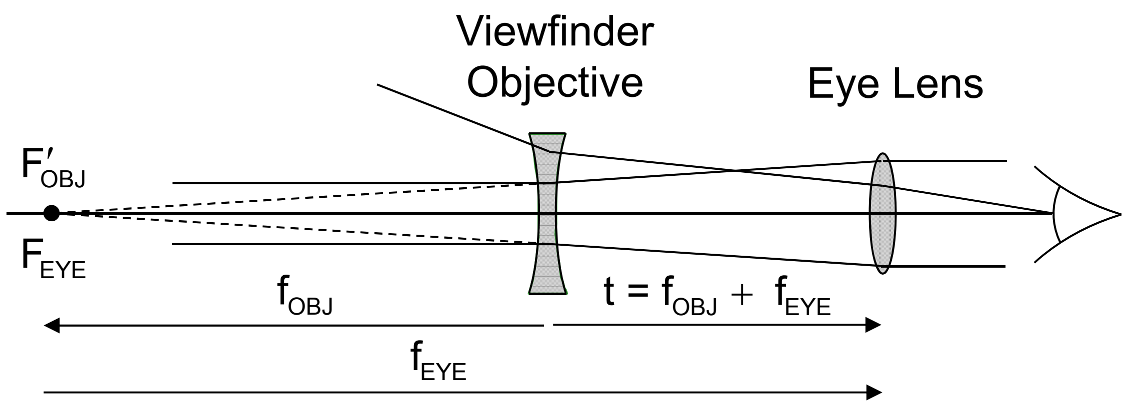




A brilliant reflex viewfinder produces a much brighter image by replacing the ground glass with a field lens. The aperture of the viewfinder lens is imaged onto the eyes of the operator. The viewfinder image is still erect but reverted.

Because both of these viewfinders use a viewfinder lens separated for the camera objective, parallax in the viewfinder image will result.

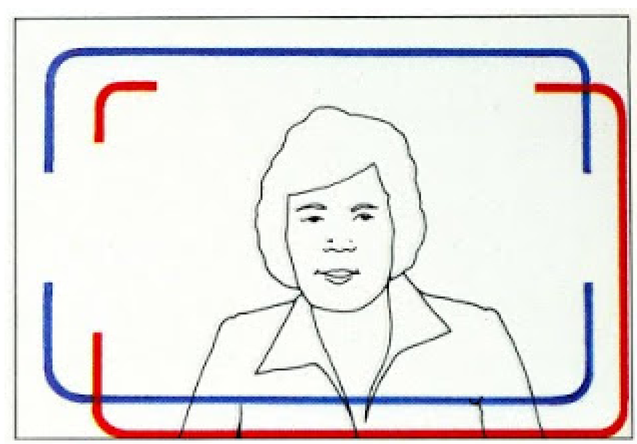
Reverse Galilean Viewfinders

The image perspective of most point-and-shoot cameras is slightly more wide angle than human vision requiring a MP < 1 for the viewfinder.  Reverse Galilean viewfinders are common in these cameras, however the lack of an intermediate image plane prevents the use of a reticle for framing marks to define the FOV.  The viewfinder stop is often at the eye.




Parallax in the viewfinder image will also result as the viewfinder is displaced (in both directions) from the camera objective.  The parallax error is worse for close objects.

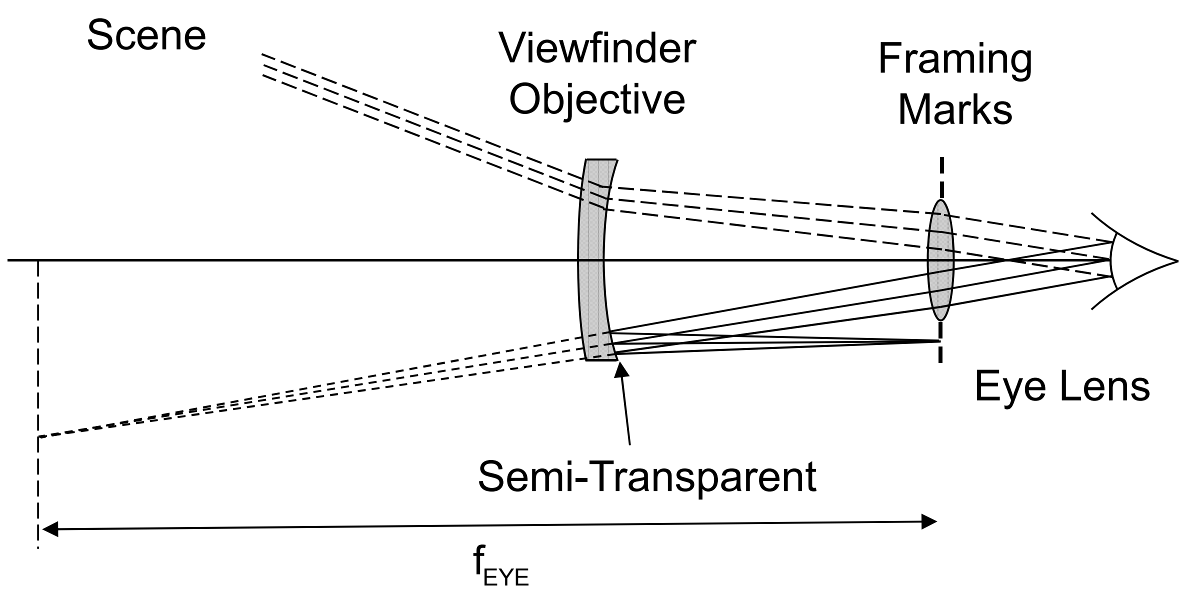
Blue: Viewfinder
Red: Recorded Image



goedlicht.blogspot.com

Van Albada Viewfinder

The Van Albada viewfinder adds framing marks by placing a partially reflecting coating on the negative lens of the reverse Galilean viewfinder. This resulting concave mirror images a framing mask or reticle (surrounding the positive eye lens) to the front focal plane of the eye lens. The framing marks, now imaged to infinity by the eye lens, are superimposed on the straight-through viewfinder image of the scene.



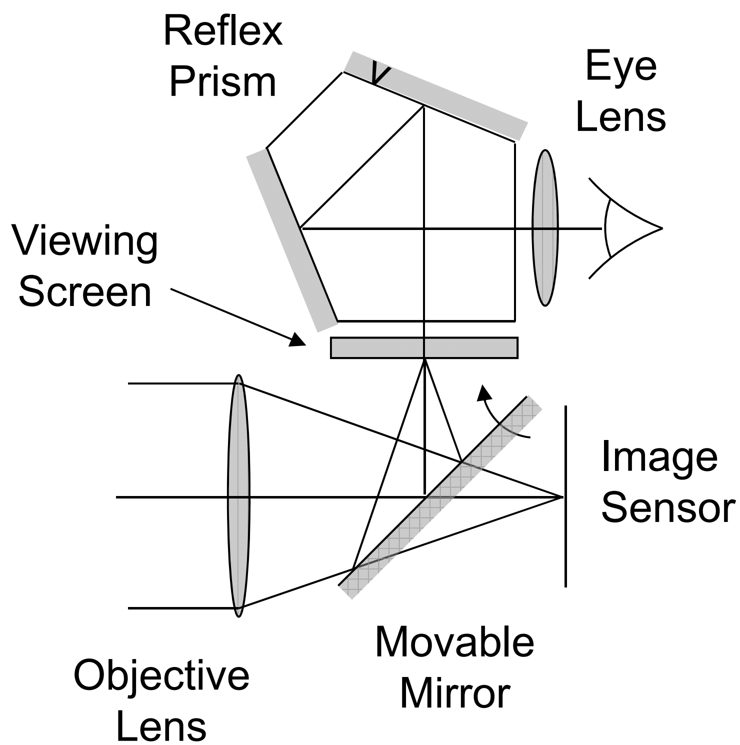

For near objects, parallax between the camera FOV and the viewfinder FOV is a problem with all of the viewfinders discussed (simple, reflex and reverse Galilean). They are also very difficult to use with interchangeable lenses.

<u>Single Lens Reflex Viewfinder</u>

The single lens reflex SLR/DSLR system solves the parallax problem by using the camera objective also for the viewfinder. The movable mirror directs the light path either through the viewfinder or to the film or image sensor. The ground glass or matte surface of the viewing screen is optically conjugate to the film, and the eye lens serves as a magnifier to view the image on this viewing screen. The reflex prism corrects the image parity and provides eye-level viewing.

The ground glass viewing screen prevents vignetting by scattering light from the entire image into the eye lens. It can be replaced by a field lens, often a Fresnel lens, for light efficiency. Commonly, the combination of a Fresnel lens and a scattering surface is also used.

Because the viewfinder shares the objective lens, the SLR system is ideal for use with interchangeable camera lenses. There is no parallax.

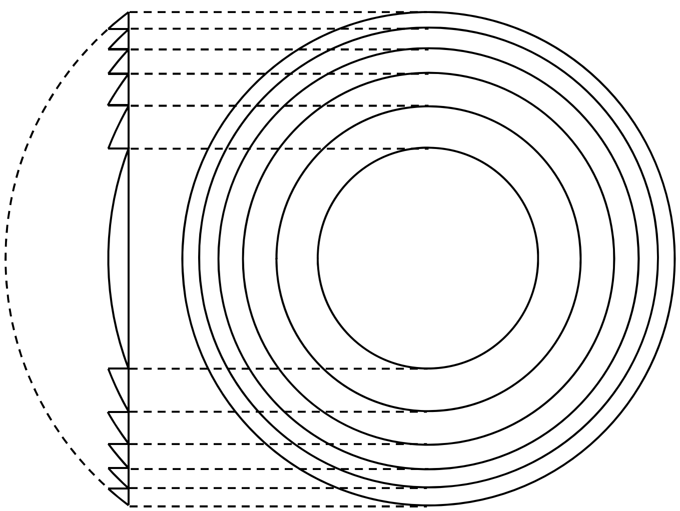


## Fresnel Lens

Conceptually, a Fresnel lens is a thick lens that is collapsed into radial zones. It can be considered to be a collection of prisms, although the face of each prism may be curved.

