Section 4

Digital Imaging Systems

Sampled Imaging Systems

Pixelated Imaging Systems

<u>Reference Books</u>

Projection Displays, 2nd Ed.	Brennesholtz and Stupp
Digital Imaging for Photographers	Davies and Fennessy
Modeling the Imaging Chain of Digital Cameras	Fiete
Formation of a Digital Image	Fiete
Sampling, Aliasing and Data Fidelity	Holst
CMOS/DDC Sensors and Camera Displays	Holst and Loheim
CCD Arrays, Cameras and Displays	Holst
Single Sensor Imaging	Lukac
Projection Displays	Stupp and Brennesholtz
Analysis of Sampled Imaging Systems	Vollmerhausen and Driggers
Analysis and Evaluation of Sampled Imaging Systems	Vollmerhausen, Reago and Driggers

Digital Imaging Systems

Most electronic imaging systems are sampled in one or both directions.

The input scene is measured only at discrete locations, and these sampling points are regularly spaced.

Examples:

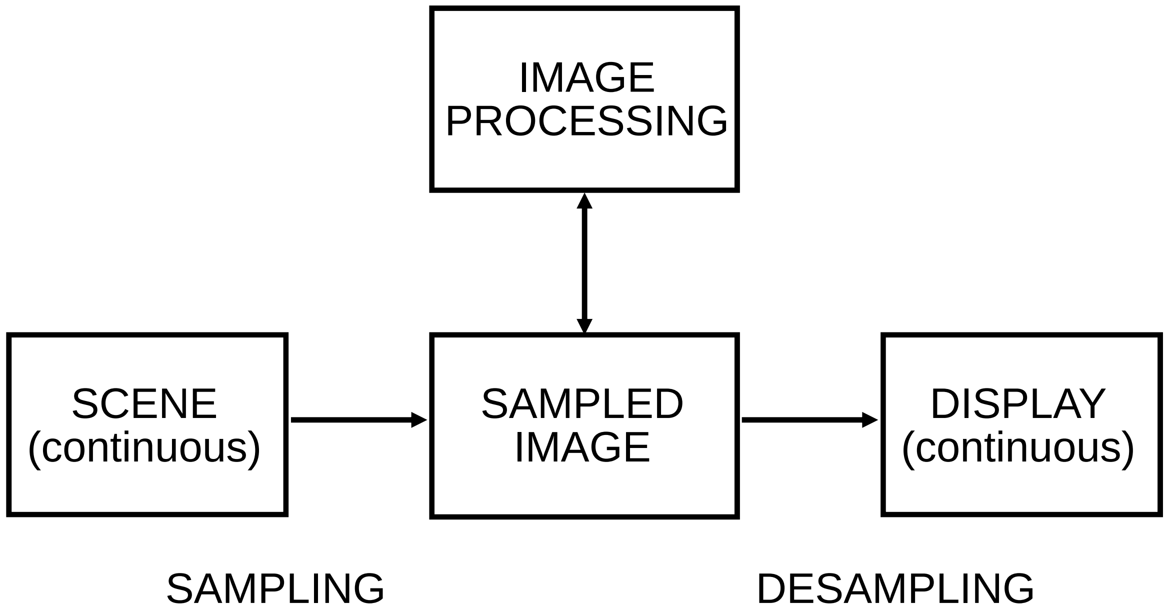
- Solid state sensors - 1D and 2D
- Raster scanned systems
    - Laser scanners
    - TV (vidicons)
- Halftone screens
- Sample and hold circuits; A/D's

Sampled versus Non-Sampled Systems

The *first-order* imaging characteristics of a sampled system are inherently different from those of a non-sampled system.

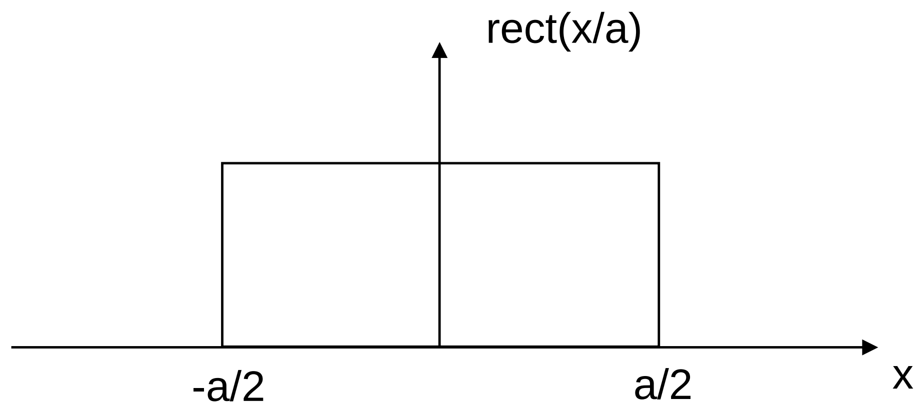
With both photographic film and the human eye, the sensing elements are randomly located.

Sampled Imaging System



The term “sampled image” is a bit of a misnomer – this image is just an array of numbers.

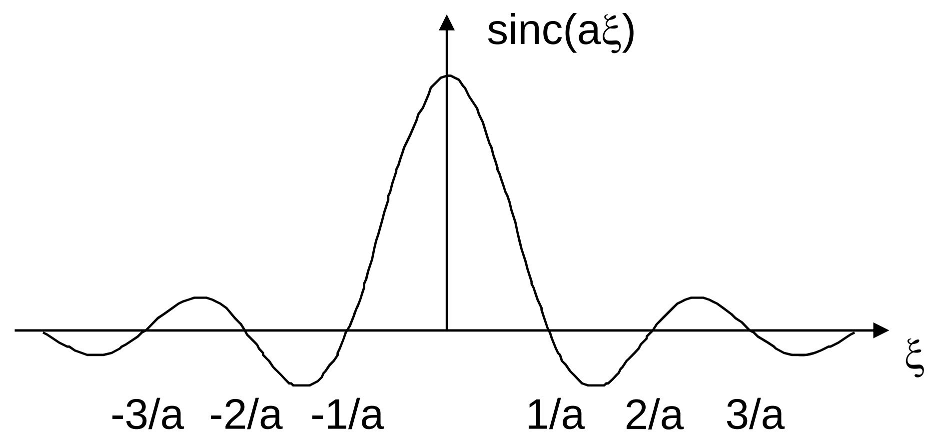
Rect and Sinc Functions



$$\mathrm{sinc}(a\xi) = \frac{\sin(\pi a \xi)}{\pi a \xi}$$

$$\mathrm{sinc}(a\xi, b\eta) = \mathrm{sinc}(a\xi)\mathrm{sinc}(b\eta)$$

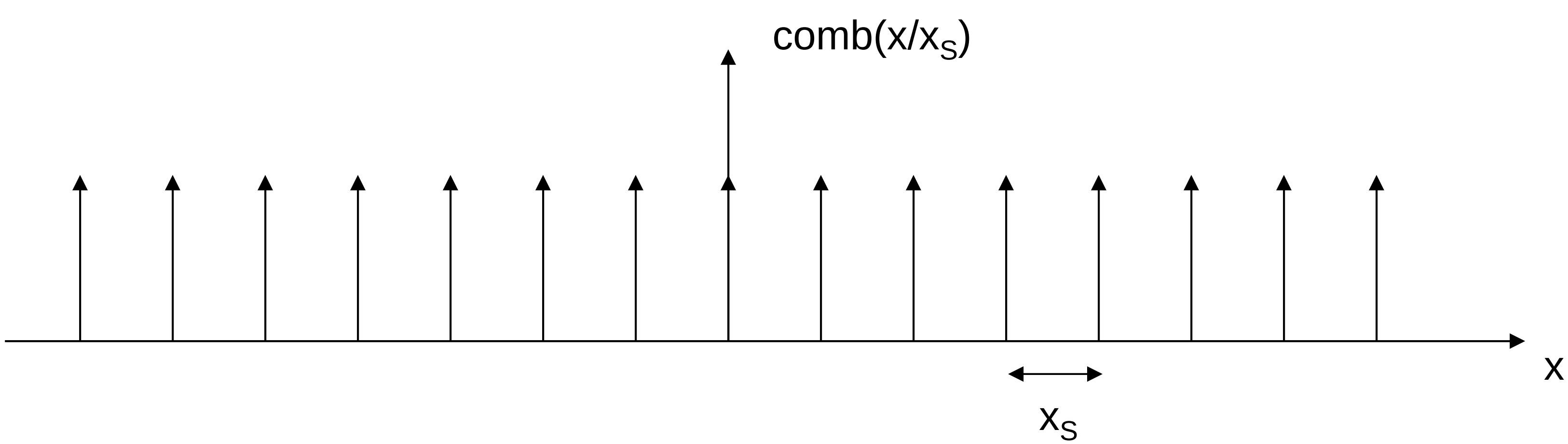
$$\mathrm{sinc}(a\xi, b\eta) = \frac{\sin(\pi a \xi)}{\pi a \xi}\frac{\sin(\pi b \eta)}{\pi b \eta}$$



<u>Comb Function</u>

$$\text{comb}\left(\frac{x}{x_S}\right) = \sum_m \delta\left(x - m x_S\right)$$

$$\text{comb}\left(\frac{x}{x_S}, \frac{y}{y_S}\right) = \sum_m \sum_n \delta\left(x - m x_S, y - n y_S\right)$$



One and two dimensional arrays of delta functions.

Non-Sampled System – Photographic Film

- First-order model
- Positive working materials
- Unity contrast

Image on print:

$$i_F(x,y) = o(x,y) ** \underbrace{h(x,y) ** f(x,y) ** l(x,y) ** p(x,y)}_{\text{System PSF}}$$

$$I_F(\xi,\eta) = O(\xi,\eta) \underbrace{H(\xi,\eta) F(\xi,\eta) L(\xi,\eta) P(\xi,\eta)}_{\text{System MTF}}$$

o(x,y)	Scene
h(x,y)	Camera lens
f(x,y)	Photographic film
l(x,y)	Enlarger lens
p(x,y)	Photographic paper

A linear shift-invariant system – MTF cascade.

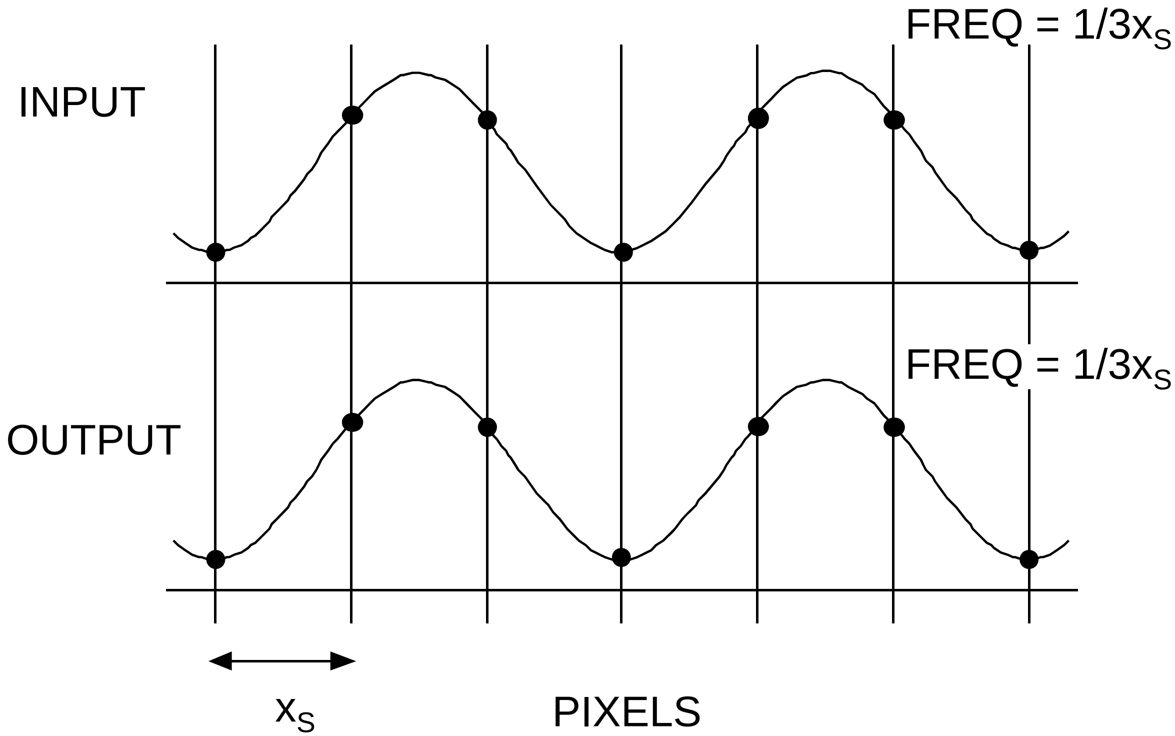
Rule of Thumb

"You can't go wrong by putting a better lens on your camera."

Using a lens with a better MTF will probably improve the resulting image. At worst, there will be no change if another MTF dominates the system performance. The same statement holds for any of the component MTFs.

Aliasing is the property of a sampled imaging system that causes the high spatial frequency content in a scene to be displayed at a low spatial frequency.

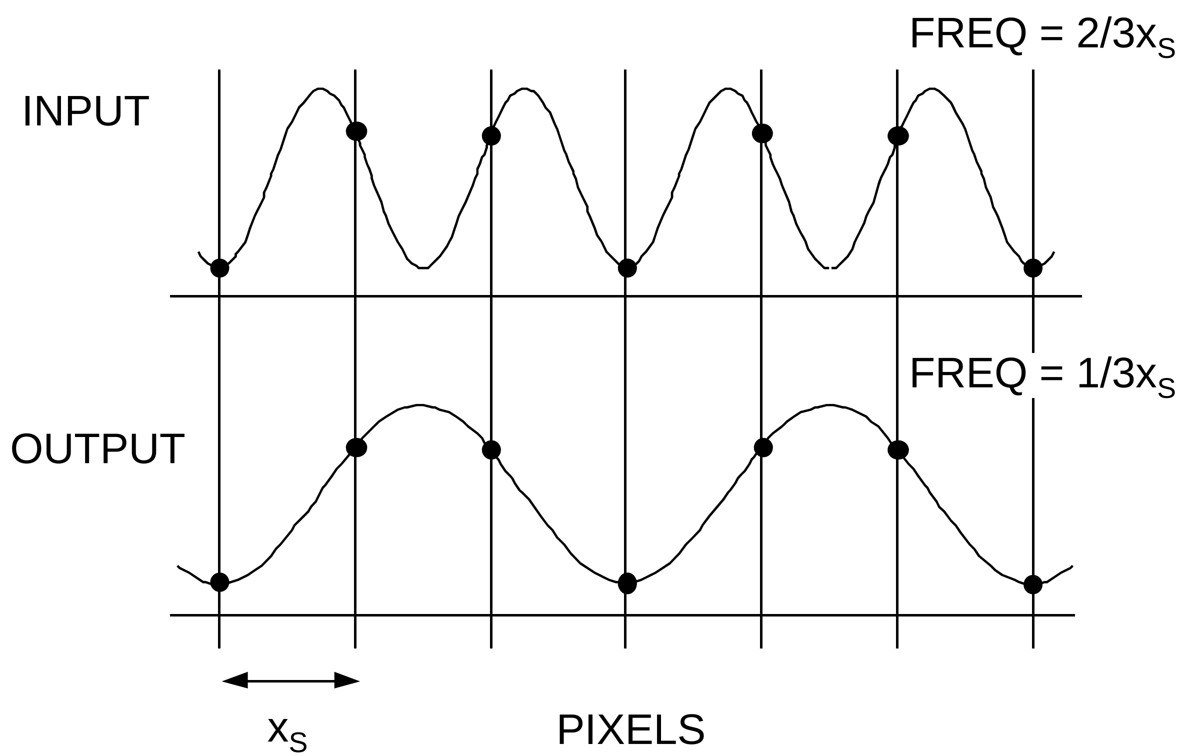
Aliasing – Sampling a Low Spatial Frequency



More than two pixels per period.

Output = Input

Aliasing – Sampling a Low Spatial Frequency



Less than two pixels per period.

Output ≠ Input

The high spatial frequency is displayed as a low spatial frequency.

Nyquist Frequency

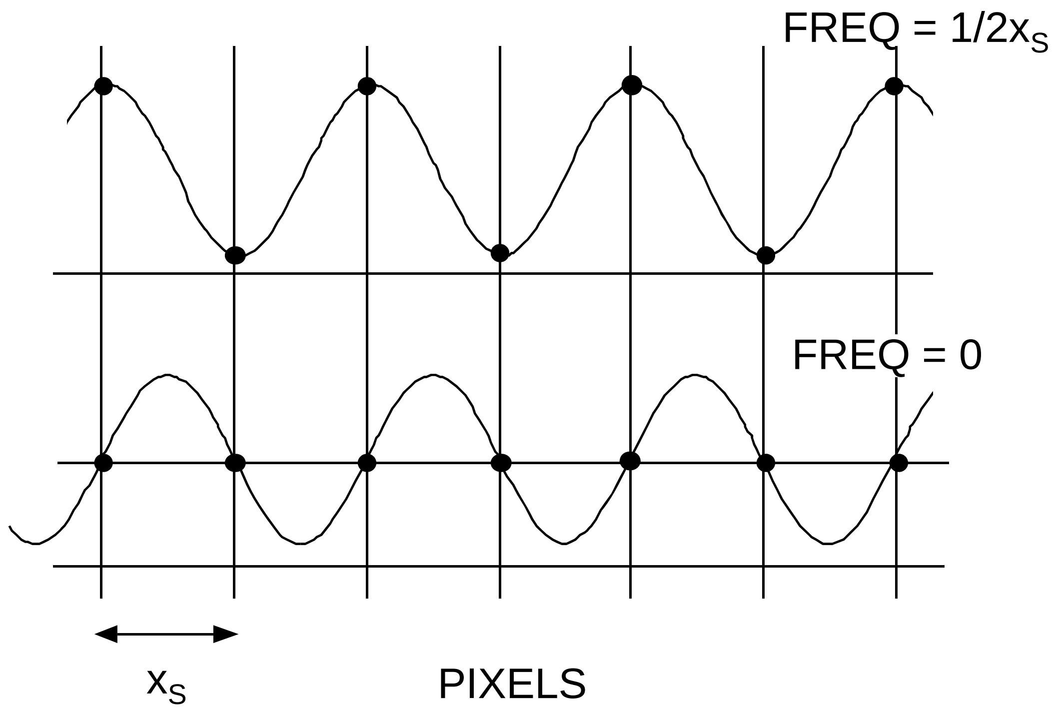
The Nyquist frequency is generally considered to be the limiting resolution of a sampled imaging system.

The Nyquist frequency is defined to be half the sampling frequency f_S.

$$f_N = f_S / 2 = 1/2x_S$$

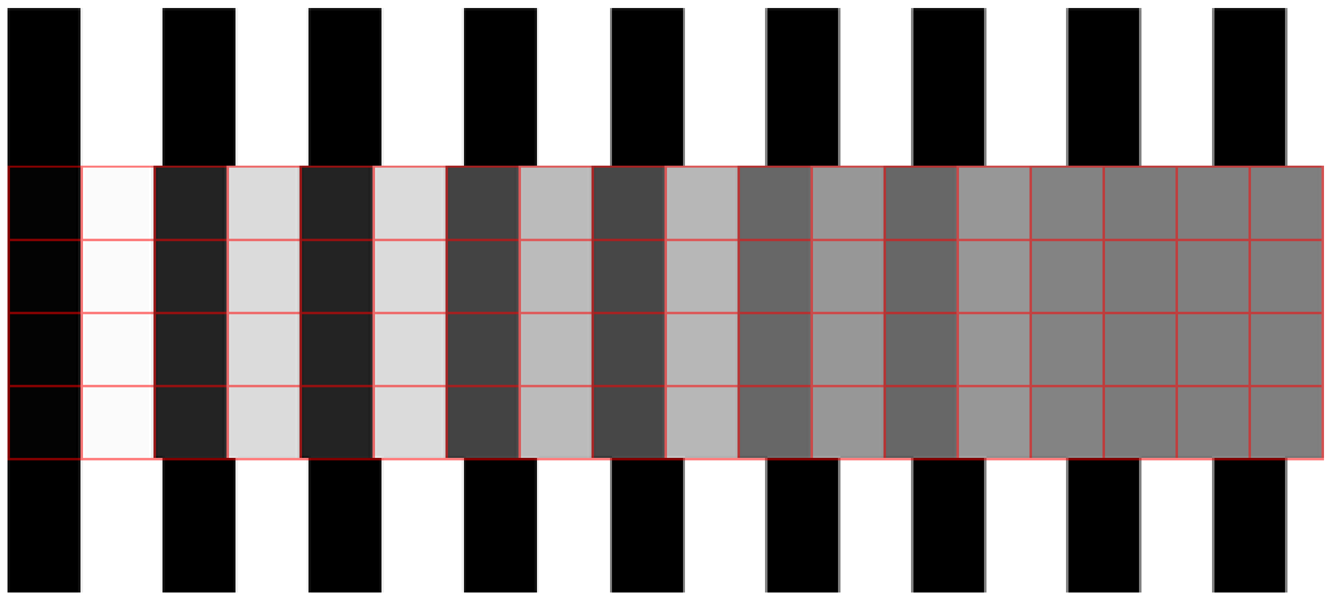
x_S is the pixel spacing

Input at the Nyquist Frequency



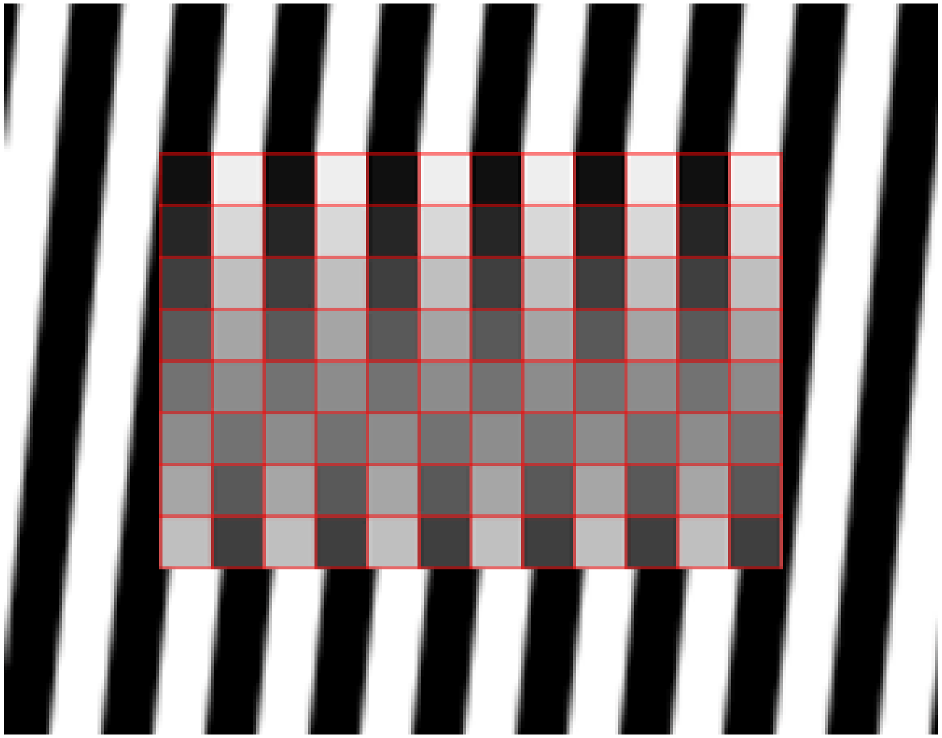
Output frequency depends on input phase.

Sampling – At the Nyquist Frequency



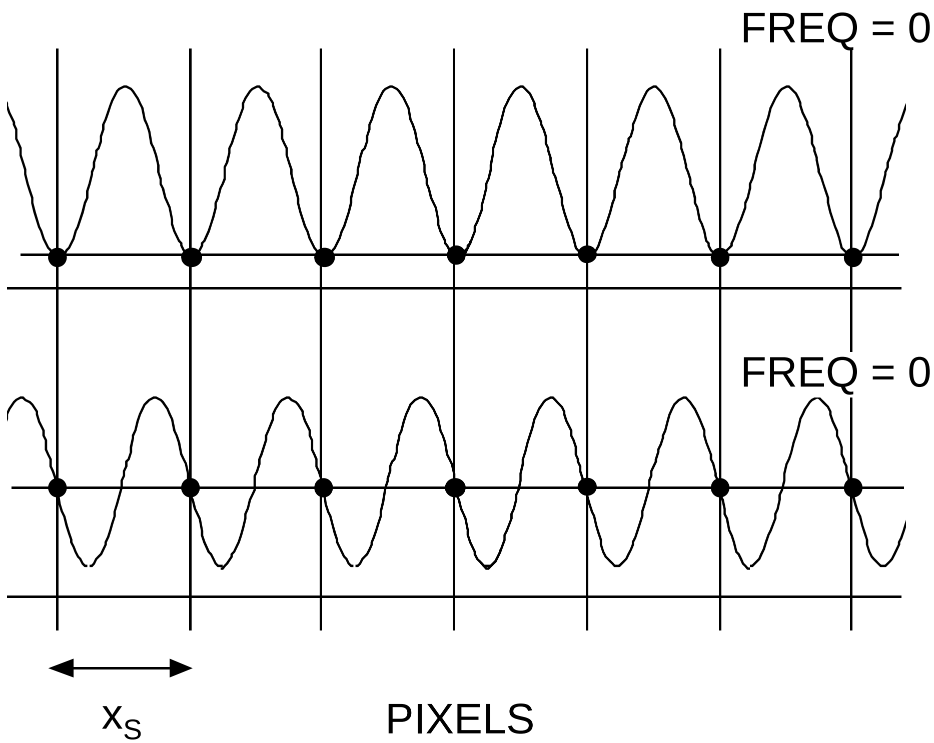
Photoacute.com

Sampling – At the Nyquist Frequency



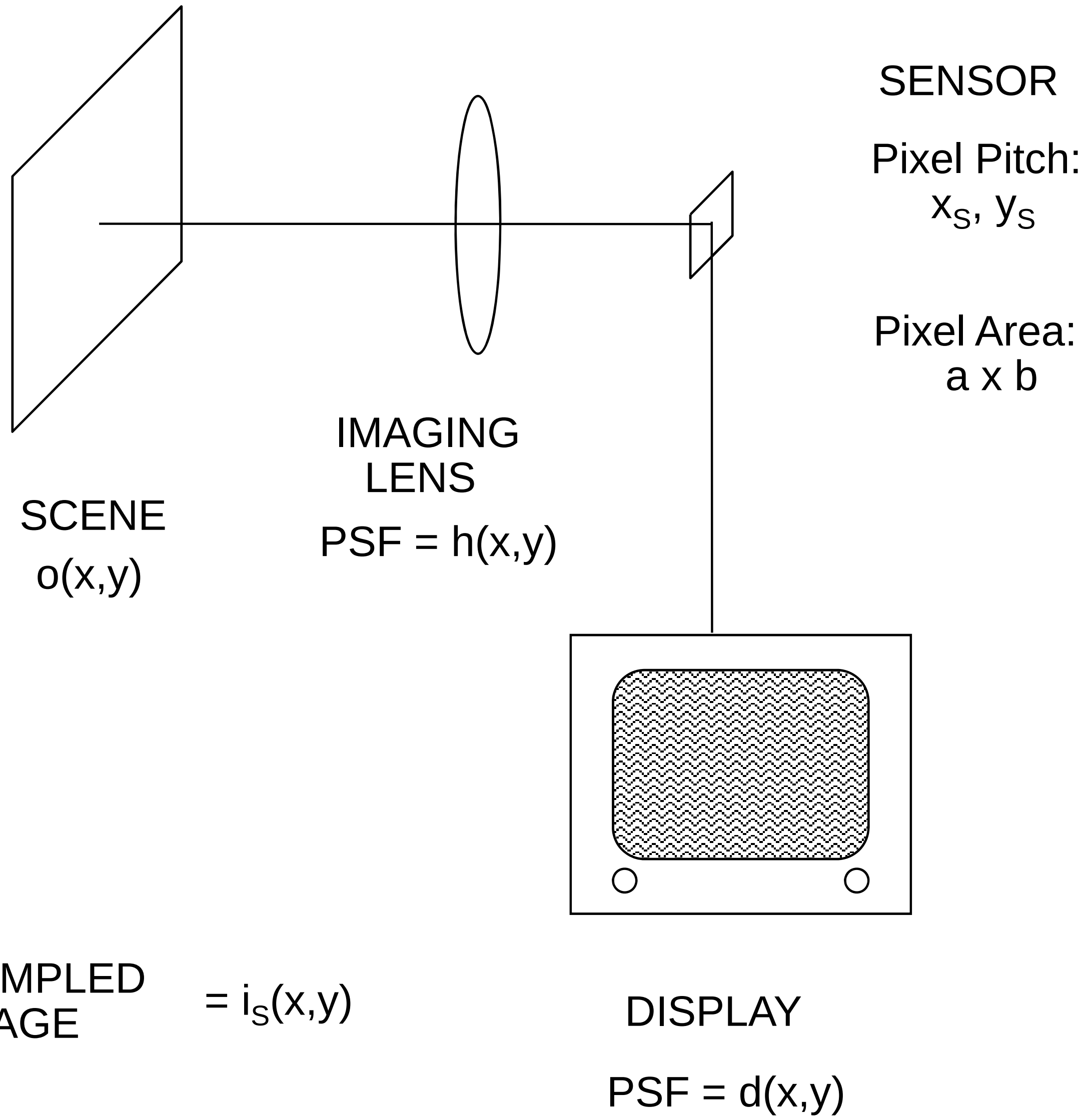
Photoacute.com

Input at the Sampling Frequency



Output frequency is zero – independent of input phase.

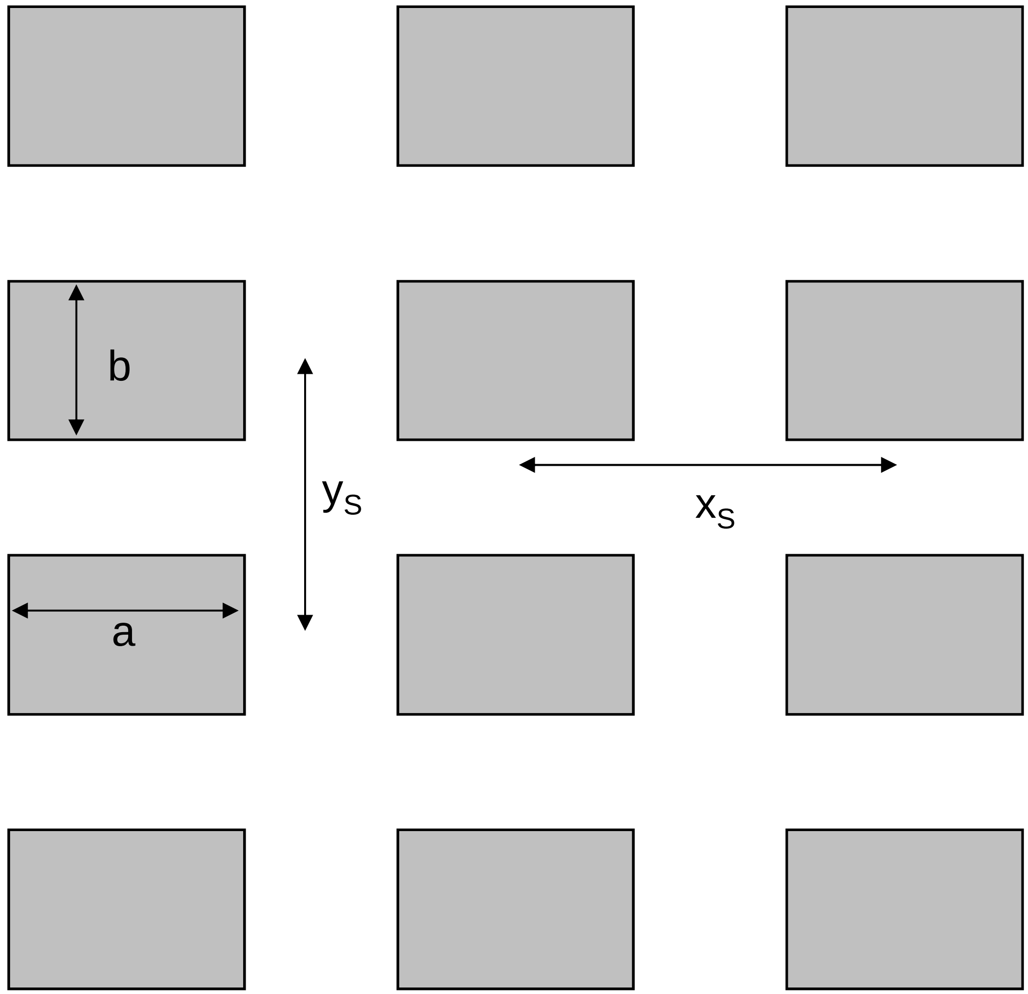
Sampled Imaging System



SAMPLED IMAGE $= i_S(x,y)$

DISPLAYED IMAGE $= i_D(x,y)$

Pixels



$$G_X = \frac{\text{Pixel Width}}{\text{Pixel Pitch}} = \frac{a}{x_S} \qquad G_Y = \frac{b}{y_S}$$

<u>Sampled Image</u>

Scene: $o(x,y)$

Image on the Sensor: $o(x,y)**h(x,y)$

Average over a pixel m,n:

$$\bar{i}\left(mx_S, ny_S\right) = \iint \left[o(\alpha,\beta)**h(\alpha,\beta)\right] \operatorname{rect}\left(\frac{\alpha - mx_S}{a}, \frac{\beta - ny_S}{b}\right) d\alpha \, d\beta$$

Sum over all the pixels:

$$i_S(x,y) = \sum_m \sum_n \bar{i}\left(mx_S, ny_S\right) \delta\left(x - mx_S, y - ny_S\right)$$

$$i_S(x,y) = \bar{i}\left(x,y\right) \sum_m \sum_n \delta\left(x - mx_S, y - ny_S\right)$$

$$i_S(x,y) = \bar{i}\left(x,y\right) \operatorname{comb}\left(\frac{x}{x_S}, \frac{y}{y_S}\right)$$

Sampled Image – Continued

$$i_S(x,y) = \left\{ \iint \left[o(\alpha,\beta) ** h(\alpha,\beta) \right] \mathrm{rect}\left(\frac{\alpha - x}{a}, \frac{\beta - y}{b} \right) d\alpha\, d\beta \right\} \mathrm{comb}\left(\frac{x}{x_S}, \frac{y}{y_S} \right)$$

The operation in the { } is a convolution integral.