An image is produced by each zone, and these images add incoherently, so that the diffraction-based resolution is that of a single zone.

Usually molded, the master is produced by computer-controlled lathes.



Side View    Top View

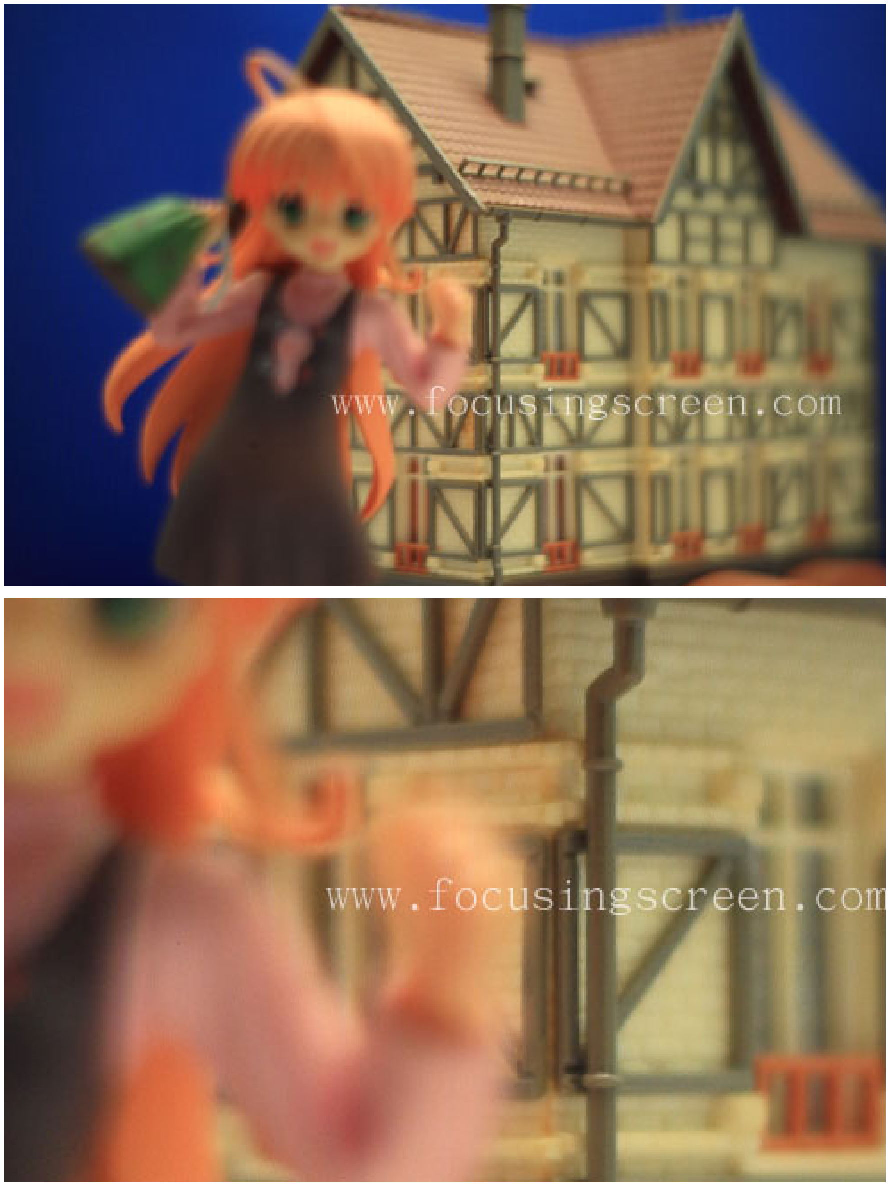
The lens can be comprised of hundreds of rings.

Wikipedia

Used for lighthouse lenses and automobile taillights!

Focusing Screens

Focused on Building

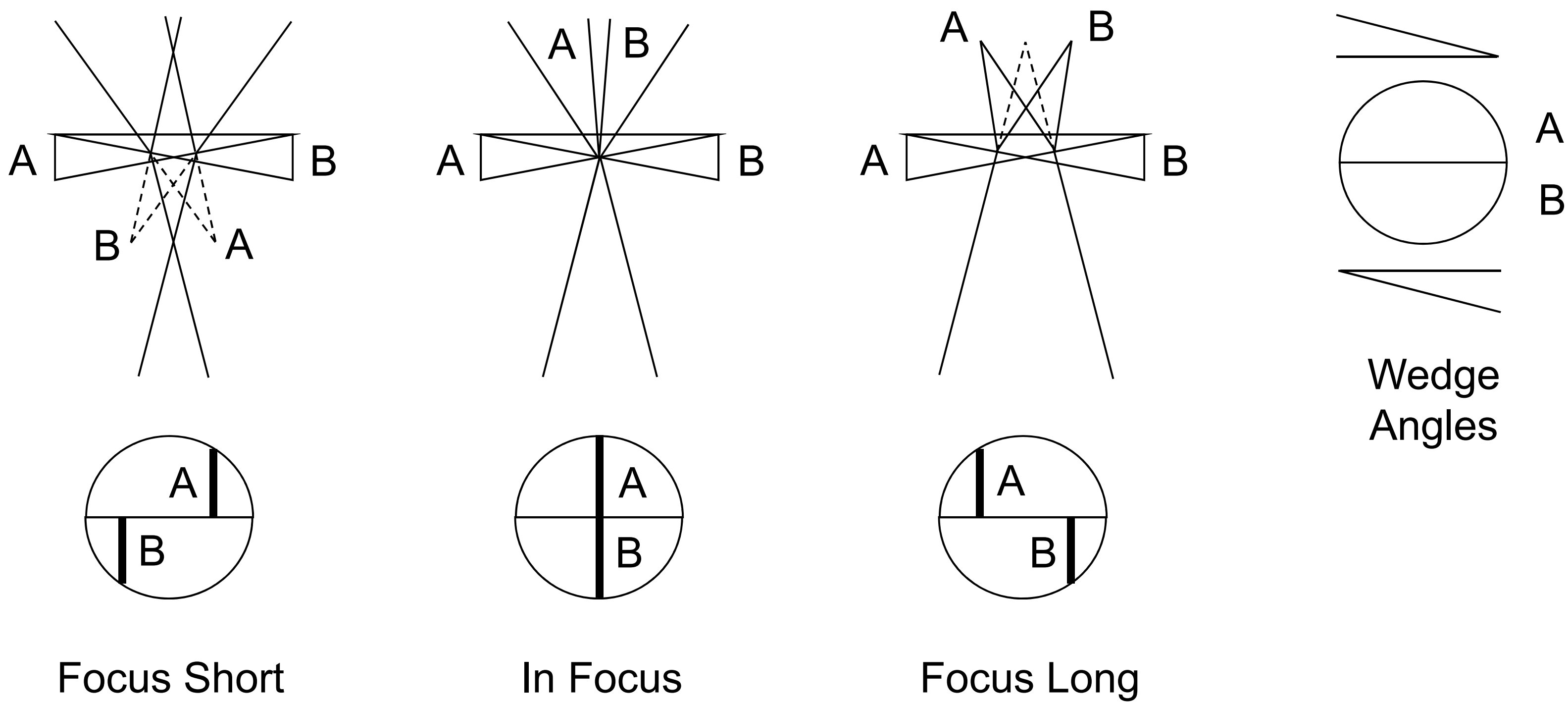



Focused on Doll

## Split Prism Focusing Aid

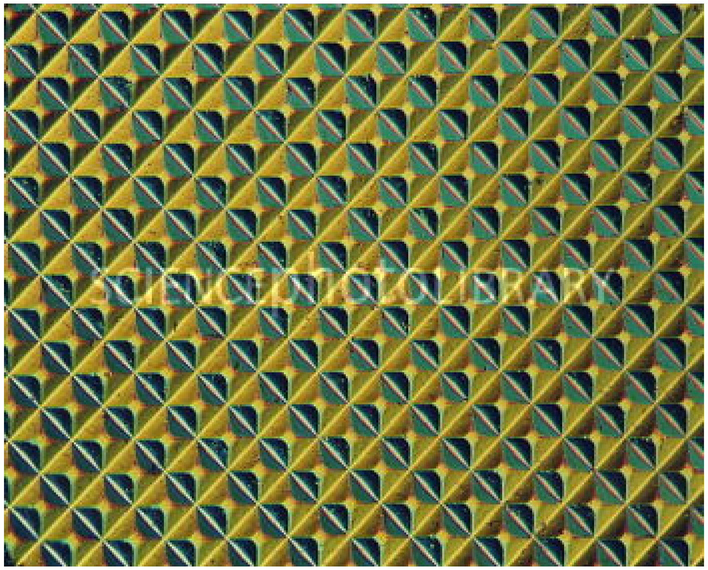
Focusing is accomplished by translating the lens and changing the image distance in the camera. This is often done by subjective visual evaluation of the image sharpness. A focusing aid can be added to the SLR viewfinder to turn focusing into an image alignment task. This method also makes use of the vernier acuity of the eye (about 5 arc sec) instead of the resolution of the eye (1 arc min).

A split wedge focusing aid consists of two opposing thin prisms placed in the center of the image plane of the viewfinder (SLRs). When the image is out of focus, the image will appear sheared by the prisms.