The sampled image:

$$i_S(x,y) = \left\{ o(x,y) ** h(x,y) ** \mathrm{rect}\left(\frac{x}{a}, \frac{y}{b} \right) \right\} \mathrm{comb}\left(\frac{x}{x_S}, \frac{y}{y_S} \right)$$

The sampled image spectrum:

$$I_S(\xi,\eta) = \left\{ O(\xi,\eta) H(\xi,\eta)\, \mathrm{sinc}\left(a\xi, b\eta \right) \right\} ** \mathrm{comb}\left(x_S \xi, y_S \eta \right)$$

This is the simplest first-order model that is possible for a sampled image.

Shift Variance

A sampled imaging system is NOT shift invariant:

- an input point can be moved anywhere inside a pixel on the screen, and no change in the output is seen.

- if the input point falls in the area between pixels, it is not recorded.

The output and output spectrum of a sampled imaging system are not in the form of a linear shift-invariant system:

$$i_S(x,y) \neq o(x,y) ** PSF(x,y)$$

$$I_S(\xi,\eta) \neq O(\xi,\eta) MTF(\xi,\eta)$$

The sampled imaging system is linear.

The sampled imaging system can be considered to be

Globally Shift Invariant
and
Locally Shift Variant

Sampled Imaging System

$$i_S(x,y) = \left\{ o(x,y) ** h(x,y) ** \text{rect}\left(\frac{x}{a},\frac{y}{b}\right)\right\} \text{comb}\left(\frac{x}{x_S},\frac{y}{y_S}\right)$$

$$I_S(\xi,\eta) = \left\{ O(\xi,\eta) H(\xi,\eta)\, \text{sinc}\left(a\xi, b\eta\right)\right\} ** \text{comb}\left(x_S\xi, y_S\eta\right)$$

It is not possible to define a system PSF or MTF.

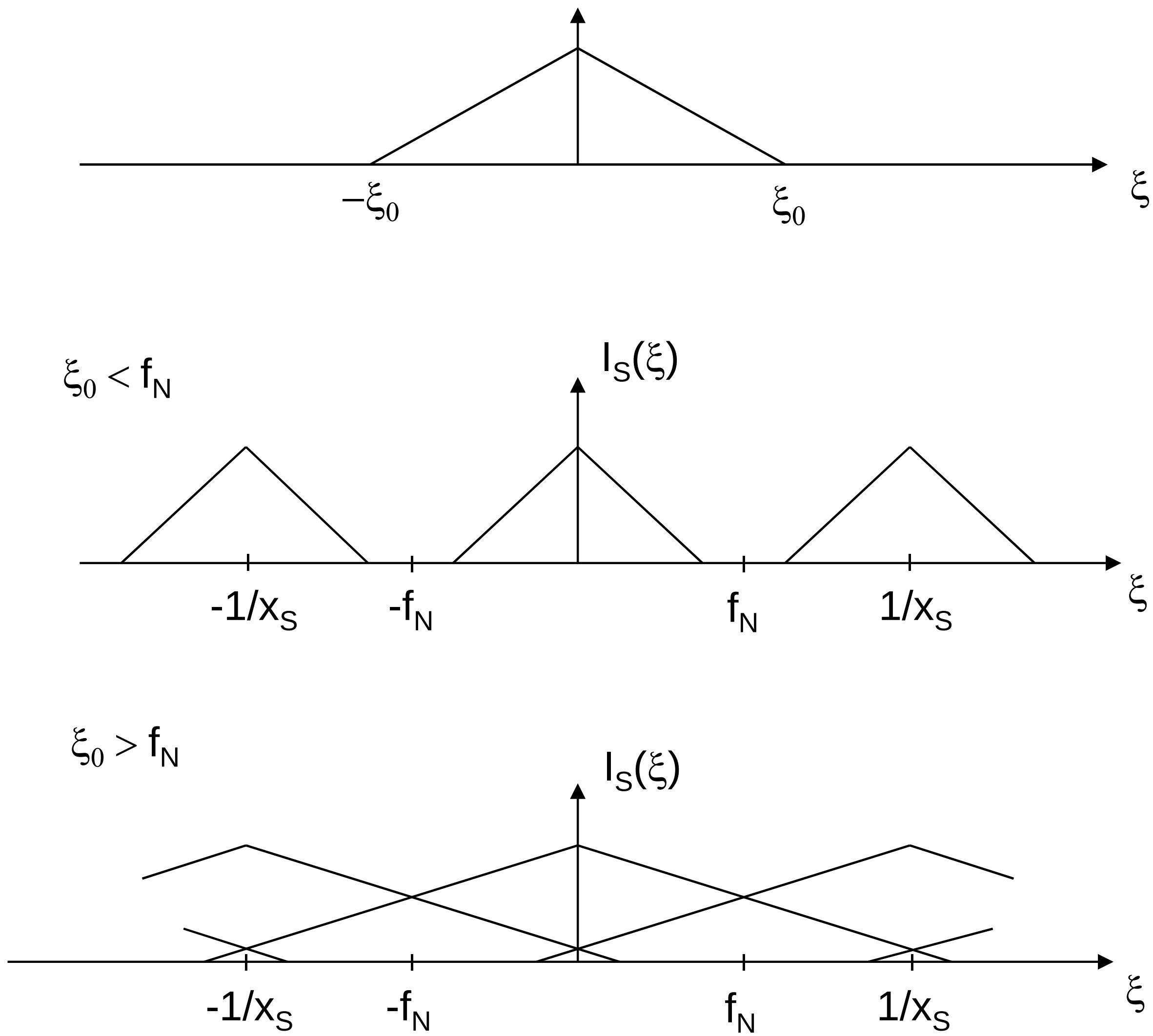
The term sinc($a\xi$, $b\eta$) is referred to as the Pixel MTF.

The image on the sensor is averaged over the active area of the pixel and a reduction in modulation results.

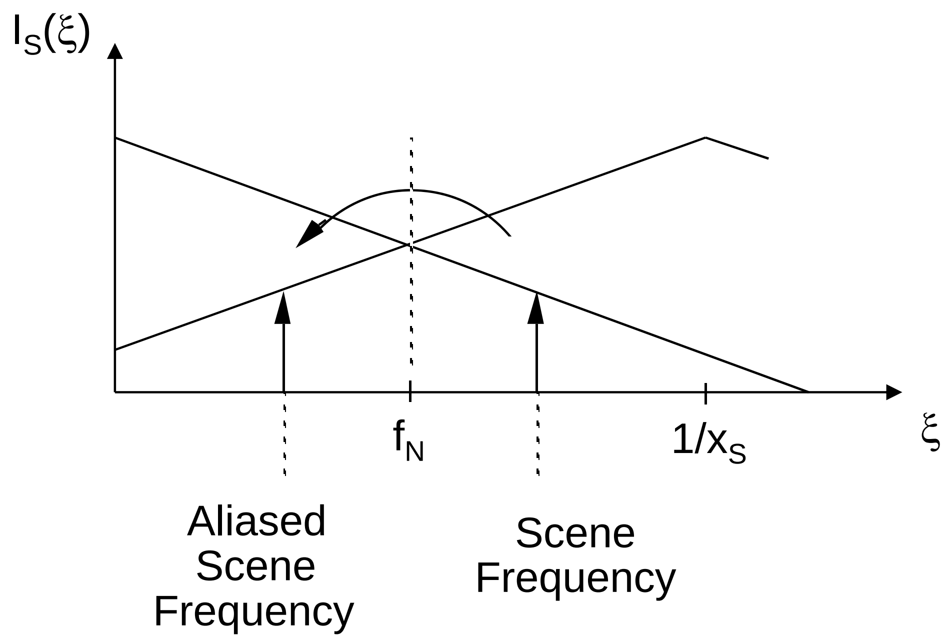
If the response of the pixel is not uniform or the pixel is not rectangular, the pixel MTF will have a different functional form.

Frequency Space Representation

Assume $O(\xi)H(\xi)\text{sinc}(a\xi)$ is band-limited:



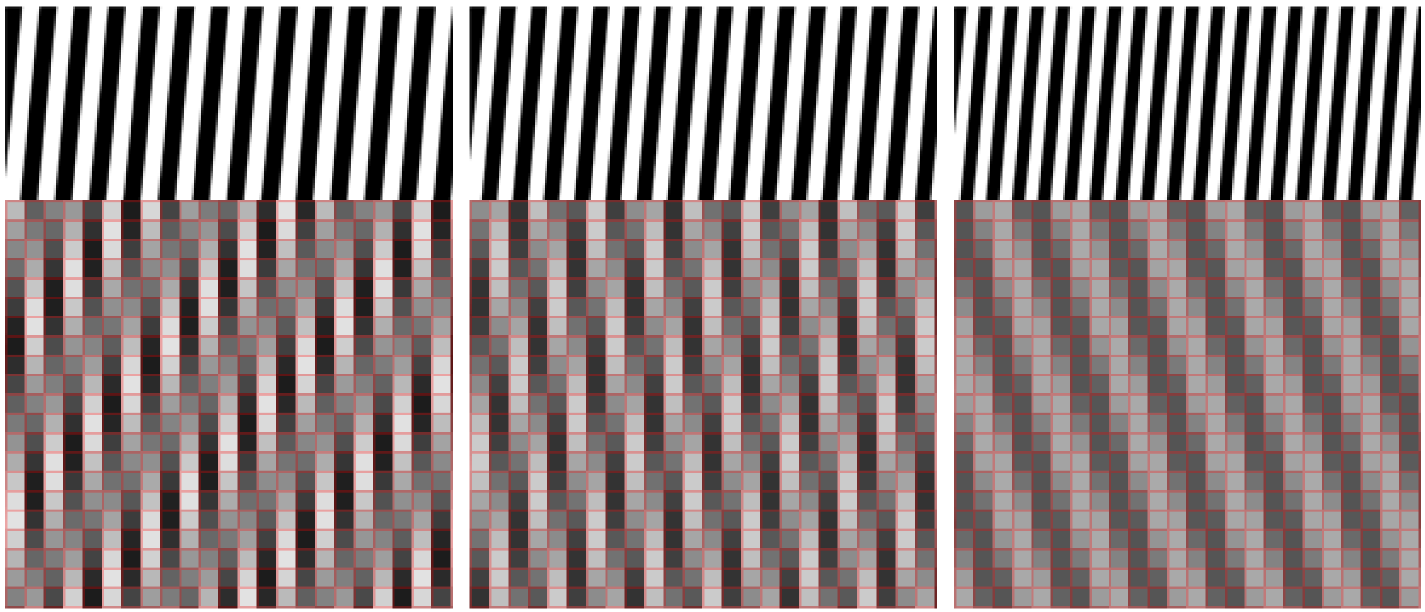
Frequency Space Representation



The high spatial frequency is mapped to a low spatial frequency

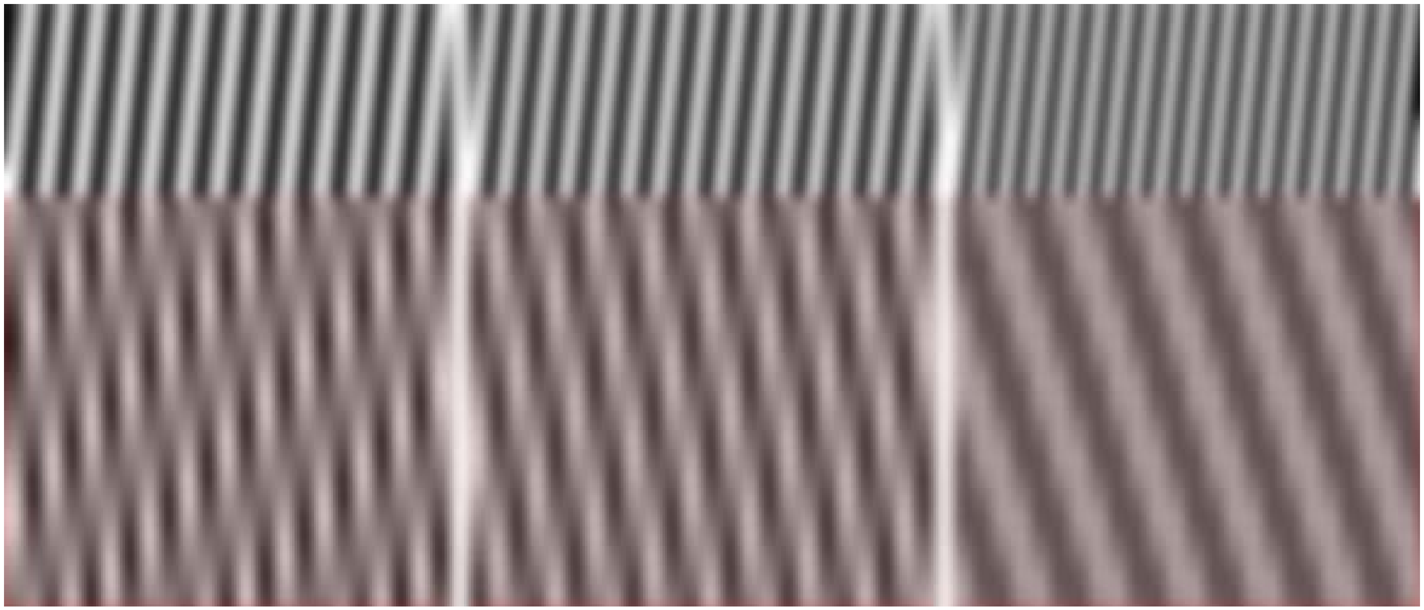
Aliasing

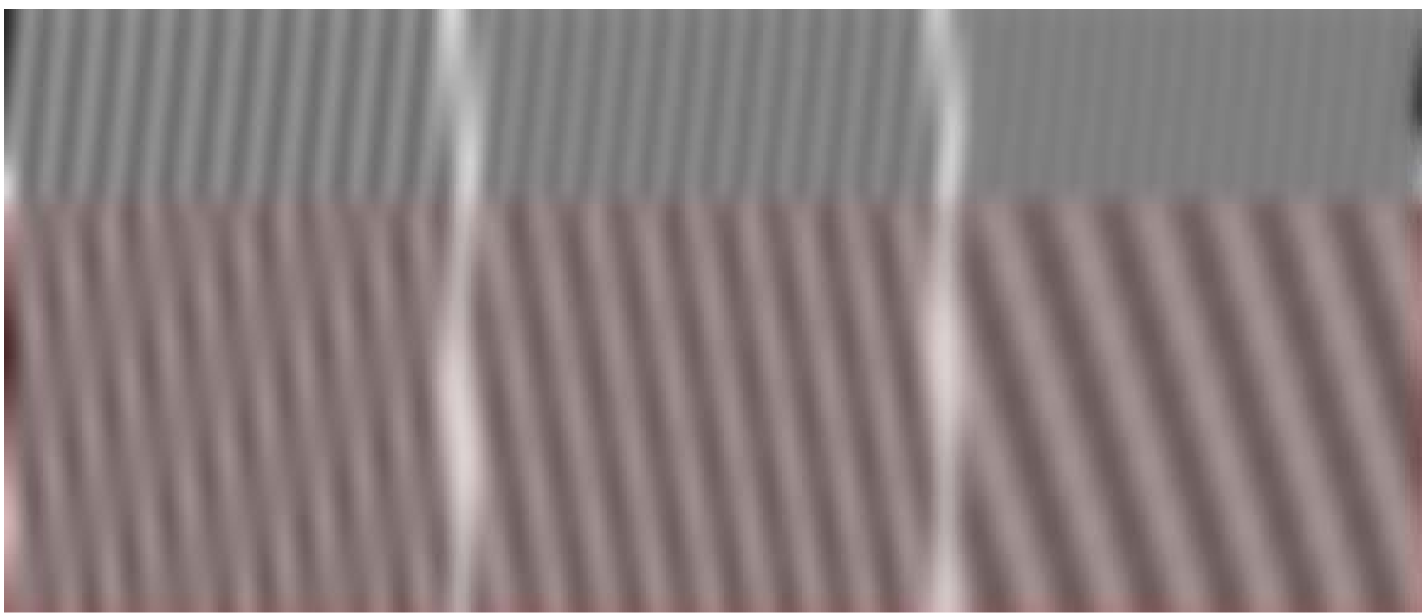
Aliasing



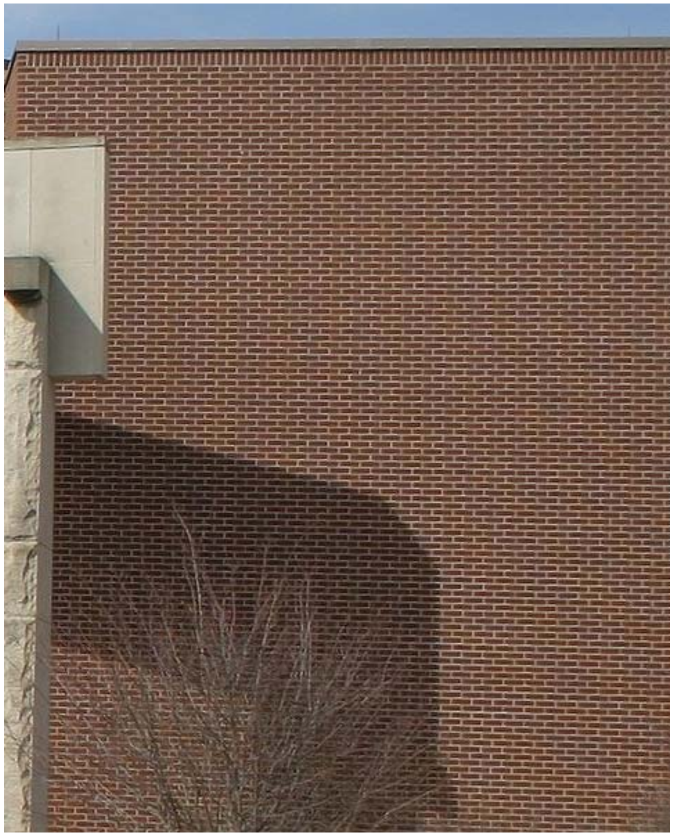
Photoacute.com

Aliasing – Blur to Remove the Visible Pixelization





<u>Aliasing</u>



Wikipedia

Aliasing

support.svi.nl

Aliasing

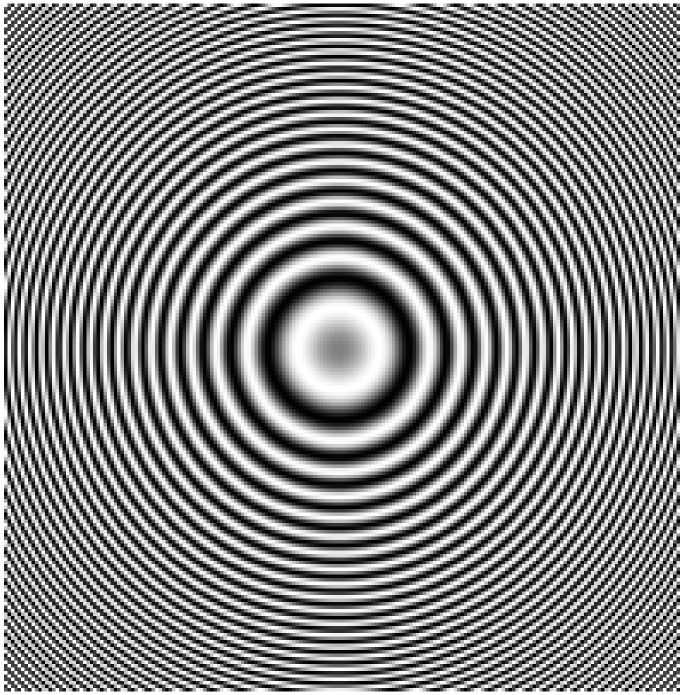
crewofone.com/2010

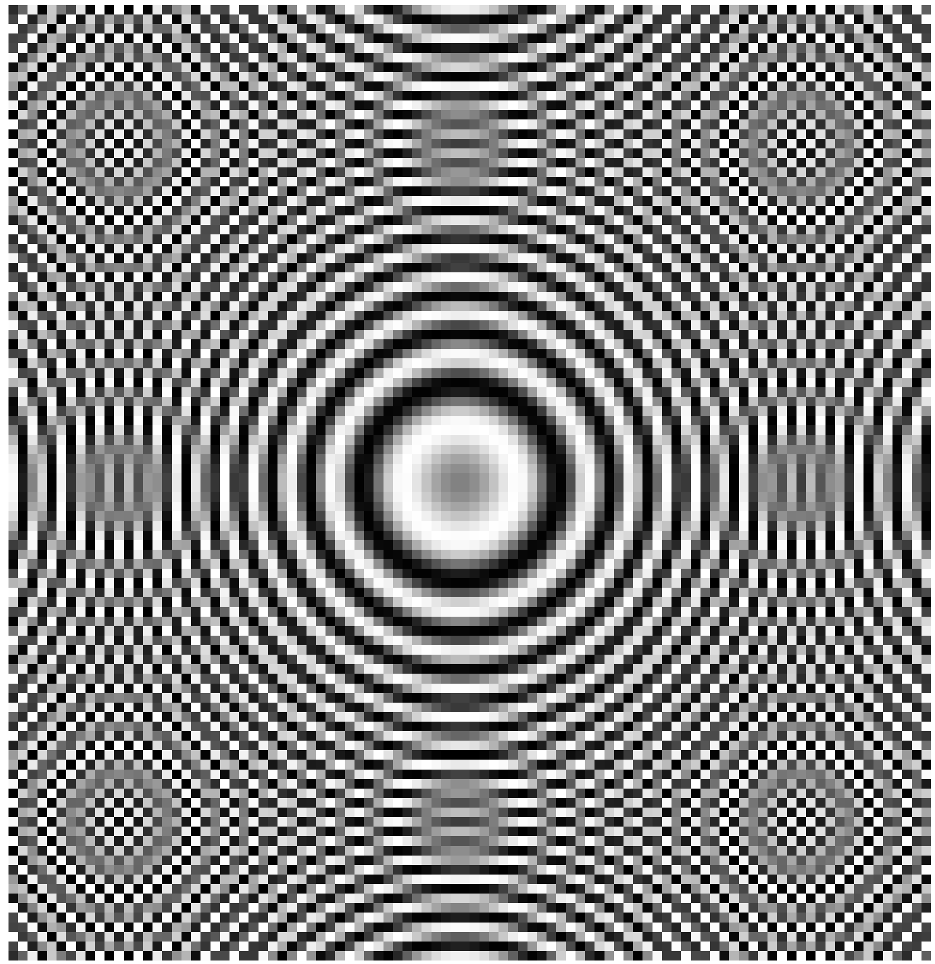
Aliasing

Two different cameras: www.xdcam-user.com

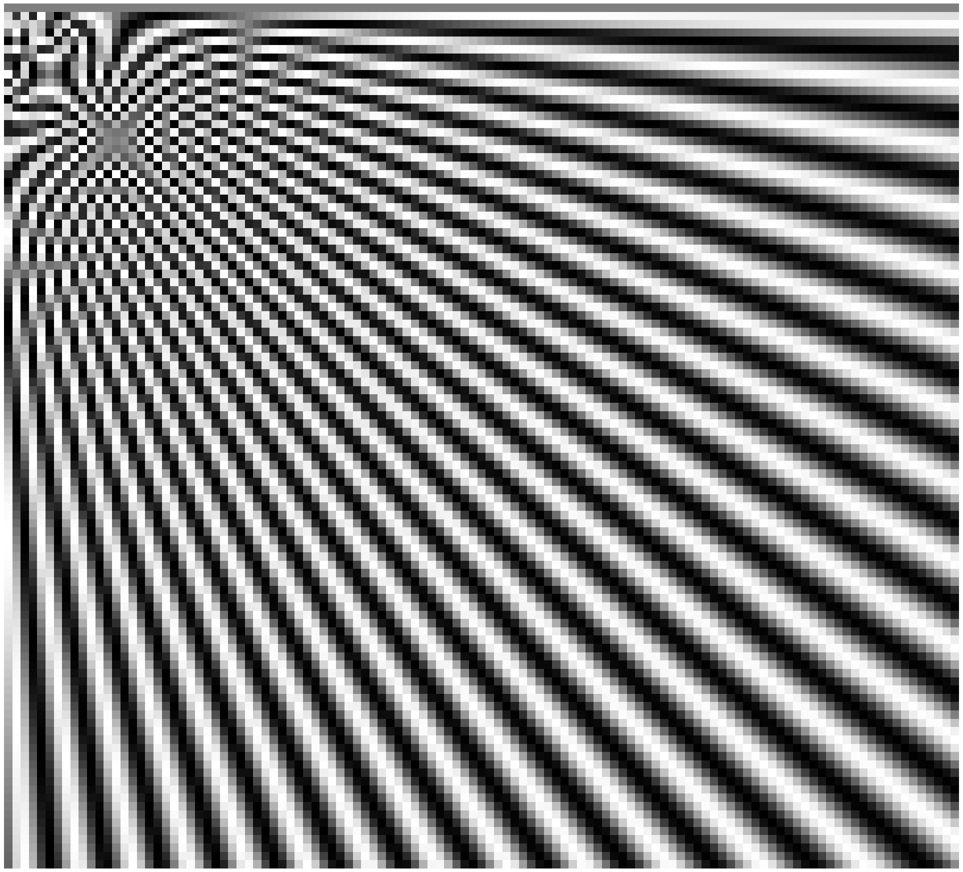
COLLEGE OF OPTICAL SCIENCES
ARIZONA

Aliasing





Aliasing



Displayed Image

Include display PSF d(x,y):

$$i_D(x,y) = i_S(x,y) ** d(x,y)$$

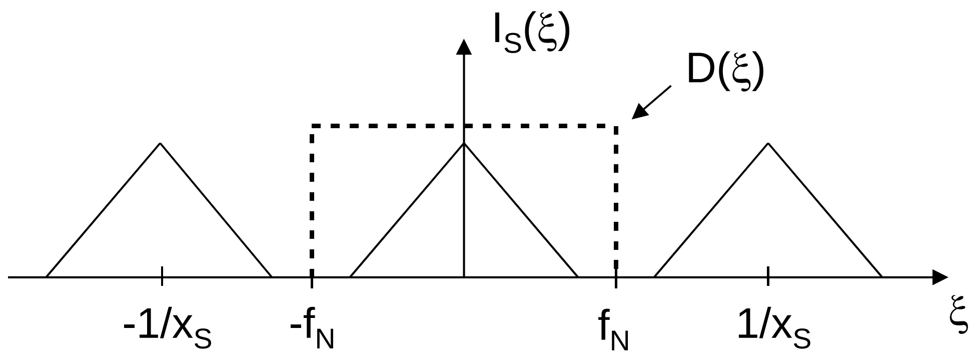
$$i_D(x,y) = \left\{ \left[o(x,y) ** h(x,y) ** \mathrm{rect}\left(\frac{x}{a},\frac{y}{b}\right) \right] \mathrm{comb}\left(\frac{x}{x_S},\frac{y}{y_S}\right) \right\} ** d(x,y)$$

$$I_D(\xi,\eta) = \left\{ \left[O(\xi,\eta) H(\xi,\eta)\, \mathrm{sinc}\left(a\xi, b\eta\right) \right] ** \mathrm{comb}\left(x_S\xi, y_S\eta\right) \right\} D(\xi,\eta)$$

The display blur or PSF cannot be used to correct the shift variance of sampled imaging system and eliminate aliasing artifacts.

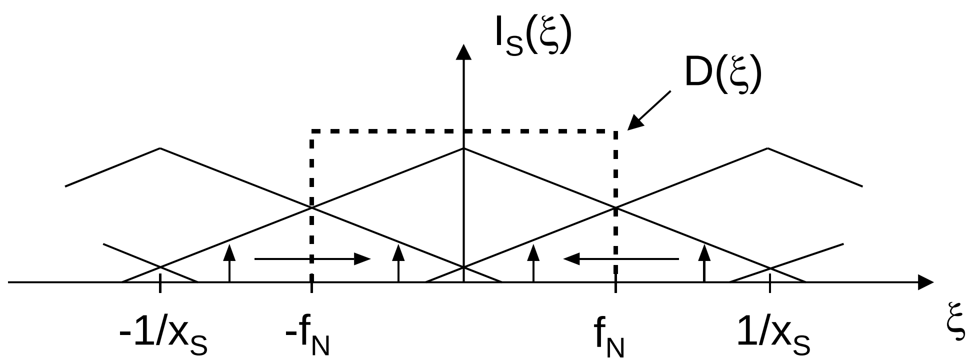
Display Blur

No Aliasing – Orders are separated:



Display MTF can select one order.

Aliasing – Orders overlap:



Display MTF cannot select one order.

Whittaker-Shannon Sampling Theorem

If a scene is bandlimited to within the Nyquist frequency of the sensor, the scene can be recovered, without error, from the sampled image.

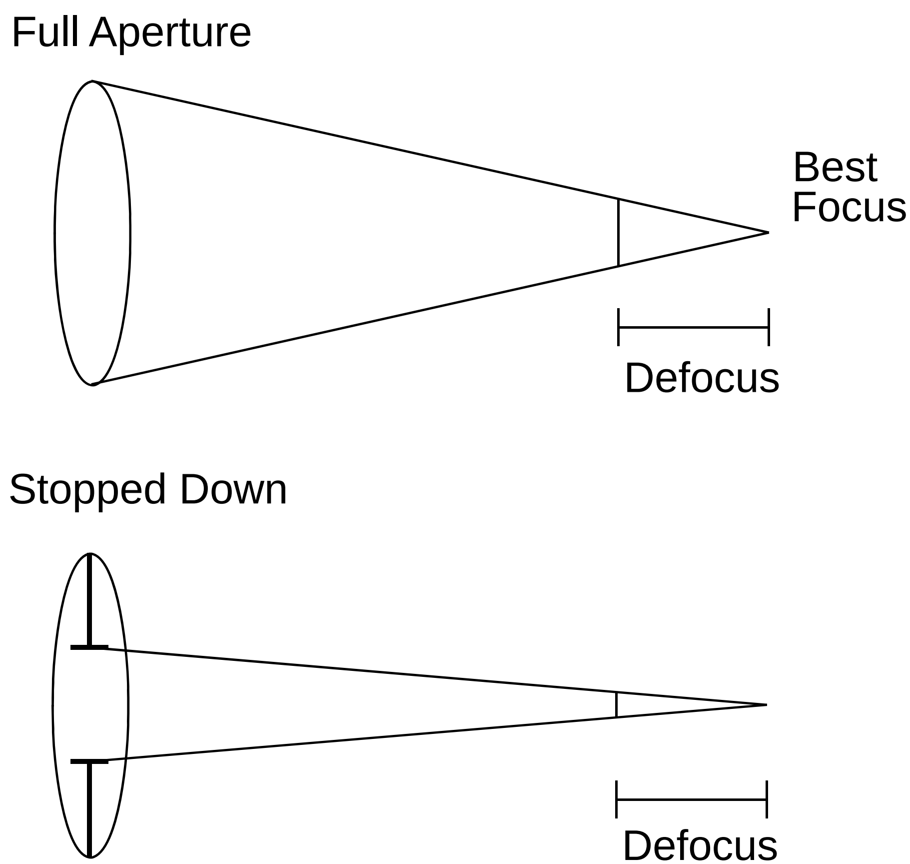
or

Any bandlimited function can be specified exactly by its sampled values, taken at regular intervals, provided that these intervals do not exceed some critical sampling interval.

To reduce aliasing:

- Increase the sampling frequency
  - More pixels, bandwidth, storage
- Blur the image reaching the sensor
  - Low pass filter
    - Lens defocus or aberrations
    - Optical prefilters
      - Birefringent blur filters

Blur Due to Defocus



Spot Size = Defocus / f/#

Blur = Cylinder Function

Spot size varies with f/#
Symmetric blur
Not the optimum MTF
Same situation for aberrations

Diffraction Limit vs. Nyquist Frequency

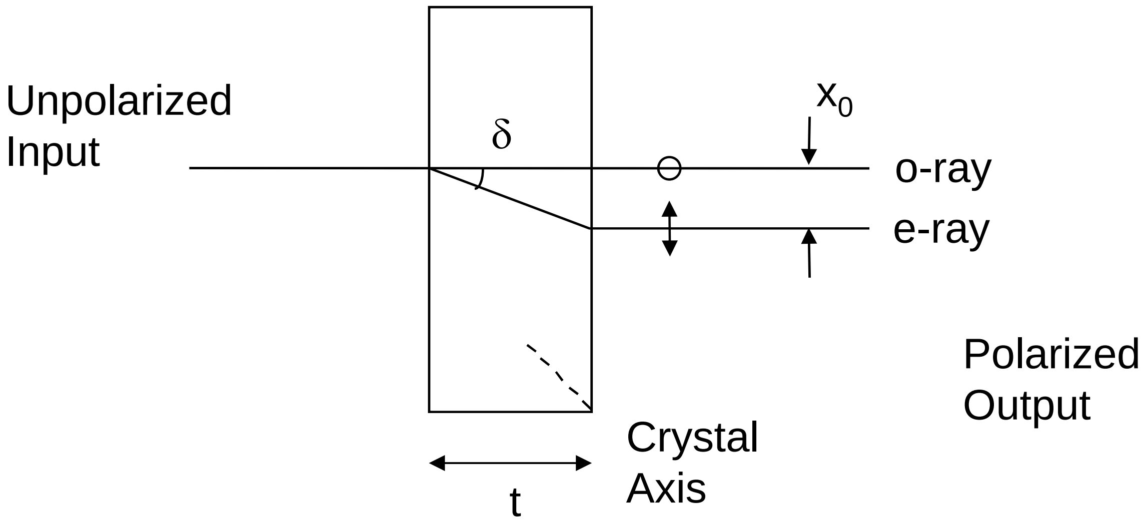
Pixel Pitch	Nyquist Frequency
5 µm	100 lp/mm
10 µm	50 lp/mm
20 µm	25 lp/mm

f/#	Diffraction Cutoff
1	2000 lp/mm
2	1000 lp/mm
4	500 lp/mm
8	250 lp/mm

The diffraction limit is well beyond the Nyquist frequency and is not an effective low pass filter.