Microprisms

An array of small prisms can also be used. Each prism shifts the image in the same manner as the split-prism focusing screen. When the image is properly focused, a clear image is seen. When the image is out of focus, the image will appear to sparkle or shimmer.



Sciencephoto.com

Combinations of a split prism and microprisms can be used.

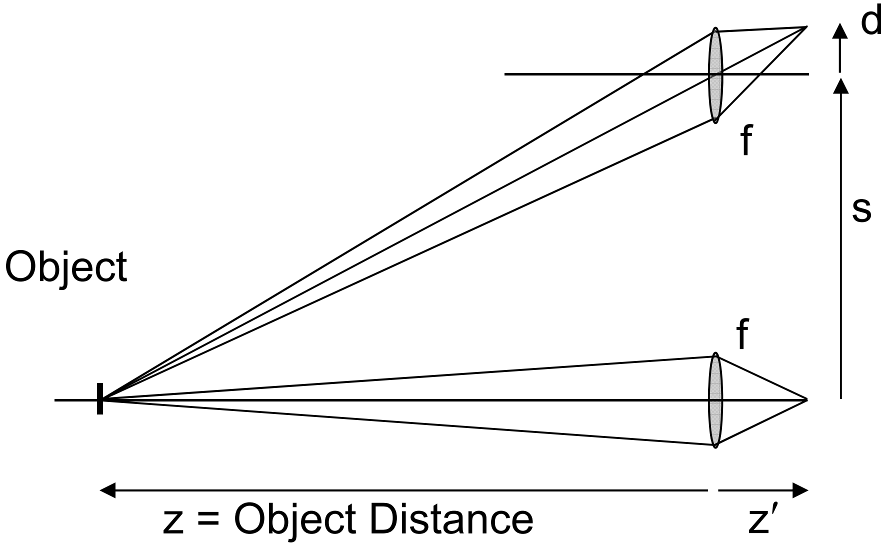
On cameras with autofocus, simpler focusing screens (ground surface plus a Fresnel lens) are used.

## Focusing Screens

Focused on Building | Focused on Doll

Parallax Triangulation

The perspective difference or parallax between images produced by separated objectives can be used to triangulate the distance to an object. The object distance $z$ is related to the relative image displacement $d$:




$$\frac{d}{z'} = -\frac{s}{z}$$

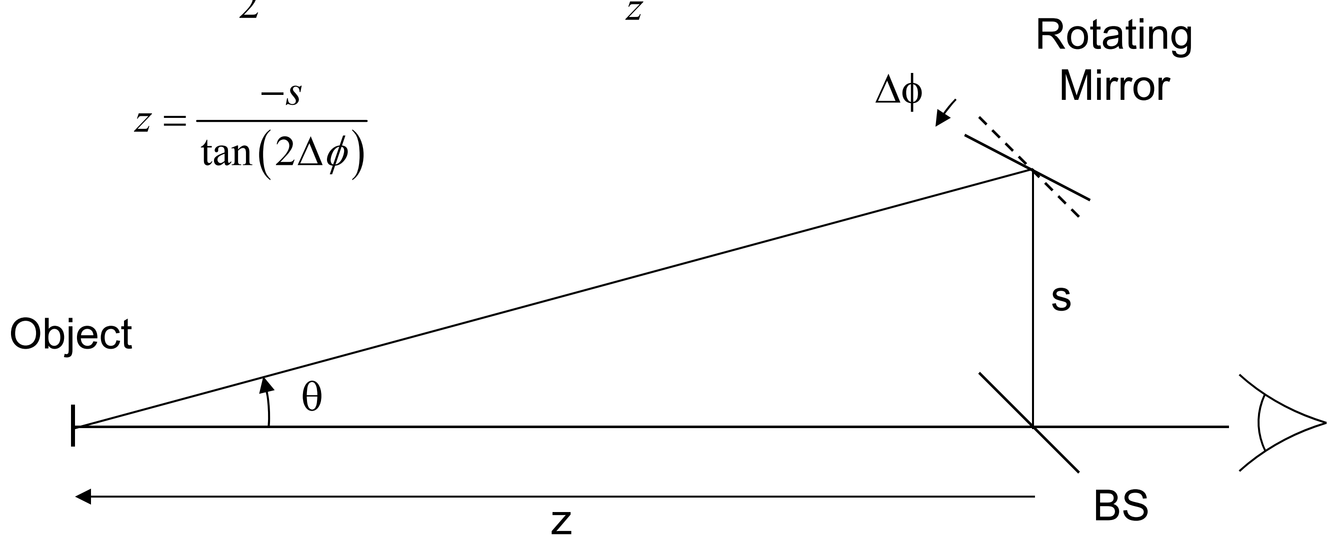
$$z = -\frac{s\,z'}{d} \approx -\frac{s\,f}{d}$$

## Image Coincidence Rangefinder

An image coincidence rangefinder is often used as a visual aid for focusing compact cameras. It is based upon triangulation and parallax. The optical path through the reverse Galilean viewfinder is directed by a beamsplitter into two separate optical paths. A mirror in one path is rotated until the two images viewed overlap. The mirror tilt angle encodes the scene distance.

$$\Delta\phi = \frac{\theta}{2} \qquad \tan\theta = -\frac{s}{z}$$

$$z = \frac{-s}{\tan(2\Delta\phi)}$$




Δϕ is measured from the nominal mirror position of 45° corresponding to an object at infinity.

The mechanical motion of the mirror is often directly coupled to the motion of the lens required for proper focus.

## Autofocus Sensors

Autofocus sensors can be classified into two basic types:

Active – energy from the camera is directed towards the scene and the reflected energy is used to determine the object distance.

Passive – the object distance is determined from the ambient light received from the scene.

All focus sensors have a failure mode. It is important to understand these modes and pick the system that is best for the application. If no focus position is detected, the camera usually defaults to an object at infinity (or to the hyperfocal distance).

The camera usually scans near to far and it focuses on the closest object detected.

Further Classifications:

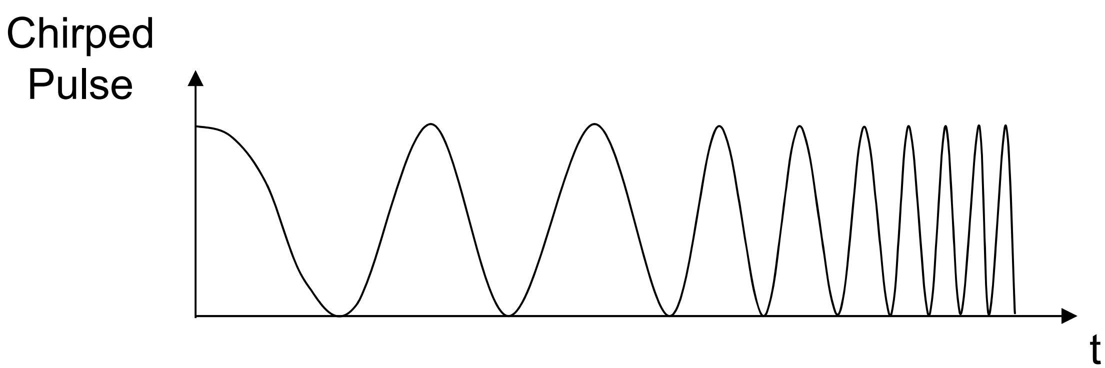
| | |
|---|---|
| Active Autofocus Sensors: | Echo<br>Triangulation |
| Passive Autofocus Sensors: | Triangulation<br>Image Contrast |

## Echo Sensors

This type of sensor is a time-of-flight system. A pulse of energy is directed at the scene and we measure the round trip transit time. Because of the speeds and time intervals that results, sound is used instead of light.

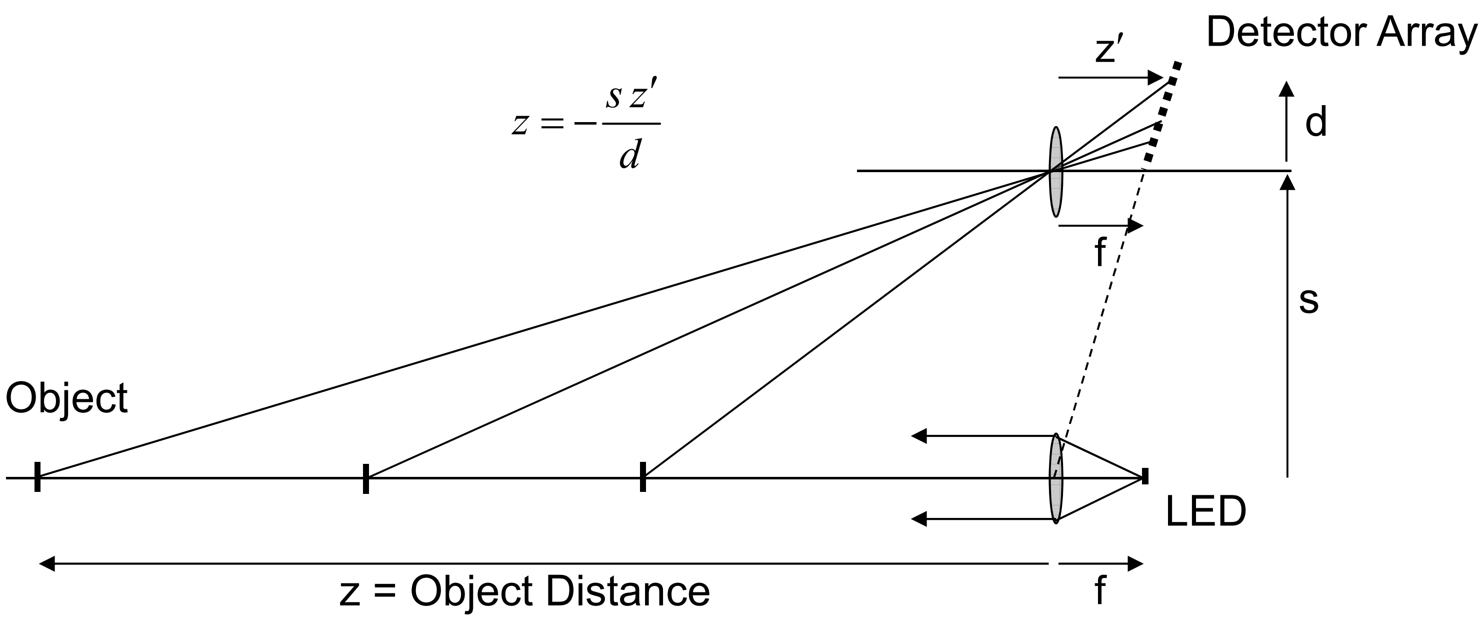
This system first appeared on the Polaroid SX-70 camera. A piezoelectric (PZT) transducer is used to emit an ultrasonic pulse. The frequency of the pulse is chirped from 50-60 kHz to allow better resolution. The round trip time is 5.8 msec/m.

The same transducer is used for both sending and receiving the pulse. The chirped pulse is used so that the returned signal can be correlated with the original waveform. This allows the system resolution (in time and therefore distance) to be better than that allowed by the total length of the pulse. Longer pulses can be used for increased signal to noise.



## Active Triangulation Sensors

The light from an LED is collimated and aimed at the subject. The subject is assumed to be a diffuse reflector. The reflected light is captured by a second lens and imaged onto a detector array. The separation of the returned spot from the axis of the second lens is a measure of subject distance. An object at infinity will produce a returned spot at the rear focal point of the lens. The number of required focus zones will depend on the focal length of the camera lens, its f/#, and the required blur size on the image detector.

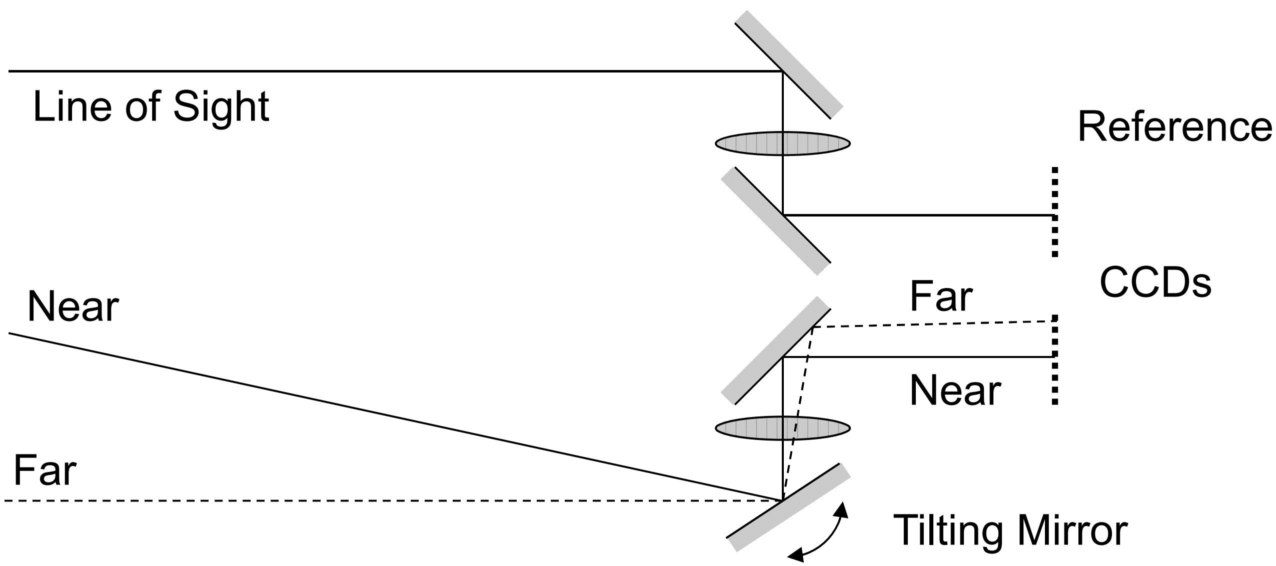



The returned spot on the detector array can be kept in focus by tilting the detector array and using the Scheimpflug condition. Other arrangements of source and detector can be used: single detector and multiple LEDs; a single moving LED and a single fixed detector; a single moving detector and a fixed LED.

## Passive Triangulation Systems

In a passive system, only existing light is used, so a reasonable ambient light level is required. The camera may also project a light pattern onto the scene at low illumination levels.

In an automated coincidence rangefinder, images with parallax are imaged onto two detector arrays. This is the direct analog of the visual image coincidence rangefinder. The mirror tilt is coupled to the lens focus position, and the lens moves from close focus to infinity. As the focus position changes, one of the images on the detectors sweeps across the detector. The other detector contains the reference image, and the two detectors signals are fed into a comparator circuit. When the images match, the camera is in focus. The lens is stopped, and the exposure is made.



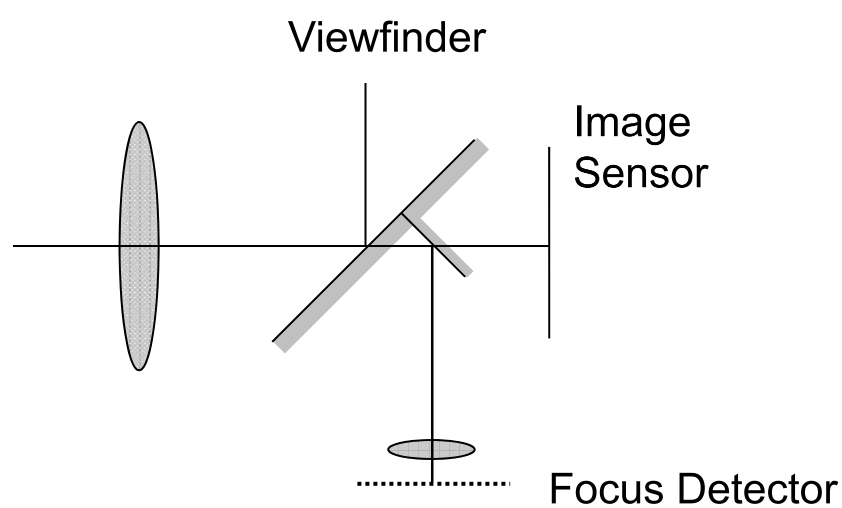

By starting close and working out, the camera focuses on the closest object.

# Through the Lens (TTL) Phase Matching Focus Sensor

Most SLR cameras use a focus detection system that creates parallax by using light from subapertures at the opposite edges of the objective lens. The geometry creates two images that are compared to determine object position.

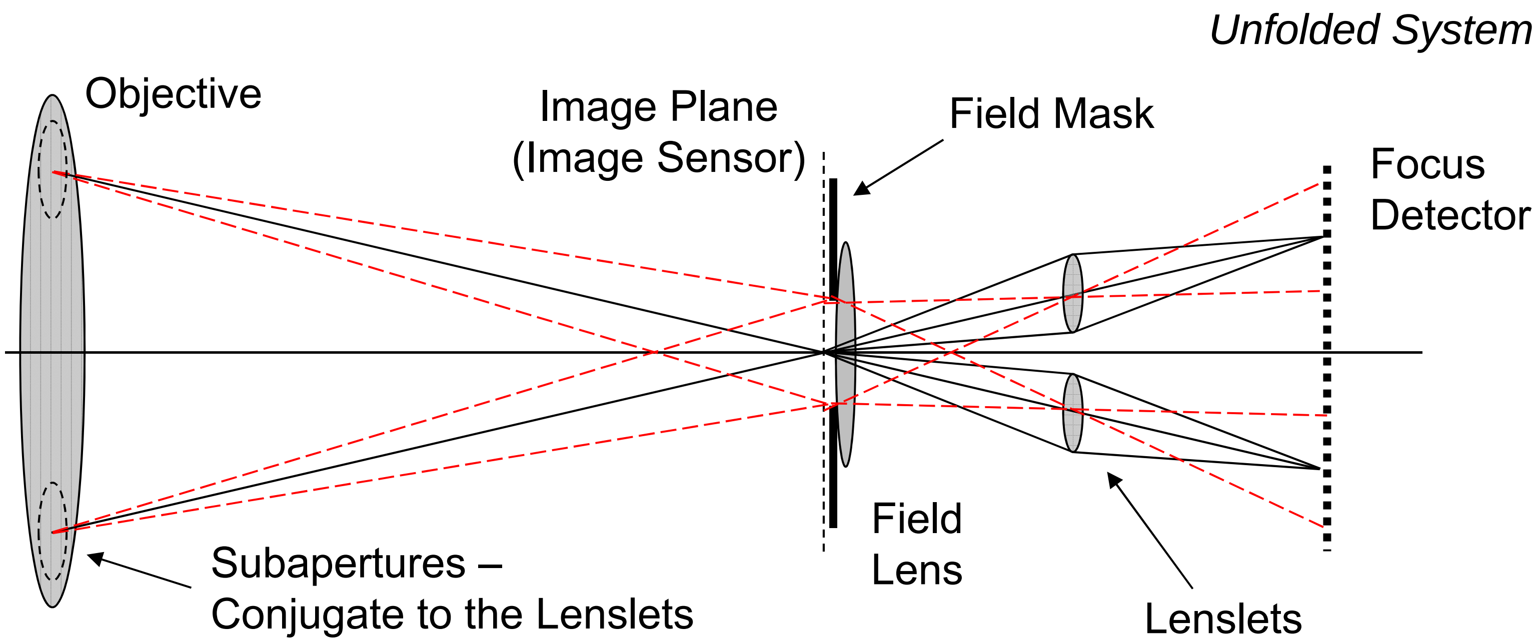
The focus detector is usually located in the bottom of the mirror box of an SLR/DSLR camera by using a partially reflective flip mirror and a small auxiliary mirror.