Optical Low Pass Filter – Birefringent Blur Filter

Double refraction effect in crystalline quartz:



$$x_0 = t\tan(\delta)$$

$$\tan(\delta) = \frac{1}{2}\left(\frac{n_e}{n_o} - \frac{n_o}{n_e}\right)$$

Crystalline Quartz:

At 580 nm: $n_o = 1.5443$
$n_e = 1.5534$

λ	Δn
450 nm	0.00937
550 nm	0.00917
650 nm	0.00903

Deviation angle δ = 0.34°

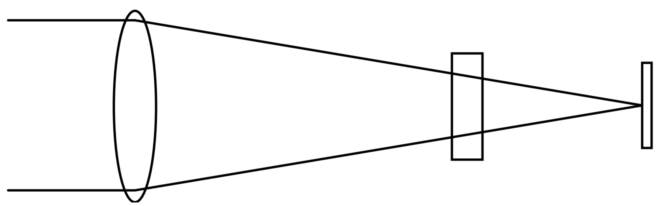
For a 12 μm spot separation, the plate should be 2 mm thick.

Birefringent Blur Filter

The blur filter is placed between the lens and the sensor.

The blur PSF consists of an array of δ-functions.

Blur by image replication.



- Blur is not a function of lens f/#.
- Light efficient.
- An asymmetric blur is often needed.
- Easy to use.
- 2D blur patterns can be constructed.

Blur PSF can be observed with a microscope focused on the image plane.

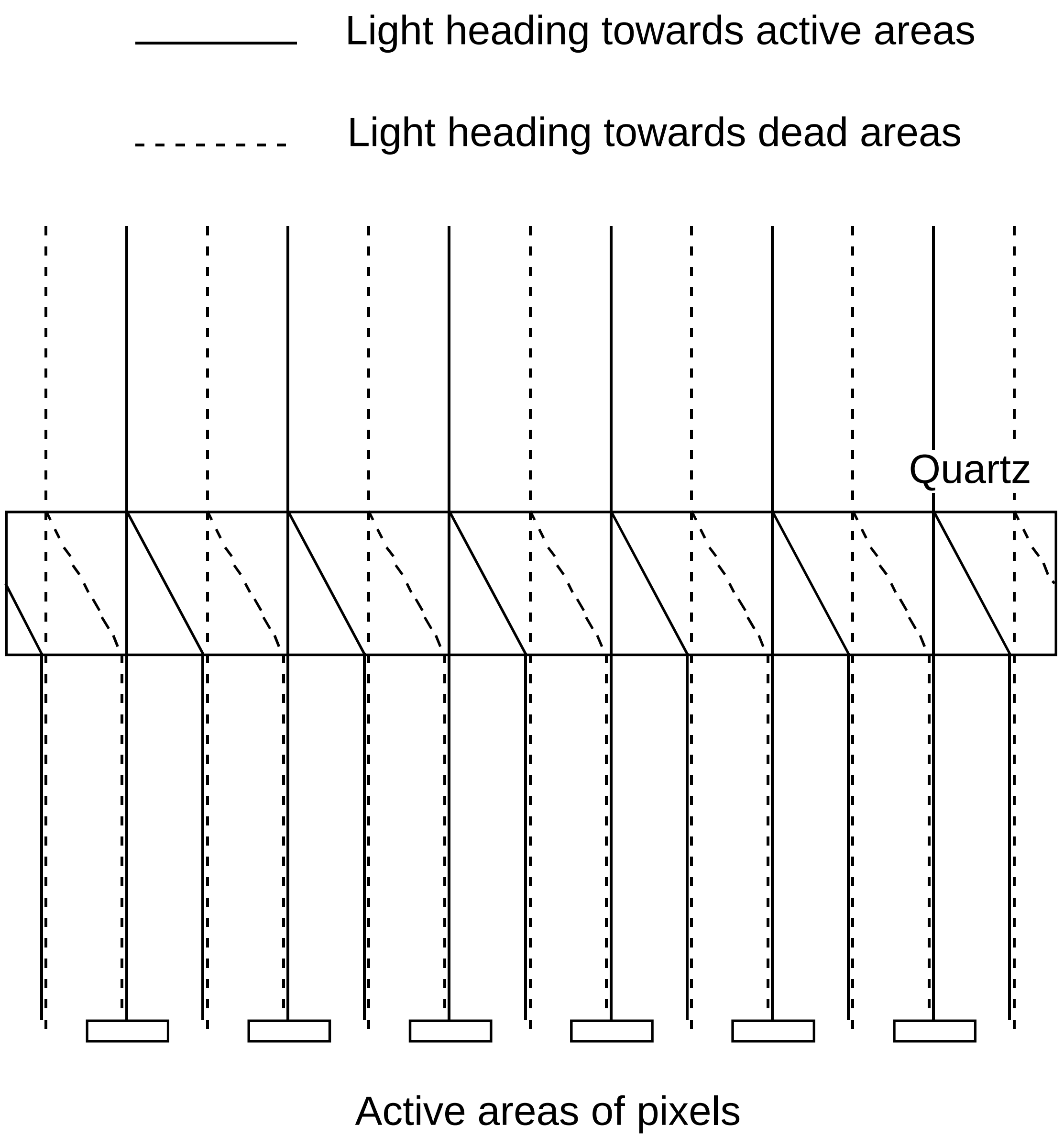
As with any glass plate, there is a focus shift introduced:

$$\Delta f = \frac{(n-1)}{n} t$$

Minimal alignment tolerances

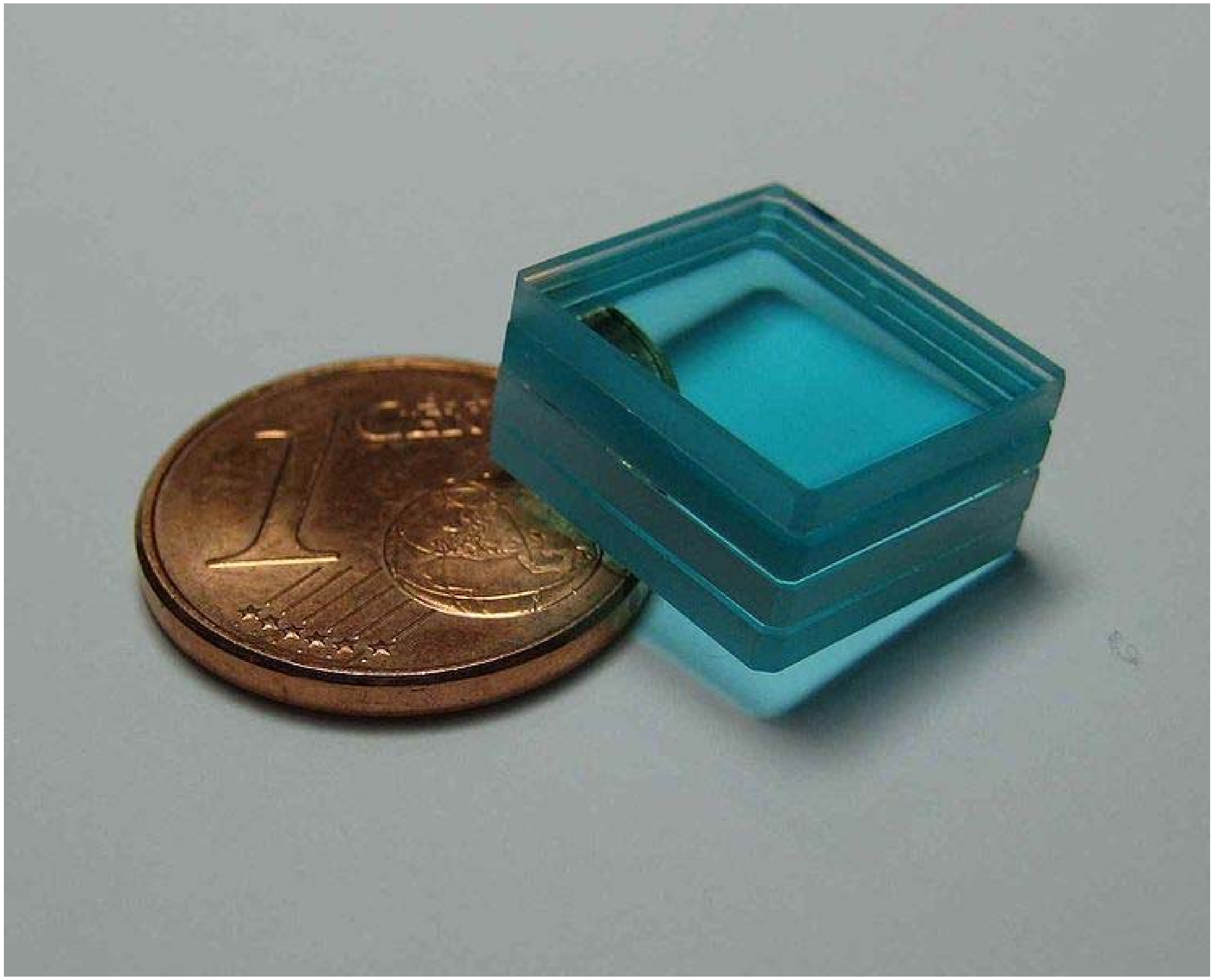
- None for X-Y-Z.
- Tip/tilt; aberrations of a glass plate.
- Rotation; alignment of blur pattern to sensor.

Birefringent Blur Filter



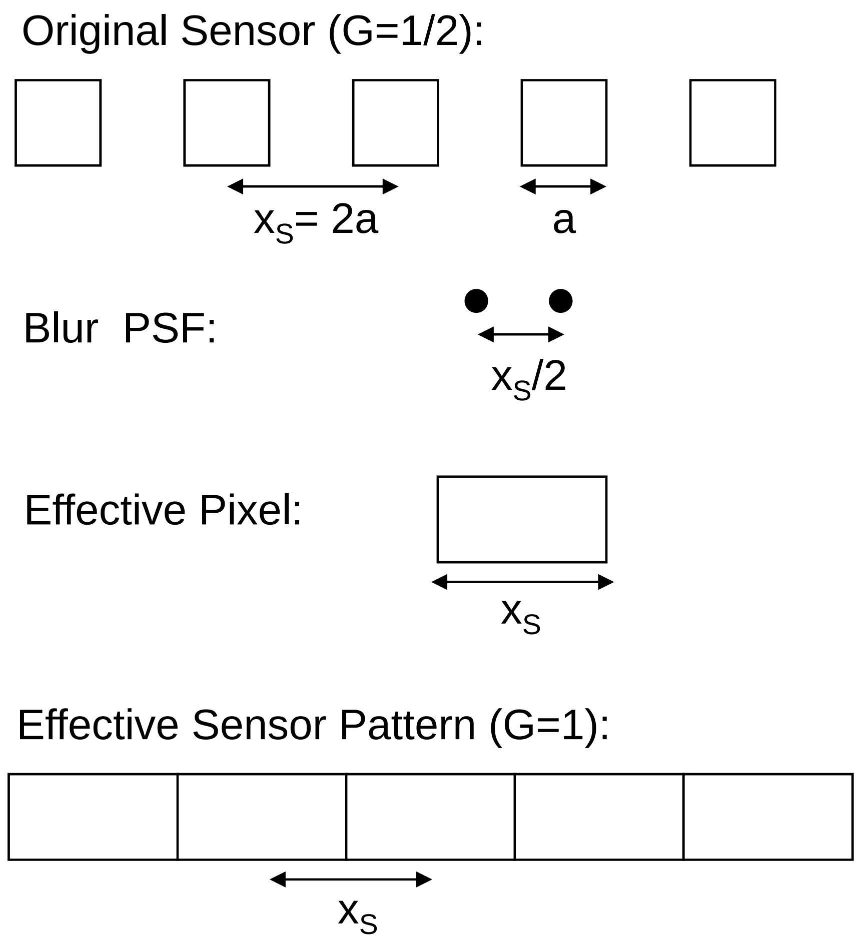
Net transmission =1

Birefringent Blur Filter



Combination of quartz plates produces a two-dimensional blur pattern.
A color-correction filter can also be included in the assembly as shown here.

Use of Blur Filter – One Dimensional Example



Pixel Duty Cycle

G is the width-to-pitch ratio of the active area of the pixels.

G = 1 is 100%; contiguous pixels

G = 1/2 is 50%

The use of a blur filter changes the effective duty cycle of the pixels on the sensor.

The G value of the effective pixels almost completely defines the aliasing properties of the sampled system.

2D systems can, and usually do, have different G's in the horizontal and vertical directions.

Effective Pixel

$$i_S(x,y) = \left\{ o(x,y) ** h'(x,y) ** \text{rect}\left(\frac{x}{a}, \frac{y}{b}\right) \right\} \text{comb}\left(\frac{x}{x_S}, \frac{y}{y_S}\right)$$

With a blur filter:

$$h'(x,y) = h(x,y) ** b(x,y)$$

where h(x,y) = Lens PSF
b(x,y) = Blur PSF

$$i_S(x,y) = \left\{ o(x,y) ** h(x,y) ** b(x,y) ** \text{rect}\left(\frac{x}{a}, \frac{y}{b}\right) \right\} \text{comb}\left(\frac{x}{x_S}, \frac{y}{y_S}\right)$$

Define:

$$p(x,y) = b(x,y) ** \text{rect}\left(\frac{x}{a}, \frac{y}{b}\right)$$

$$i_S(x,y) = \{ o(x,y) ** h(x,y) ** p(x,y) \} \text{comb}\left(\frac{x}{x_S}, \frac{y}{y_S}\right)$$

Effective Pixel PSF and MTF

$$p(x, y) = b(x, y) ** \operatorname{rect}\left(\frac{x}{a}, \frac{y}{b}\right)$$

p(x,y) is the effective pixel or the effective sampling aperture for the system.

It combines the effects of both the active area of the pixel and the blur filter.

Its use simplifies the analysis of sampled imaging systems.

In a similar manner, P(ξ,η) is the effective pixel MTF, and it combines the effects of the blur filter and the pixel active area.

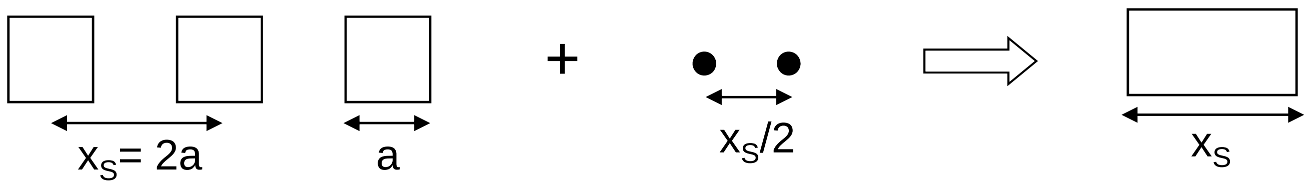
$$P(\xi,\eta) = B(\xi,\eta)\operatorname{sinc}(a\xi,b\eta)$$

Effective Sensor

The effective sensor is a fictitious sensor which has the same effects on image quality as the combination of the blur filter and the actual sensor.

If the sensor and blur filter are thought of as a unit, the effective sensor is what the scene "sees" as it looks back at the camera. An effective pixel has replaced each pixel on the sensor.