Focus detection can occur while the viewfinder is active (flip mirror down).



## Through the Lens (TTL) Phase Matching Focus Sensor

A field mask in the image plane (optically conjugate to the image sensor) selects the portion of the FOV to measure. The two small lenses (lenslets) image this mask (and the object/image) onto the focus detector arrays (black). The field lens images the objective lens aperture onto the lenslets (dashed red). The size and offset of the two lenslets selects light from different parts of the pupil of the objective lens defining subapertures for the triangulation. The focus detector array is conjugate to the image plane.

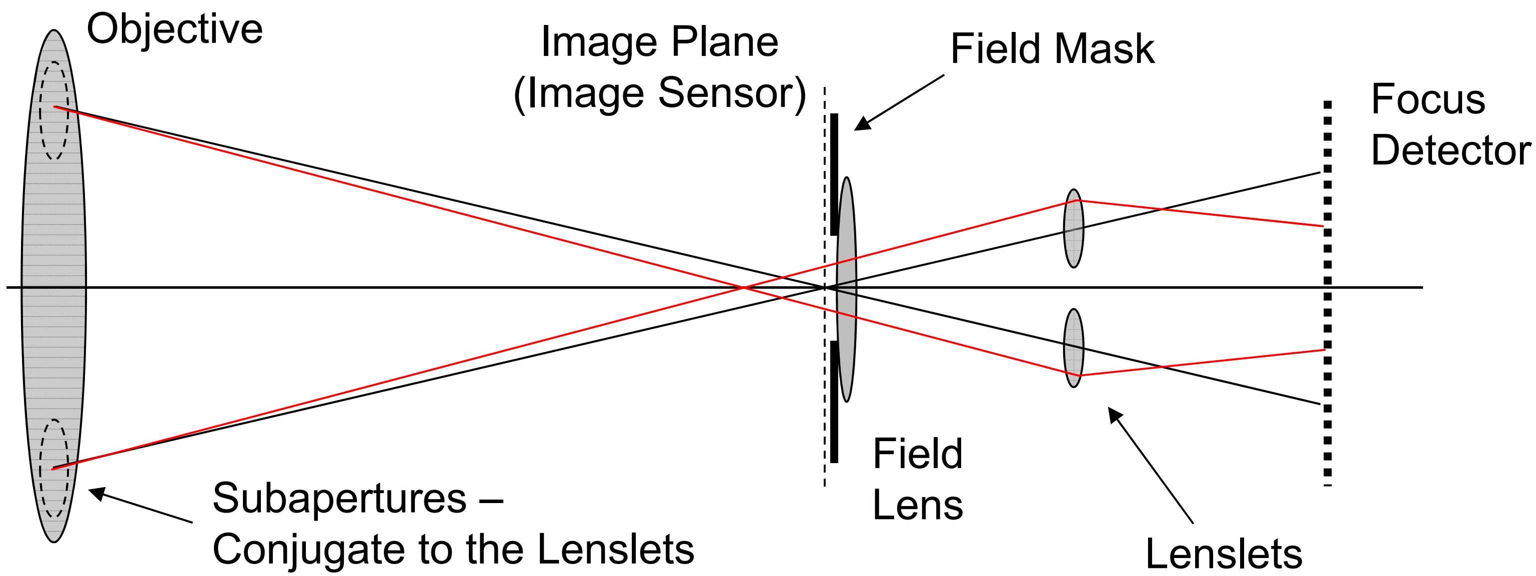



A point in the object will produce two images on the focus detector with a specific separation.

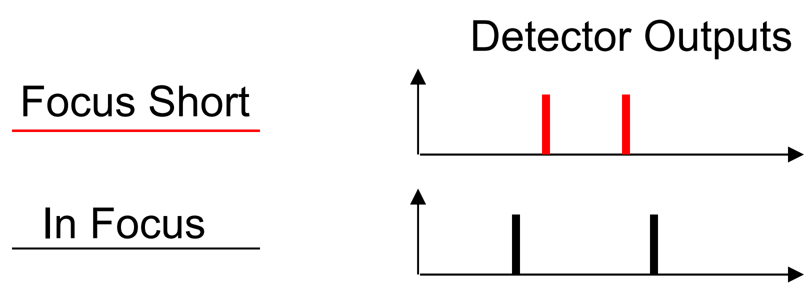
# Through the Lens (TTL) Phase Matching Focus Sensor

Now consider an object point that focuses in front of the defined image plane. It will be out of focus on the image sensor.

For clarity, only the central rays are shown. The lenslets are slow and the reimaging on the focus detector has a large depth of focus. Refraction at the field lens is also ignored.

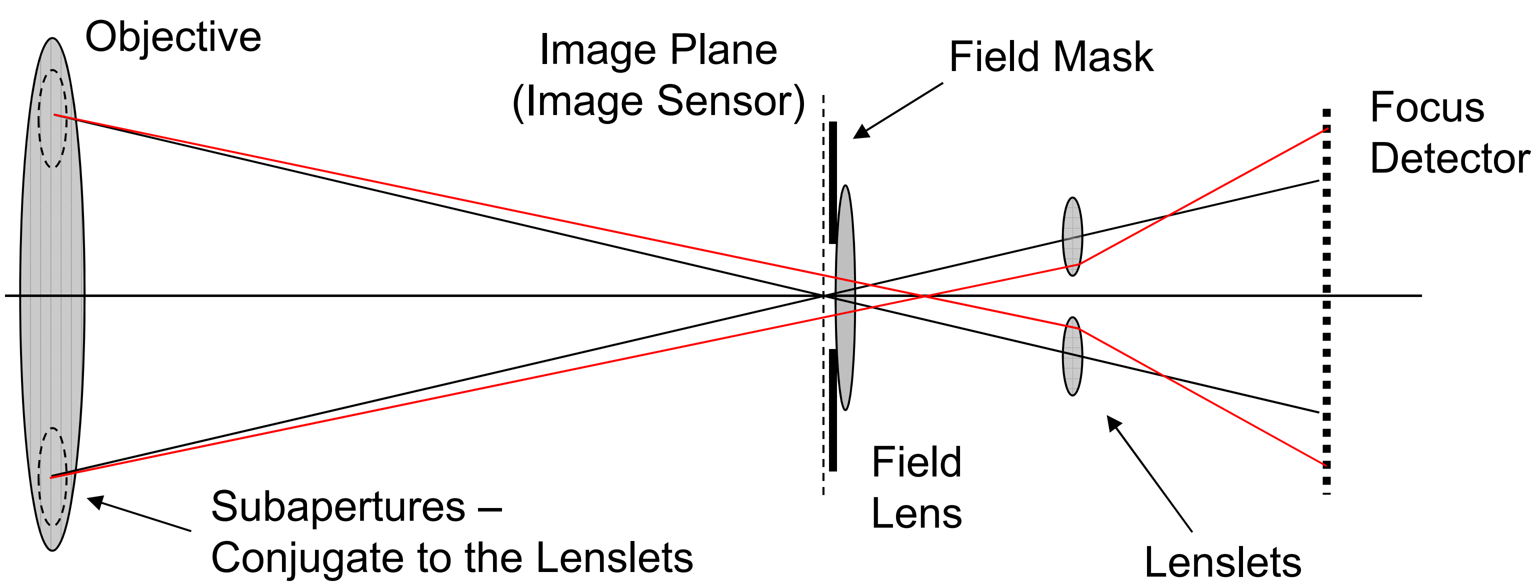



The separation of the two images produced on the focus detector by an object point is reduced.

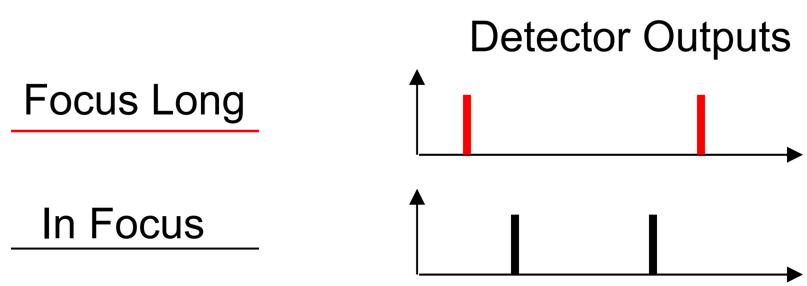


## Through the Lens (TTL) Phase Matching Focus Sensor

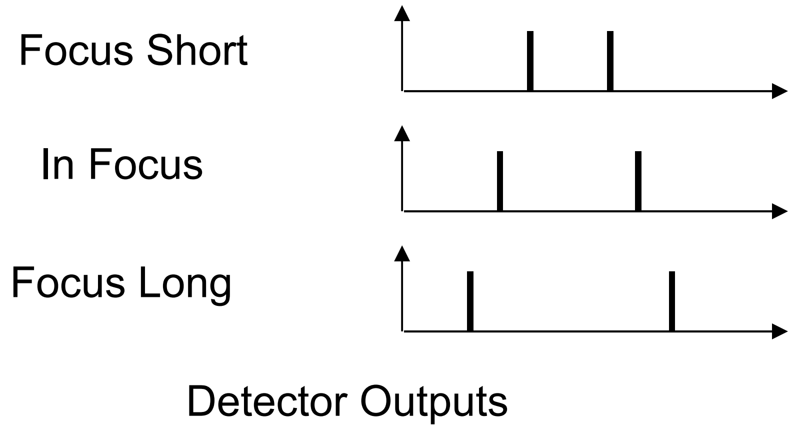
In a similar manner, an object point that focuses behind the defined image plane will produce a focus detector output that has a larger separation than the in-focus object.




Calibrated against an in-focus images separation, the measured separation determines the direction and amount to refocus the lens in order to bring the image into focus.



# Through the Lens (TTL) Phase Matching Focus Sensor

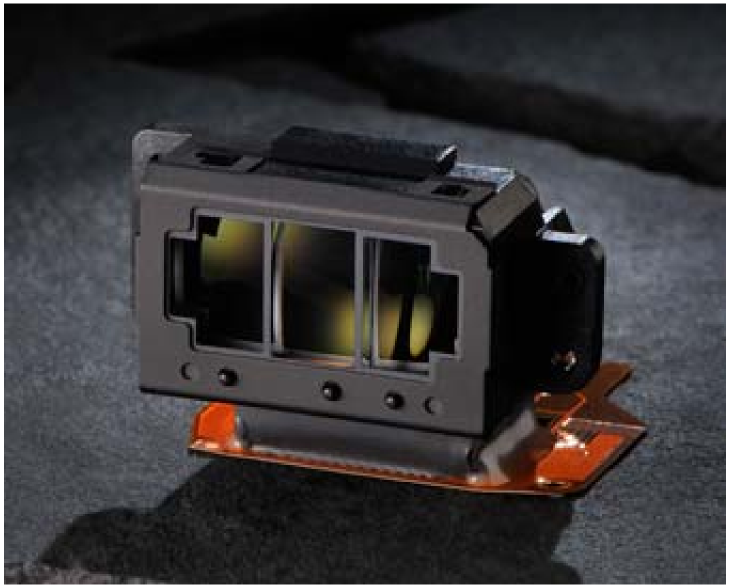


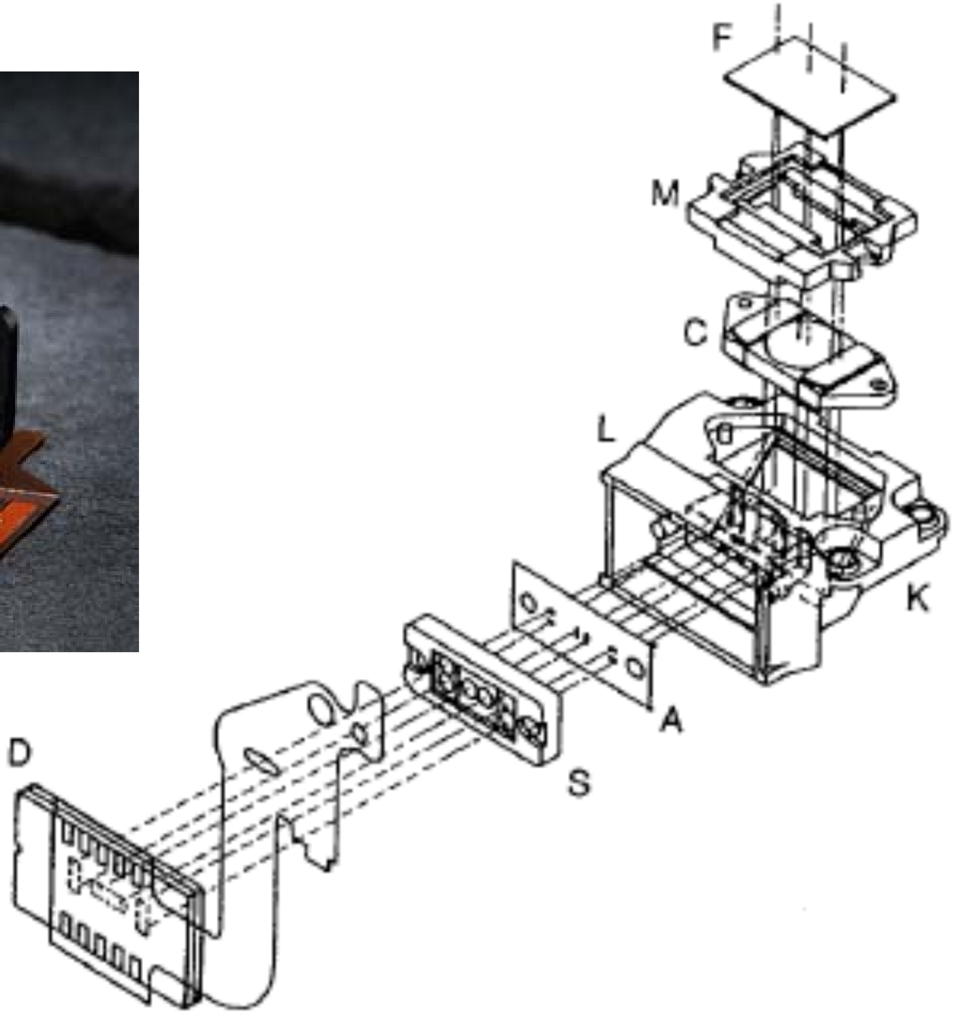

The system is calibrated for the in-focus image separation.

Multiple regions of the scene can be measured – multipoint autofocus. A field aperture with a field lens and a pair of lenslets is used at each field point to be measured. The lenslet pair can also be oriented vertically to detect horizontal scene detail.

This method of focus detection has the advantage of being fast and also works when the flip mirror is in the viewfinder position. Issues arise with objectives having slow maximum f/#s.

Through the Lens (TTL) Phas





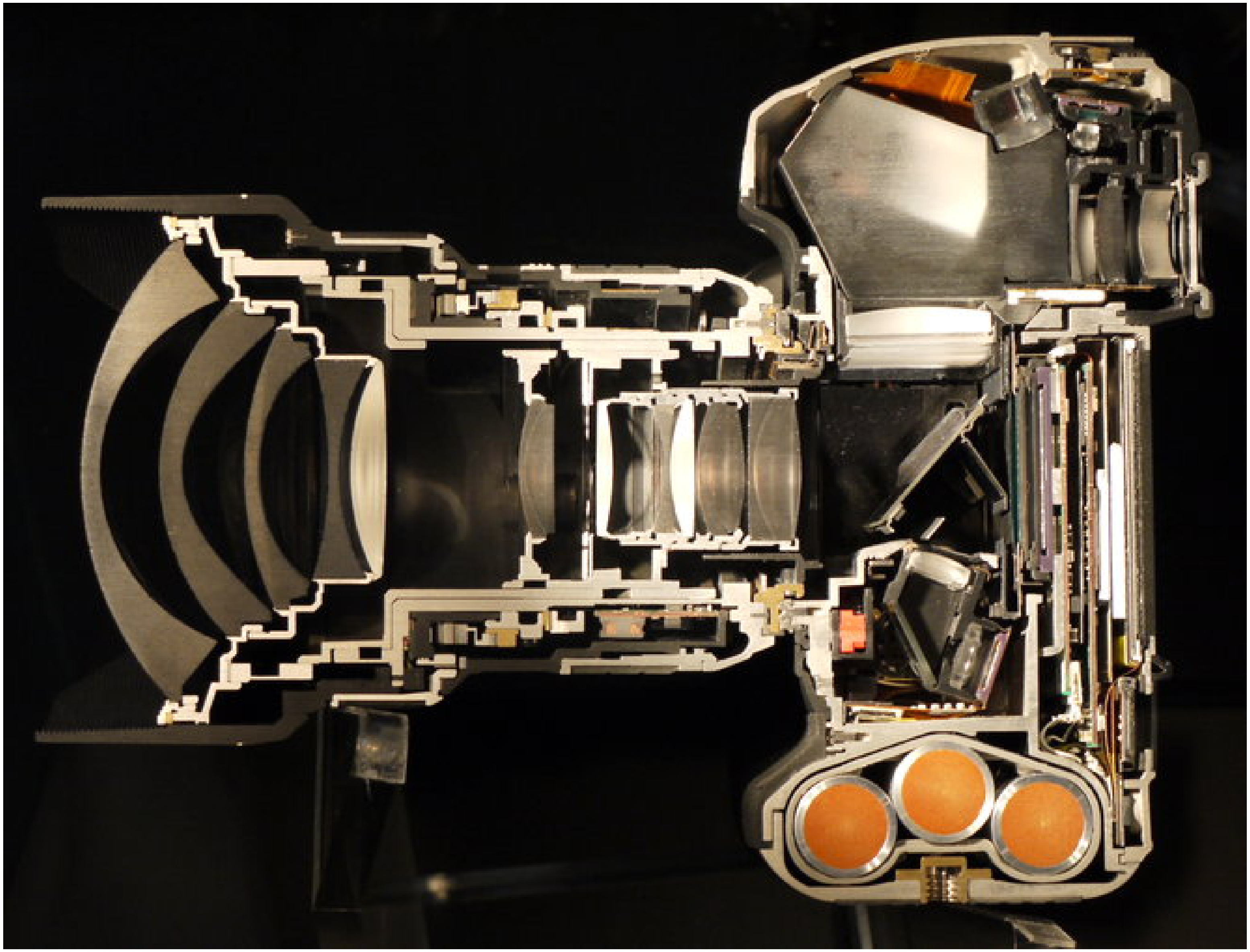

S. Ray; *Applied Photographic Optics*

F: Filter, M: Mask. C: Condenser or Field Lens, K: Mirror, A&S: Lenslets with Apertures, D: Focus Detector

The diagrammed system measures three field positions. The central position measures horizontal detail; the other two measure vertical detail. The aperture mask defines the lenslet apertures.