One Dimensional Example



$$i_S(x) = \left\{ o(x) * h(x) * \mathrm{rect}\left(\frac{2x}{x_S}\right) \right\} \mathrm{comb}\left(\frac{x}{x_S}\right)$$

G = 1/2

$$b(x) = \frac{1}{2}\delta\left(x + \frac{x_S}{4}\right) + \frac{1}{2}\delta\left(x - \frac{x_S}{4}\right)$$

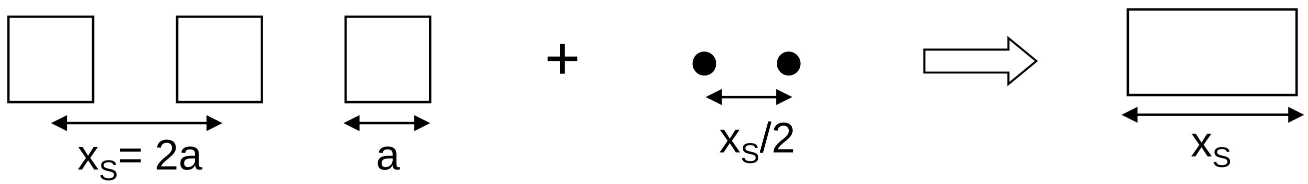
$$p(x) = \left\{ \frac{1}{2}\delta\left(x + \frac{x_S}{4}\right) + \frac{1}{2}\delta\left(x - \frac{x_S}{4}\right) \right\} * \mathrm{rect}\left(\frac{2x}{x_S}\right)$$

$$p(x) = \frac{1}{2}\mathrm{rect}\left(\frac{x}{x_S}\right)$$

$$i_S'(x) = \left\{ o(x) * h(x) * \mathrm{rect}\left(\frac{x}{x_S}\right) \right\} \mathrm{comb}\left(\frac{x}{x_S}\right)$$

G = 1

One Dimensional Example – Frequency Domain



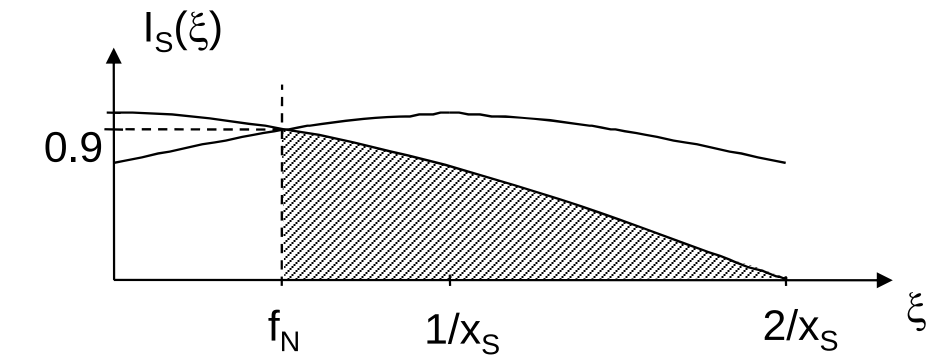
$$I_S(\xi) = \left\{ O(\xi) H(\xi)\, \mathrm{sinc}\left(\frac{x_S \xi}{2} \right) \right\} ** \,\mathrm{comb}\left(x_S \xi \right) \qquad G = 1/2$$

$$I'_S(\xi) = \left\{ O(\xi) H(\xi)\, \mathrm{sinc}\left(x_S \xi \right) \right\} ** \,\mathrm{comb}\left(x_S \xi \right) \qquad G = 1$$

One Dimensional Example

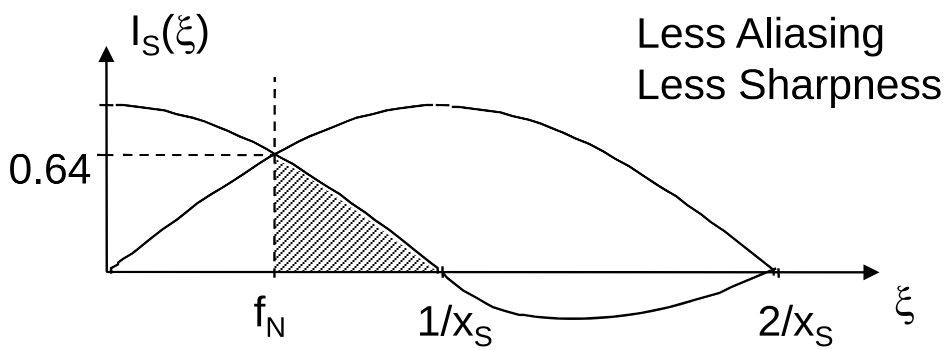
G= 1/2

Assume: $O(\xi)H(\xi) \approx 1$



High frequency content is folded back into the sensor baseband.

G = 1



Good Lens Assumption: The imaging lens MTF is relatively high out to the Nyquist Frequency. It does not limit system performance. When this approximation is not valid, the lens MTF can also be included in the effective pixel size and MTF.

Resolution and Sharpness – Susceptibility to Aliasing

The resolution of a sampled imaging system is limited to the Nyquist frequency, even if the effective pixel MTF extends well beyond this value.

The image sharpness or contrast is determined by the value of the effective pixel MTF between zero and the Nyquist frequency.

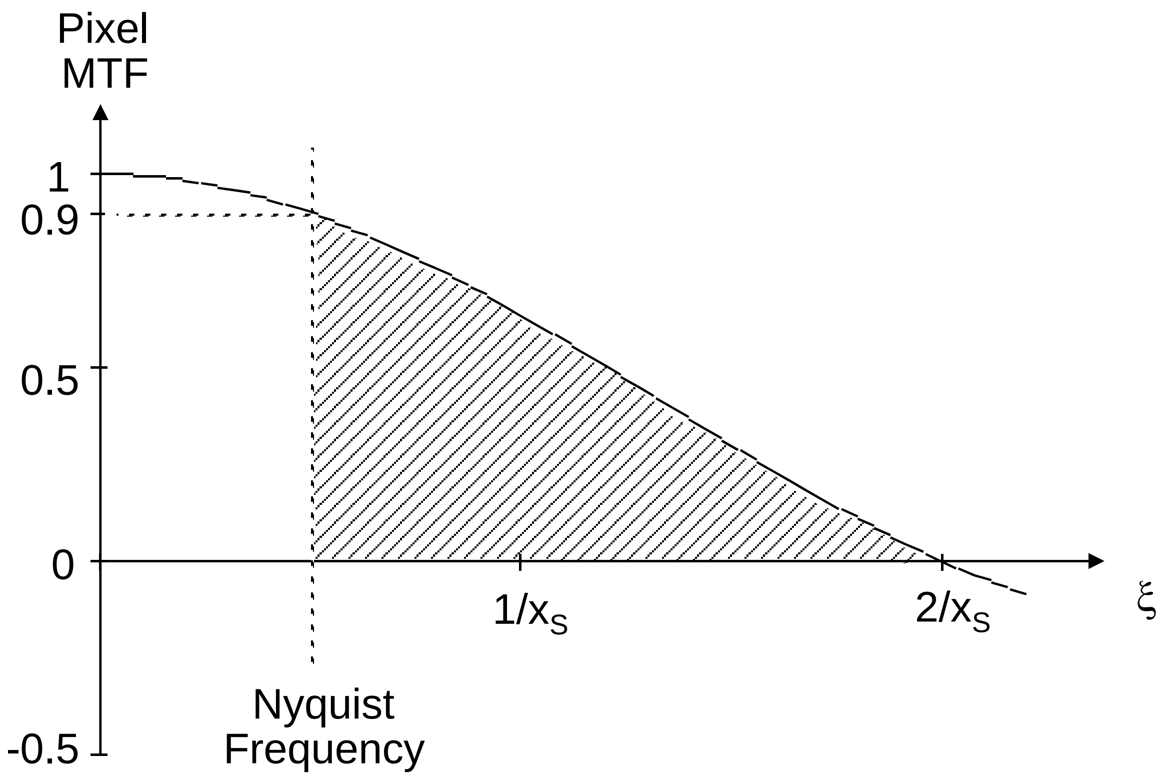
The value of the MTF at the Nyquist frequency can be used as a measure of sharpness.

Since the scene spectrum is generally unknown, it is only possible to predict how likely the system is to alias.

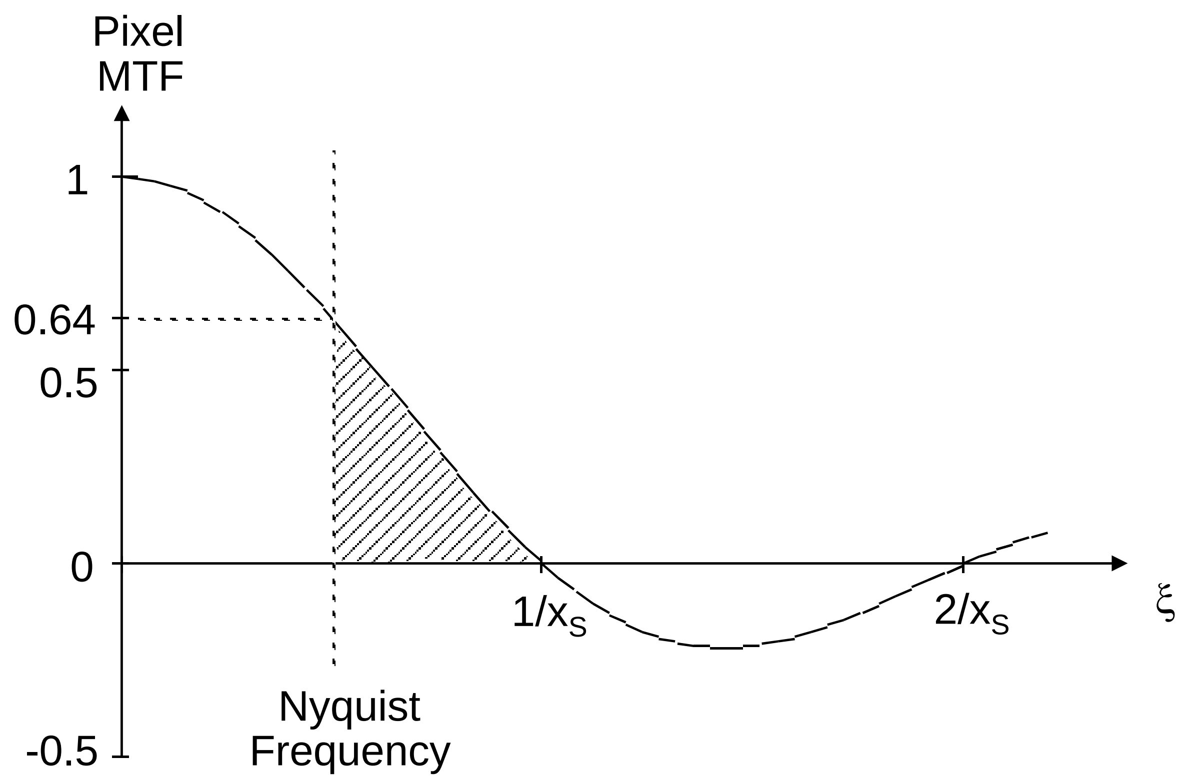
One measure of the susceptibility of the system to aliasing artifacts is the area under the effective pixel MTF curve from the Nyquist frequency to the first zero of the curve.

This is the amount of scene content that could potentially be imaged onto the sensor and be mapped back into the baseband of the system to appear as aliasing artifacts.

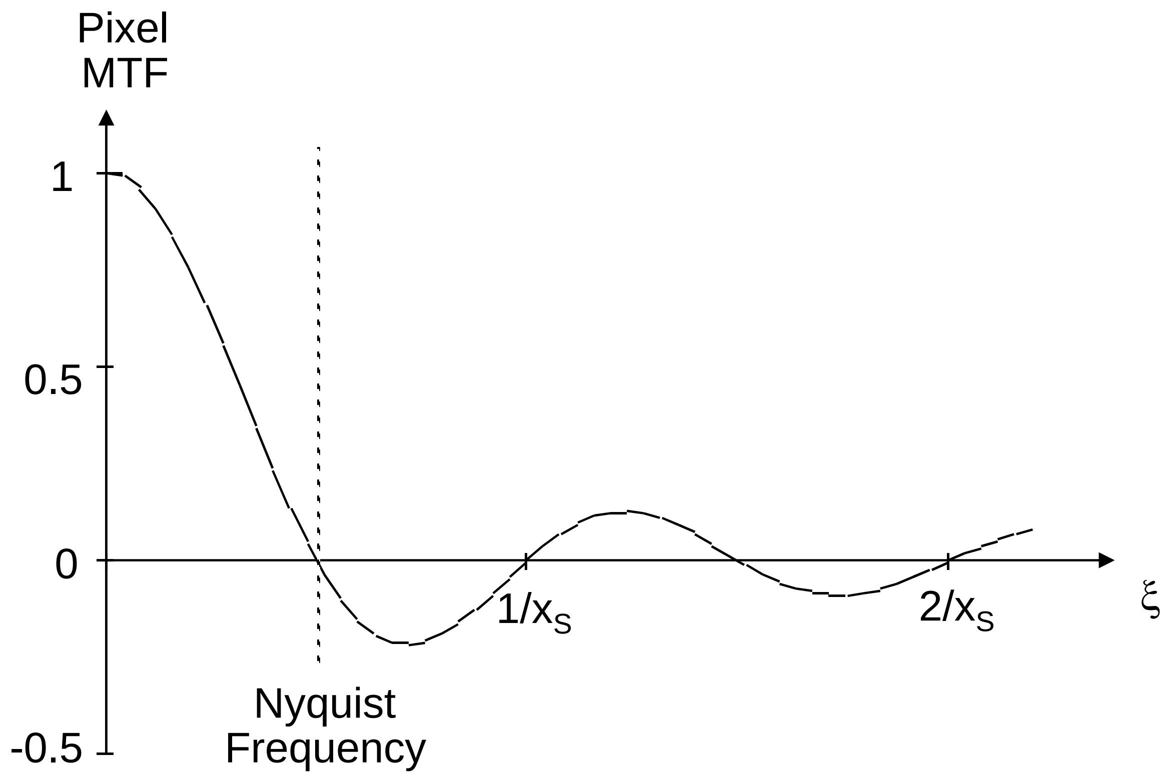
G = 1/2 – 50% duty Cycle



G = 1 – 100% duty Cycle



G = 2 – 200% duty Cycle



Pixel MTFs

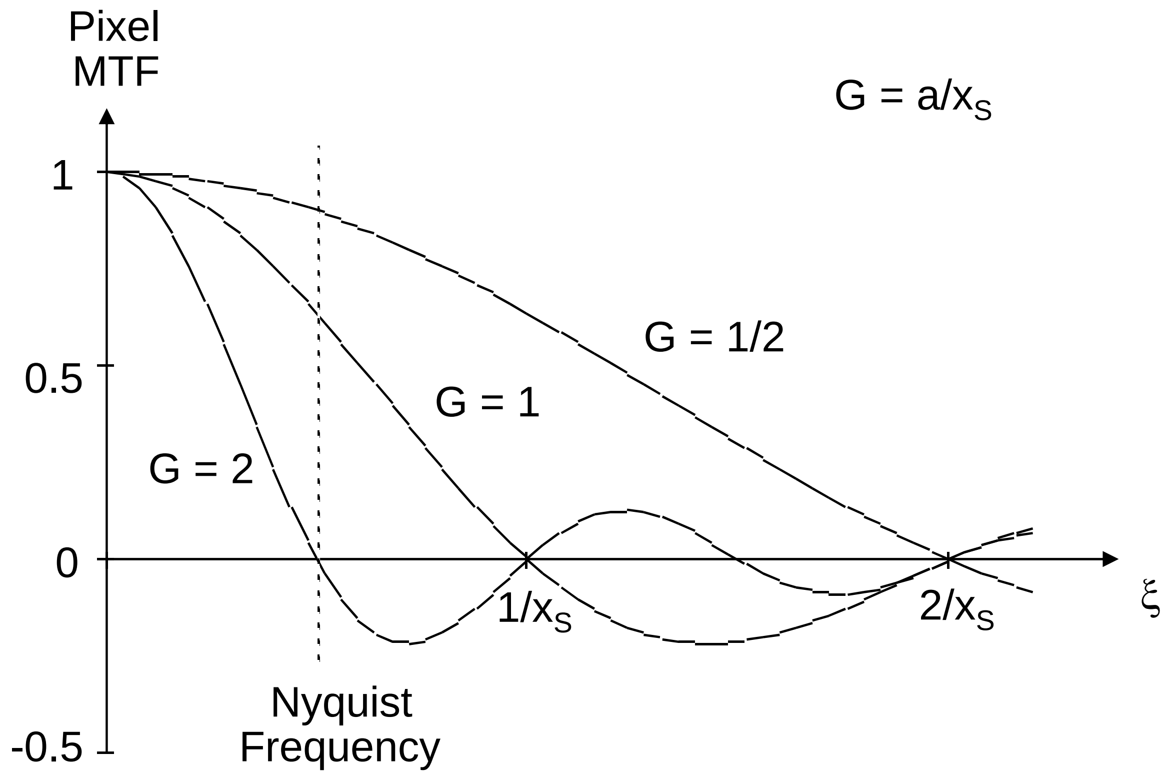


Image Quality

The quality of a sampled imaging system depends not only on the resolution and sharpness of the image, but also on the severity of aliasing artifacts in the displayed image. Improving the system MTF's does not guarantee an improvement in overall system performance.

Putting a better lens on an electronic imaging system might actually result in lower quality images.

The purpose of the blur filter is to degrade the lens MTF in a specified and predictable manner.

Sharpness-Aliasing Tradeoff

For a given sensor resolution or Nyquist frequency, the important factor is the pixel width-to-pitch ratio, G.

Decreasing G:
- More Sharpness
- More Aliasing

Increasing G:
- Less Sharpness
- Less Aliasing

With a blur filter, the effective pixel width-to-pitch ratio is used.

For a given Nyquist frequency:

G	Sharpness	Aliasing Susceptibility
1/2	.90	1.39
1	.64	0.31
2	0.00	0.00

Sharpness is the pixel MTF at the Nyquist frequency.

Aliasing susceptibility is the area under the pixel MTF beyond the Nyquist frequency, expressed as a fraction of the Nyquist frequency.

Choice of Effective G

It is impossible to define a blur or effective G that is optimum for all applications. Some applications are more susceptible to aliasing or have significant penalties for aliasing artifacts.

For consumer video applications, the optimum solution appears to be G = 1; contiguous effective pixels.* At this point, reasonable sharpness remains (MTF = 0.64) and a significant amount of aliasing is eliminated.

The first zero of the effective pixel MTF occurs at the sampling frequency for G = 1. Since scene content at the sampling frequency aliases to zero spatial frequency, this choice prevents DC aliasing. This type of aliasing is extremely objectionable, especially with motion.

Like defocus, the lens MTF is not of the appropriate form to correct aliasing.* It is better to use the MTF of the blur filter.

The lens MTF should extend beyond the Nyquist frequency and will primarily effect the image sharpness. For most applications the lens MTF should be maintained at a reasonable level at the Nyquist frequency (perhaps greater than 0.3).

*Note: This discussion assumes that the system design is trying to make use of all of the capability of the pixels on the sensor. In many compact cameras, the lens MTF is incapable of supporting the sensor resolution, and the image on the detector is band-limited below the Nyquist frequency. The image is oversampled.