Through the Lens (TTL) Phase Matching Focus Sensor

Nikon D4 Camera

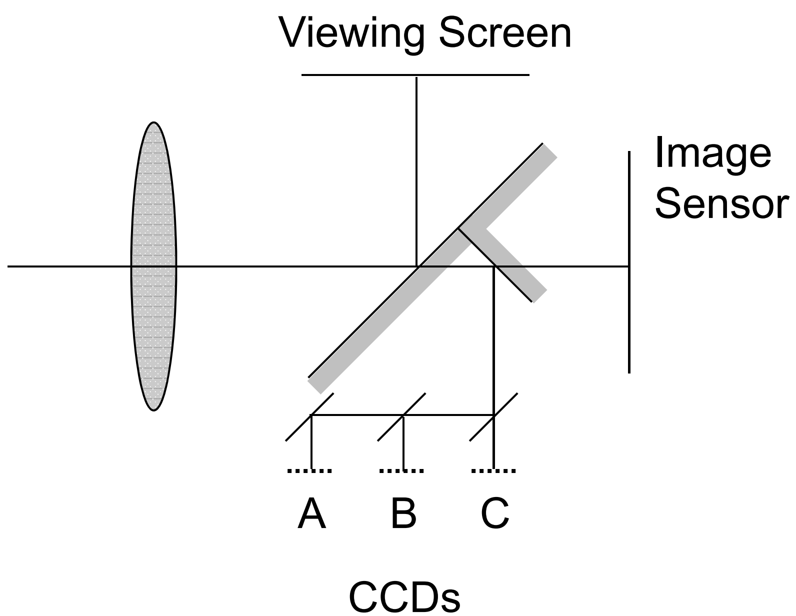


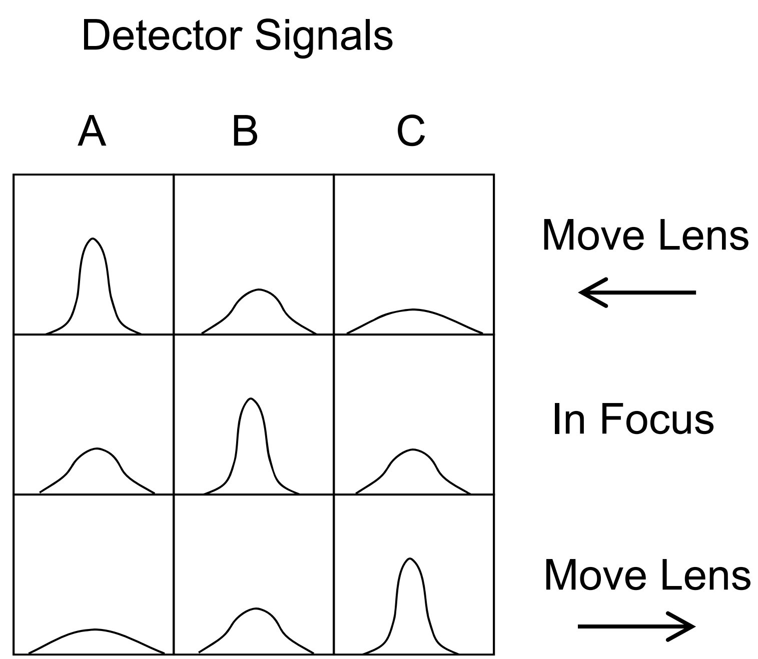
ephotozine.com/article/nikon-at-photokina-2012-20300

# Through the Lens (TTL) Image Contrast Measurement

SLR cameras also use image contrast for focus detection. A small portion of the light is allowed to pass through the flip mirror. This light is then directed to three detector arrays that are located at different longitudinal positions. One of the arrays (B) is optically coincident with the image sensor. The contrast of the three detector images can be analyzed for contrast to determine the direction of lens motion needed to get the image in focus.

A single detector array can also be used and the lens is moved back and forth to optimize the image quality on this single detector.



## Live-View Autofocus

In cameras that do not have shutters or reflex mirrors (non-SLR), the image captured by the camera's image sensor can be examined to obtain maximum image contrast. The lens focus is shifted and the image contrast is measured.

The camera lens would start at near focus and work towards more distant objects. This can be an iterative process and is generally slower than phase matching.

In order to use live-view autofocus in an SLR camera, a separate image sensor is used.

<u>Close-Up or Macro Photography</u>

Macro Photography refers to taking pictures of small objects. The image on the detector can sometimes be larger than the actual object, so the optical magnification can exceed 1:1. However, many macro systems do not approach 1:1 magnification, and only the displayed image is larger than the object.

Traditionally, macro photography uses a bellows or extension tubes to position the camera lens away from the detector to obtain the required large image distance. For high magnifications, the image distance is larger than the object distance and the camera objective is often reversed.

$$m = \frac{z'}{z}$$


Wikipedia

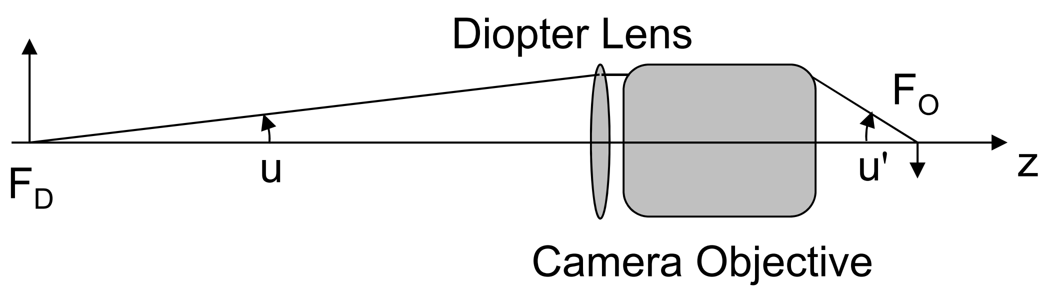
Modern macro lenses, especially on digital cameras, can use internal focusing arrangements (complex lens element motions) to obtain a large magnification without the use of extension tubes.

In both situations, a limited working distance often results.

Close-Up or Diopter Lenses

A close-up or diopter lens is a simple lens that is added to a camera objective to allow for close-up photography without requiring a special lens or extension tubes.

The diopter lens is placed directly in front of the objective lens so that in the nominal configuration, an object at the front focal point of the diopter lens is imaged to the rear focal point of the objective lens. The objective lens is focused at infinity.




$$m = \frac{u}{u'}$$

$$m = -\frac{f_{Objective}}{f_{Diopter}}$$

A set of diopter lenses usually contains lenses with powers of +1, +2 and +4 diopters. They can be combined to obtain a range of +1 to +7 diopters. An advantage of this configuration is that a long working distance is preserved, however high magnification ratios are not obtained because the focal length of the diopter lens is graeter than that of the objective.

Of course, objects not at the front focal point of the diopter lens can be imaged by changing the focus setting of the camera objective lens. In this case, the magnification is given by

$$m = \frac{u}{u'} = \frac{z_{Diopter}}{z'_{Objective}}$$

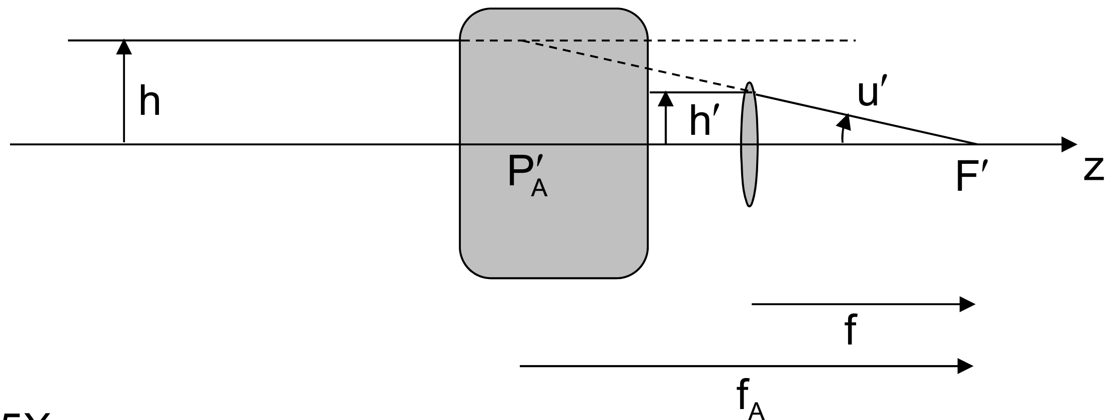
Afocal Adapters

The FOV of a camera lens can be changed by adding an afocal adapter. These come in both wide angle and telephoto versions. This Galilean telescope changes the focal length of the system.

The lens diameters must be designed to cover the new FOV without vignetting.


1.6X

Telephoto Example:





0.75X

$$m_A = \frac{h'}{h}$$

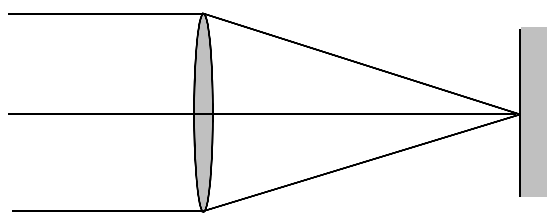
$$u' = \frac{h'}{f} = \frac{h}{f_A}$$

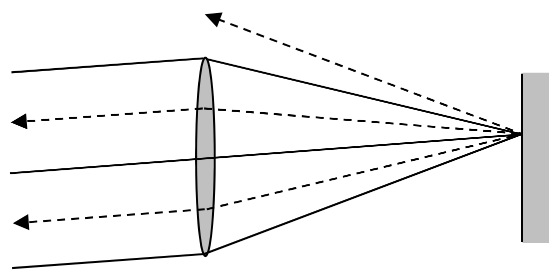
$$MP_A = \frac{1}{m_A} = \frac{h}{h'}$$

$$f_A = \frac{h}{h'} f = MP_A f$$

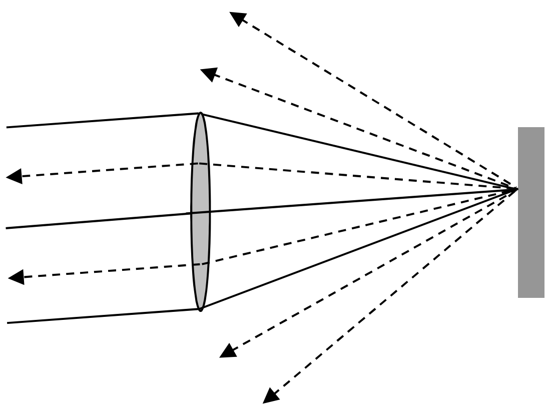
Cat's Eye Reflection

A cat's eye retroreflector is constructed out of a lens and a mirror. On axis, all of the light is reflected back through the lens and re-collimated. The light is sent back to the source. Off axis, the beam is also re-collimated and directed back to the source, however the angular acceptance or efficiency of this configuration is limited by vignetting of the reflected beam by the lens aperture.





The angular performance cam be improved by using a diffuse reflector instead of a mirror, however the light efficiency is reduced.



Reflective street signs and reflective paint use this effect by incorporating glass beads as lenses. The paint or coating serves as a matrix to hold the beads away from a reflective back surface.

## Red Eye

Red eye in flash photography is caused by the cat's eye reflection from the blood-rich human retina. The retina can be considered as a scattering surface.

To minimize red eye:

- Position the flash as far from the camera lens as possible. The retroreflection will be directed back to the flash and will not be seen by the camera lens. Because of the spot size on the retina and scattering, the retroreflected beam will not be "collimated" and will have an angular spread.

- Use a pre-flash or light to reduce the size of the eye's pupil. Less light gets into the eye and the smaller pupil size allows less of the scattered light to be returned in the retroreflection. A simple area argument would predict that the strength of the red-eye reflection will go as the pupil diameter to the fourth power.

In many animals, the cat's eye reflection is not red because the retinal reflection occurs from the tapetum lucidum. This tissue layer usually lies immediately behind the retina and reflects light back through the retinal to improve light sensitivity. It is especially prevalent in nocturnal animals. This resulting cat's eye effect is called Eyeshine.

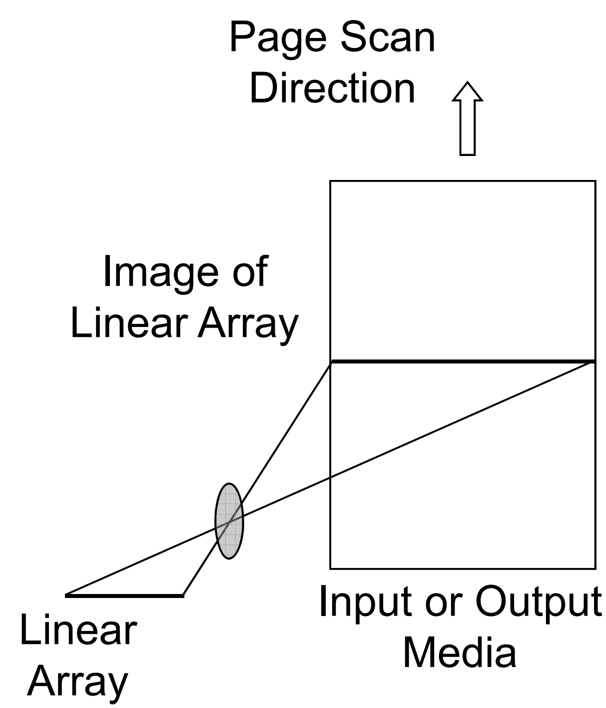
# Scanners

Scanners are used to convert a scene into an electronic signal or digital image or to convert a digital image or electronic signal into an image. There are three basic configurations for scanners based upon the source or detector configuration: area, line or spot.

The area scanner uses a two-dimensional sensor. This is really just a camera.

A linear array scanner or push broom scanner uses a linear detector array or a linear array of sources such as LEDs. One line of the scene is imaged or recorded at a time. The scene is scanned by moving the 2-dimension output media or scene through the image of the linear array.

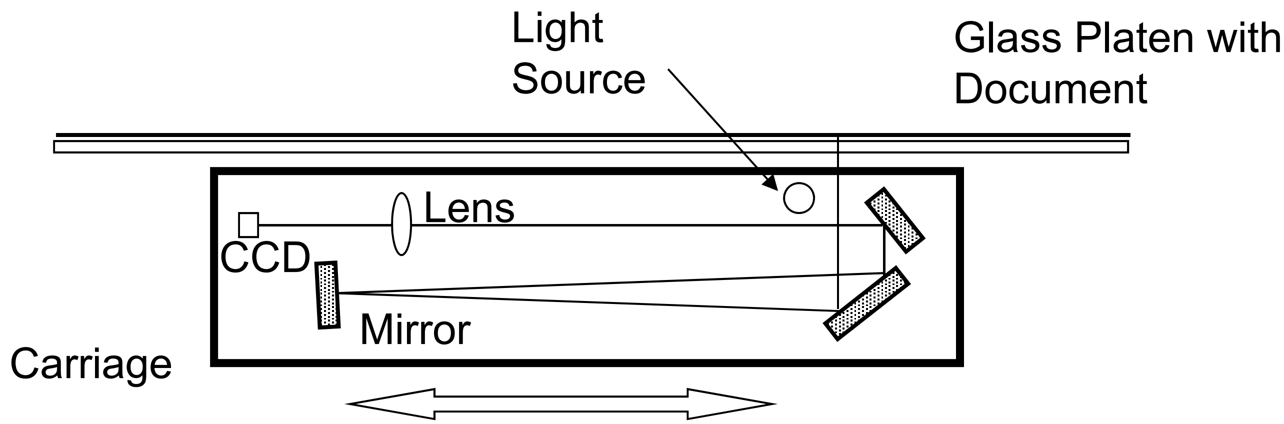
Examples are thermal printers, high resolution film scanners, flatbed document scanners and earth resources satellites.



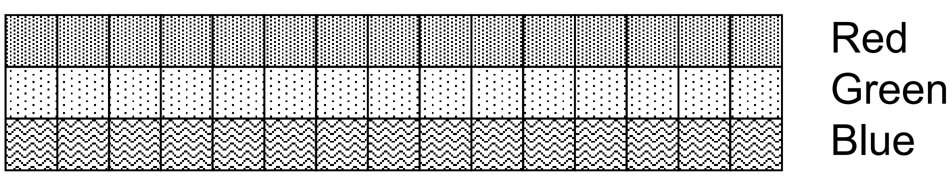
# Linear Array Scanner – Example – Flatbed Computer Scanner

A linear CCD array is imaged with about an 8:1 magnification onto the paper surface with a single lens. The optical path is folded with a series of mirrors.

The carriage contains the entire optical system and the light source. It is mounted to a ground metal rod and driven along the length of the paper by a motor and a belt drive.

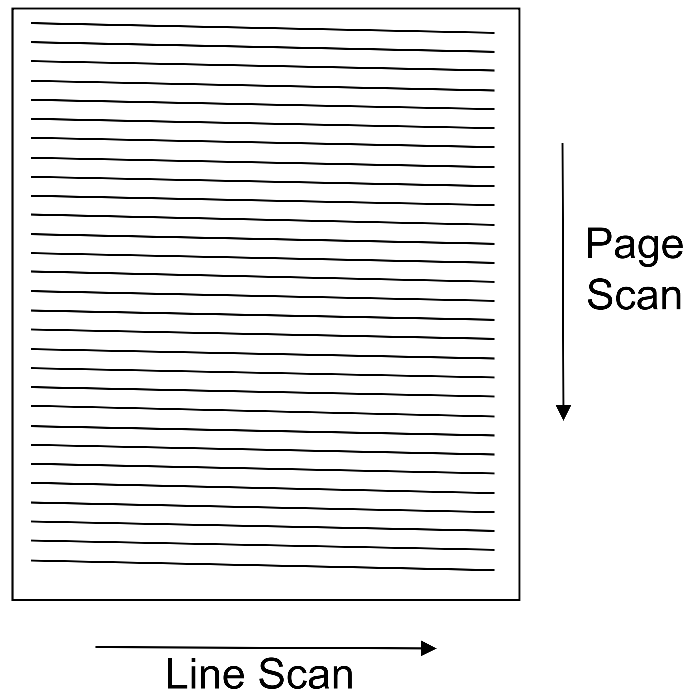



To obtain color images, a tri-linear CCD array is used. Each line is covered by a different color filter. The CCD array is about 1 inch long. The three color signals are registered in software.



# Flying Spot Scanners

In a flying spot scanner, a point detector or source is scanned in a two-dimensional pattern over the scene or output surface. The two common options for the fast line scan in an optical flying spot scanner are a galvanometer mirror or a polygon scanner. The primary example is a laser printer where the page scan is accomplished by moving the photosensitive recording medium. Laser light shows use two galvanometer mirrors. CRTs are electron based flying spot scanners.




Two pertinent television definitions related to scanners:
- Progressive scan: all of the TV lines are written in a single pass down the screen (HDTV and some scientific cameras).
- Interlace scan: two fields are written per frame. Each field contains every other line in the image. In the U.S. (NTSC), the frame rate is 30 Hz, and the field rate is 60 Hz. Phosphor lag and the response of the eye combine the two fields into a single image without noticeable flicker.