Comparison to Other Blurs

The choice of the blur function b(x) is limited to physically realizable functions. It must be positive only.

Four possible functions and their MTF's:

1) Two point blur (birefringent filter):

$\cos(\pi \xi x_S / 2)$

2) Rectangular blur (defocus):

$\mathrm{sinc}(\xi x_S)$

3) Diffraction grating (Ronchi ruling):

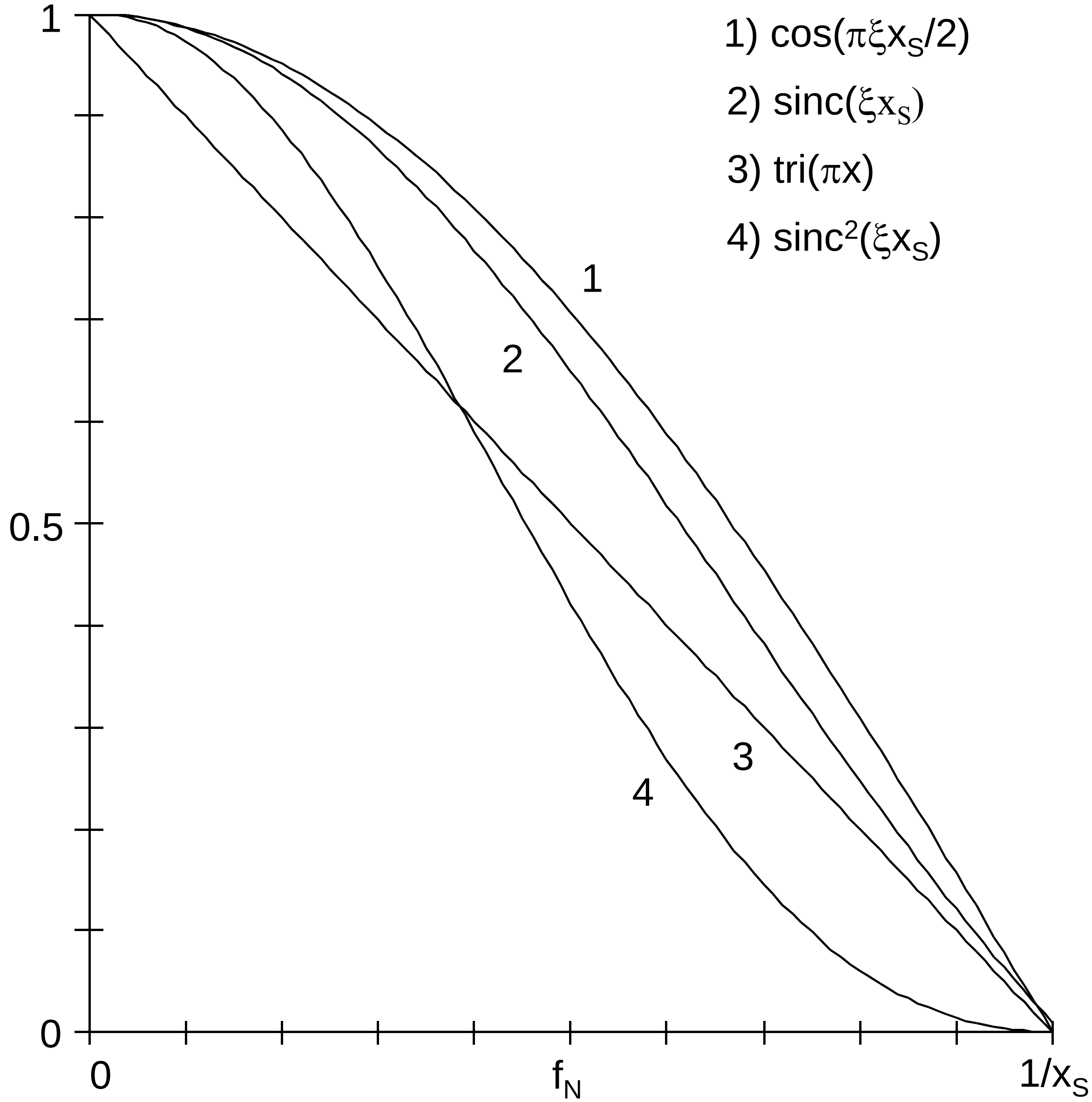
$\mathrm{tri}(\xi x_S)$

4) Triangular blur:

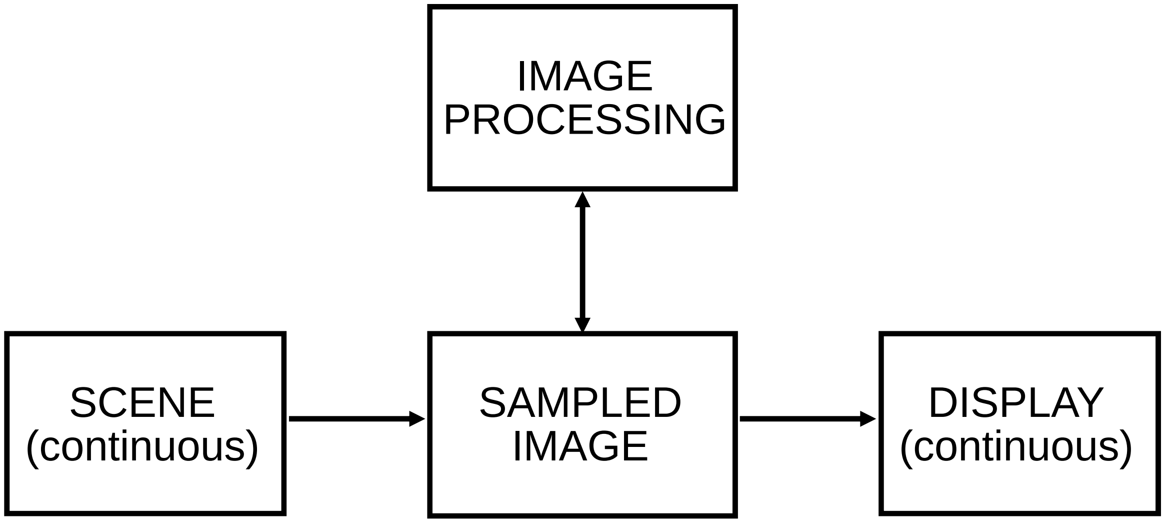
$\mathrm{sinc}^2(\xi x_S)$

The plots on the next page are scaled to the same first zero, and the blur due to the birefringent filter has the highest MTF.

Blur MTF Comparison



Sampled Image System



SAMPLING

DESAMPLING

Aliasing Artifacts

Optical Prefilter

High Spatial Frequencies to Low Spatial Frequencies

Desampling and Interpolation Artifacts

Desampling is the process of converting the stored sampled image into a continuous displayed image.

Characteristics are determined by the display postfilter, $d(x,y)$ or $D(\xi,\eta)$.

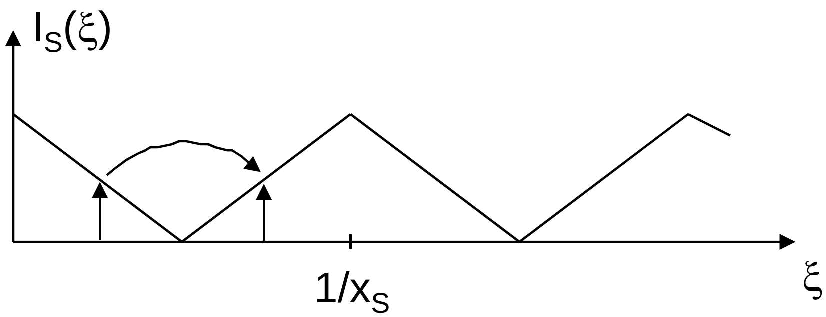
Errors appear as interpolation artifacts.

Interpolation artifacts occur in the display of the sampled image.

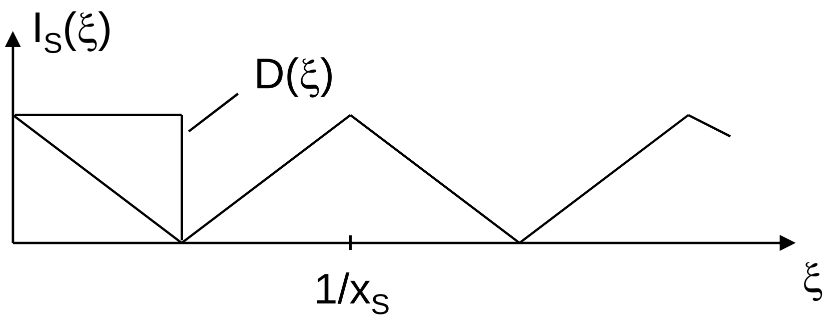
Artifacts can be present even when there is no aliasing.

Artifacts are influenced by the choice of the display blur or MTF.

Display Postfilter

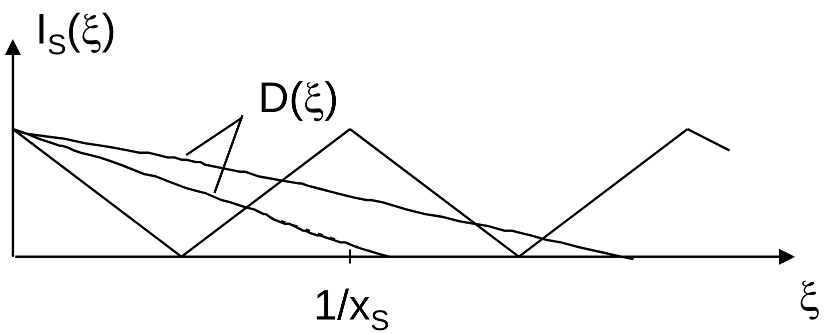


Ideal Postfilter:



Only the zero order is selected.

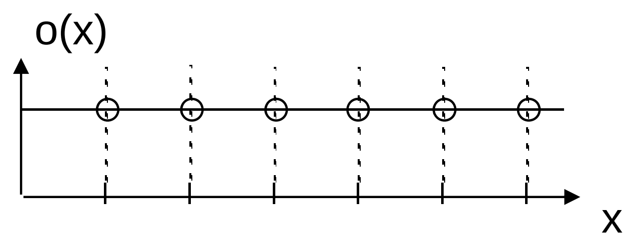
Real Postfilter:



More than one order can be selected. Low spatial frequencies in the scene are displayed at a higher spatial frequency.

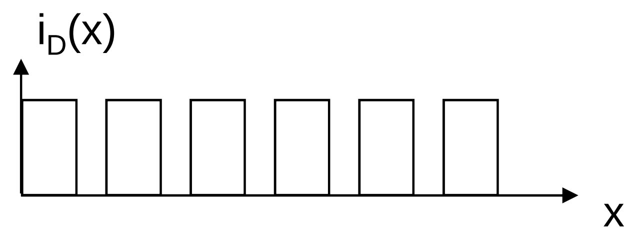
Interpolation Artifacts – Raster Lines

Consider a uniform scene:

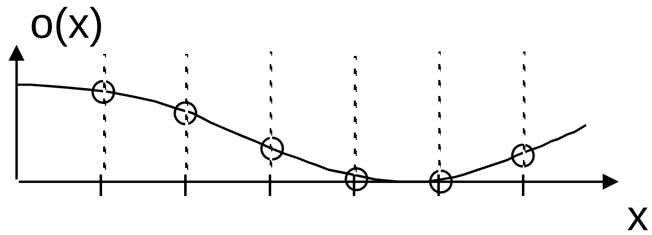


Apply a display blur less than pixel width:

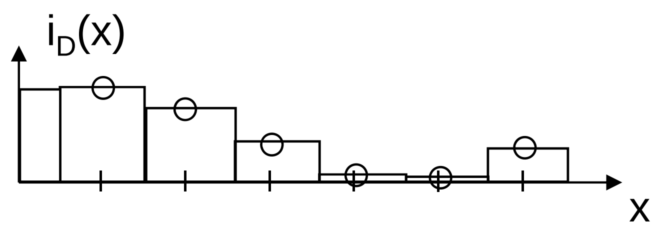
A non-uniform output image results:



Interpolation Artifacts – Pixelation



Blur equals pixel width – sample and hold:



Improper smoothing – the pixels are each represented by squares in the image.

Pixelation

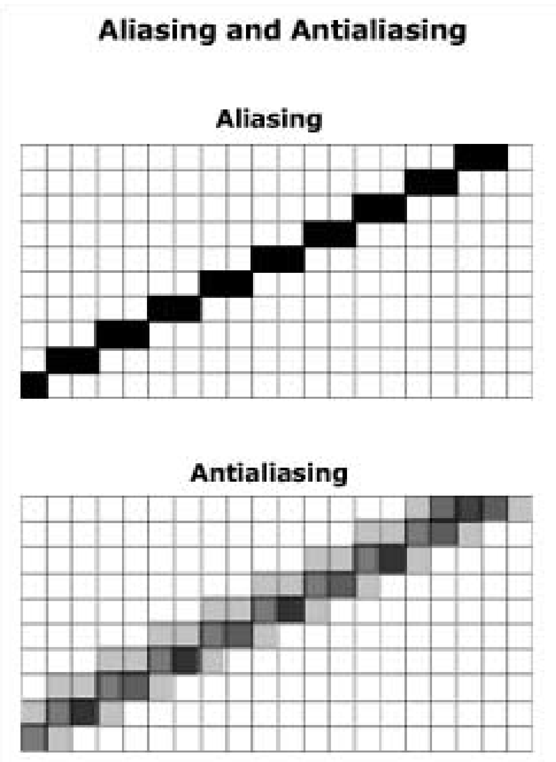
CNN.com

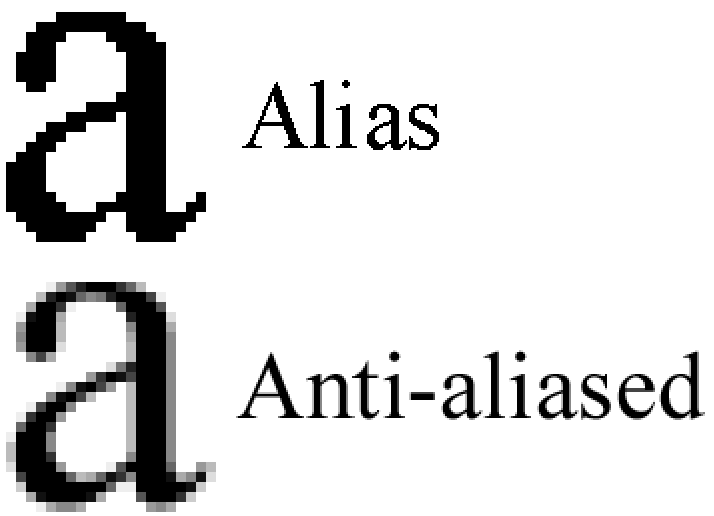
Pixelation

CNN.com

Pixelation Artifacts

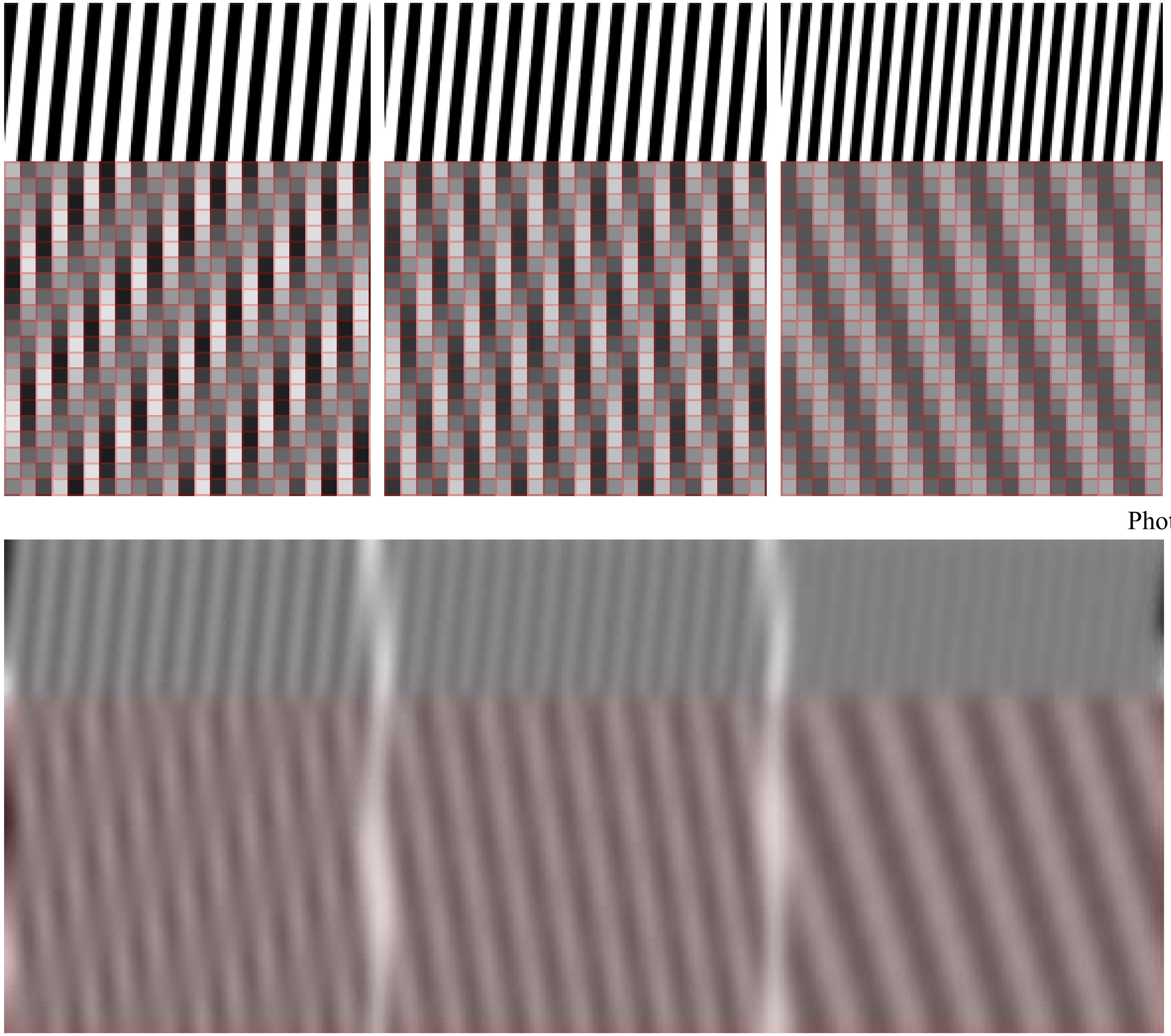
The interpolation artifact that results in pixelation is known as *aliasing* in the computer graphics and gaming world. Attempts to remove this artifact are known as *anti-aliasing*.





Be careful!!

Interpolation Artifacts – Low Pass Filter

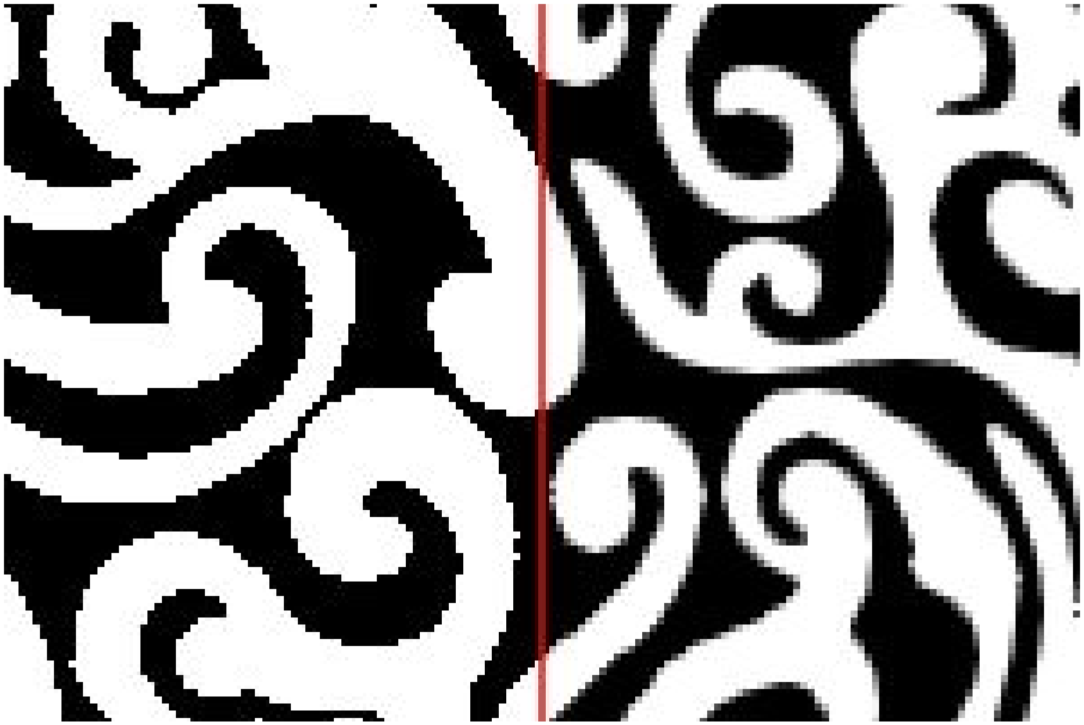


Photoacute.com

Pixelation Artifacts and "Anti-Aliasing"

Eurogamer.net

Pixelation Artifacts and “Anti-Aliasing”



Pixel Bender Filter – Adobe.com

Pixelation Artifacts and "Anti-Aliasing"

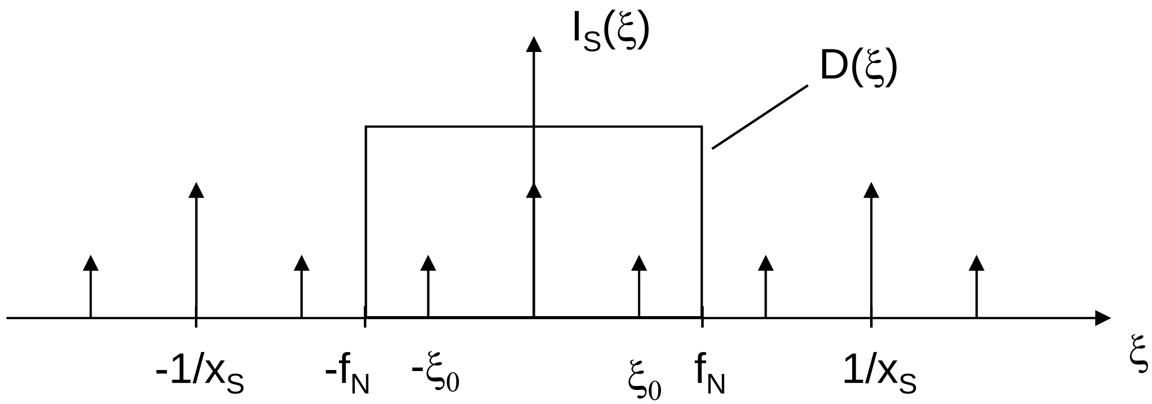
Flightgear.org

Display Bandwidth

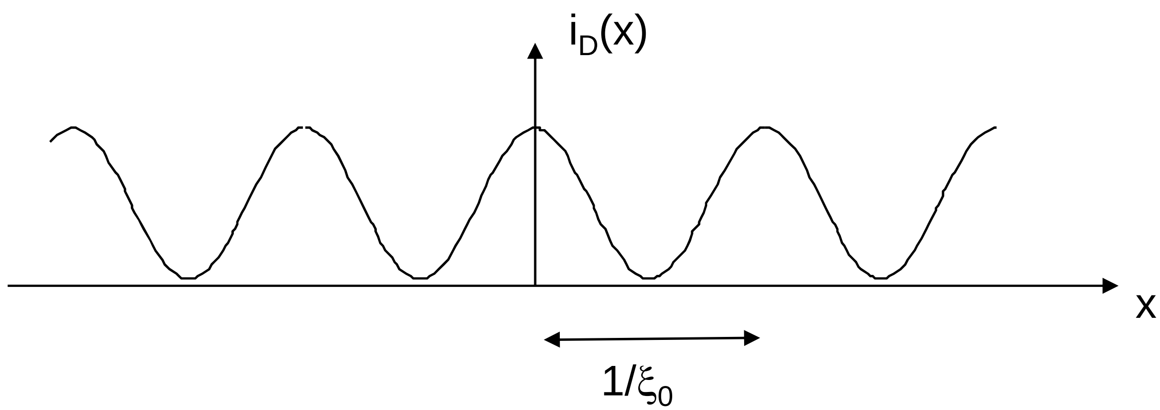
Input: A single unaliased spatial frequency: $\xi_0 < \xi_N$

$$o(x) = 1 + \cos(2\pi\xi_0 x)$$

Case 1: Display bandwidth equals the Nyquist frequency:

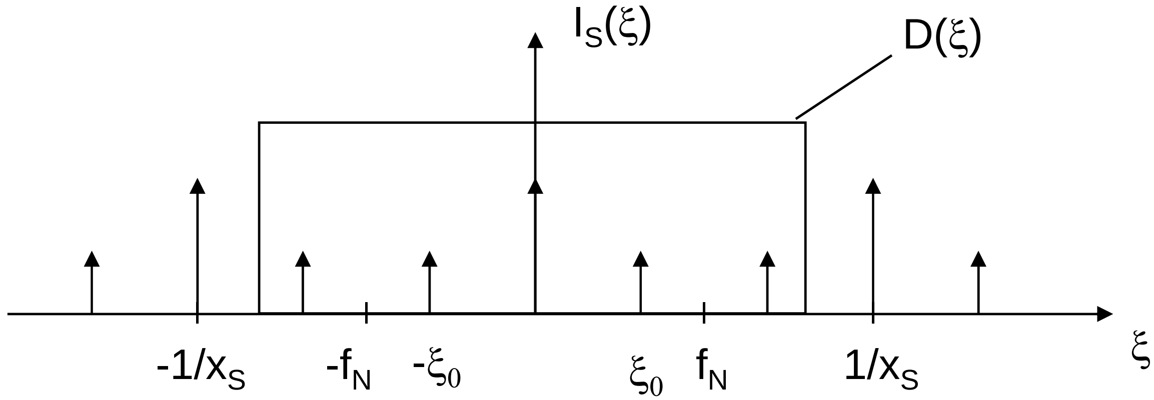


The displayed output equals the input:



Display Bandwidth

Case 2: Display bandwidth is greater than the Nyquist frequency plus ξ_0:

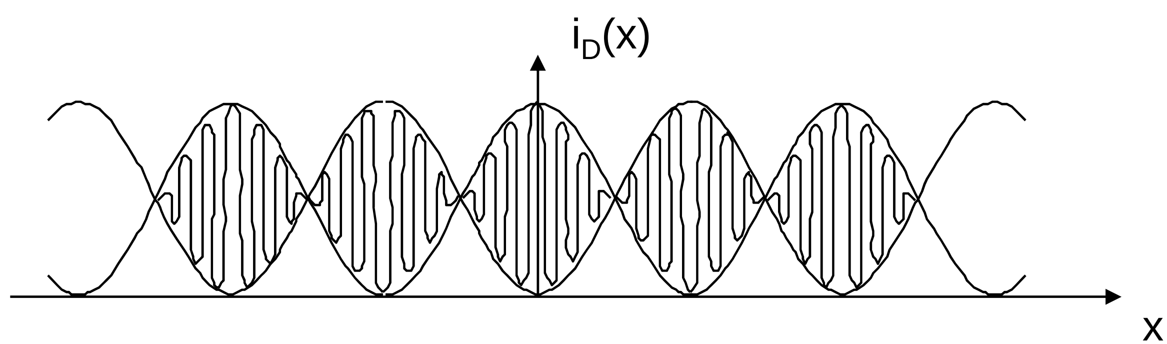


The displayed output bears little resemblance to the input:

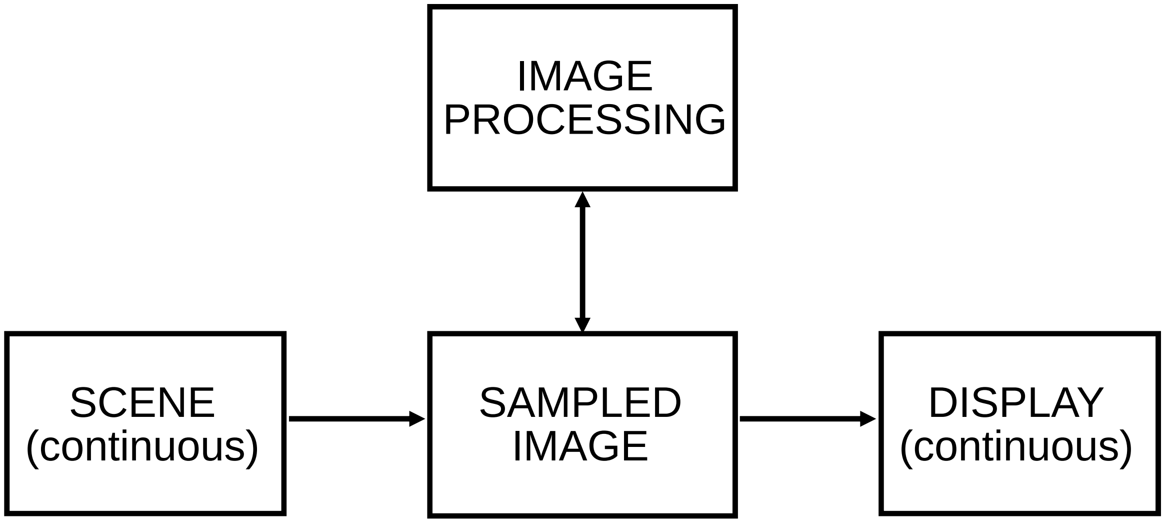
$$i_D(x) = 1 + \cos(2\pi\xi_0 x) + \cos\left[2\pi(2f_N - \xi_0)x\right]$$

$$i_D(x) = 1 + \cos(2\pi f_N x)\cos\left[2\pi(f_N - \xi_0)x\right]$$

The displayed output is the Nyquist frequency modulated by a low-frequency envelope:



Sampled Image System



SAMPLING

Aliasing Artifacts

Optical Prefilter

High Spatial Frequencies to Low Spatial Frequencies

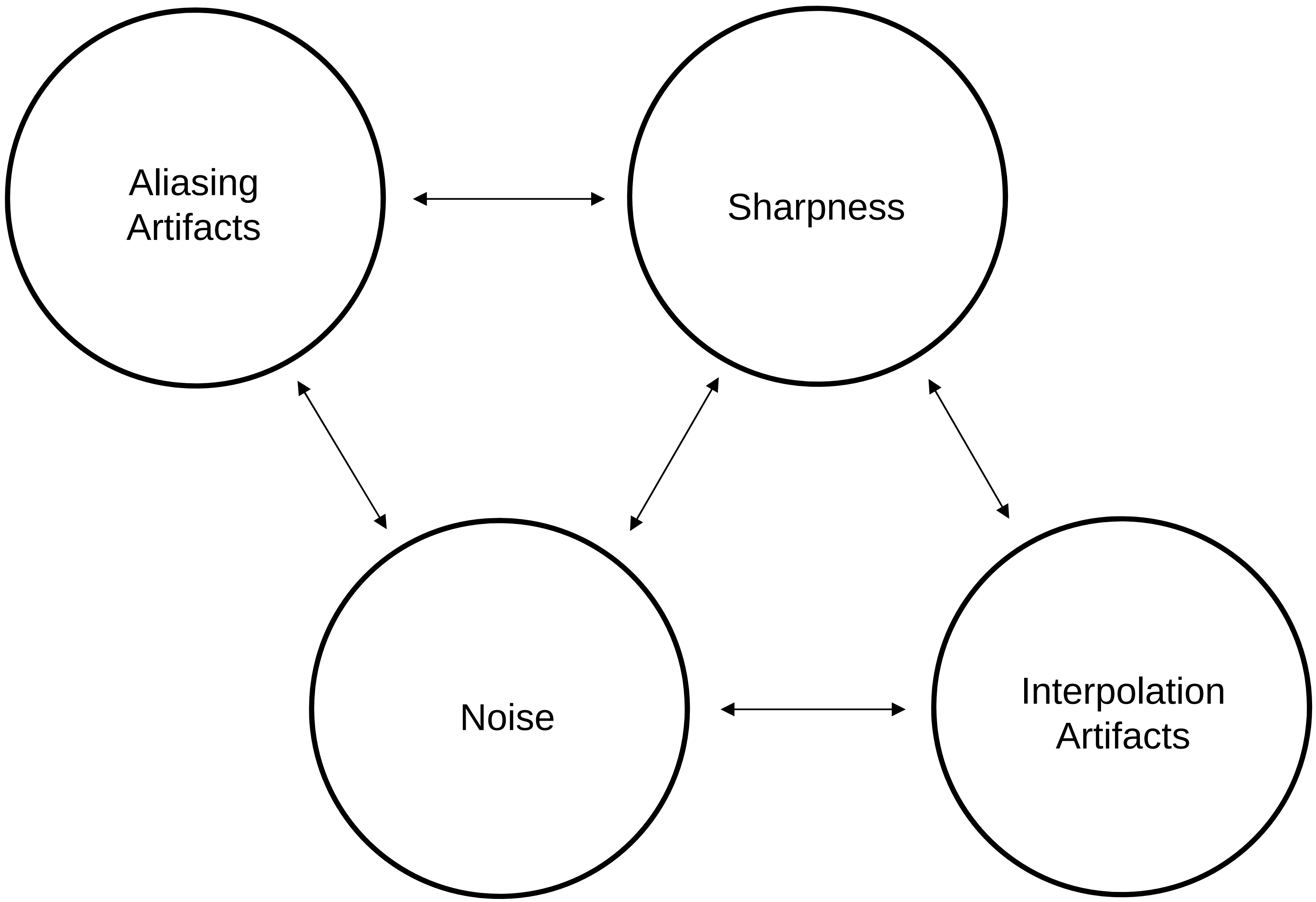
DESAMPLING

Interpolation Artifacts

Display Postfilter

Low Spatial Frequencies to High Spatial Frequencies

System Tradeoffs



Temporal Aliasing

All of this theory can be applied to temporal aliasing.

Temporal aliasing can be an important concern in video imaging systems:

Wagon wheels don't really roll backwards.

If the frame rate matches the "spoke rate," the wheel will appear to not move.

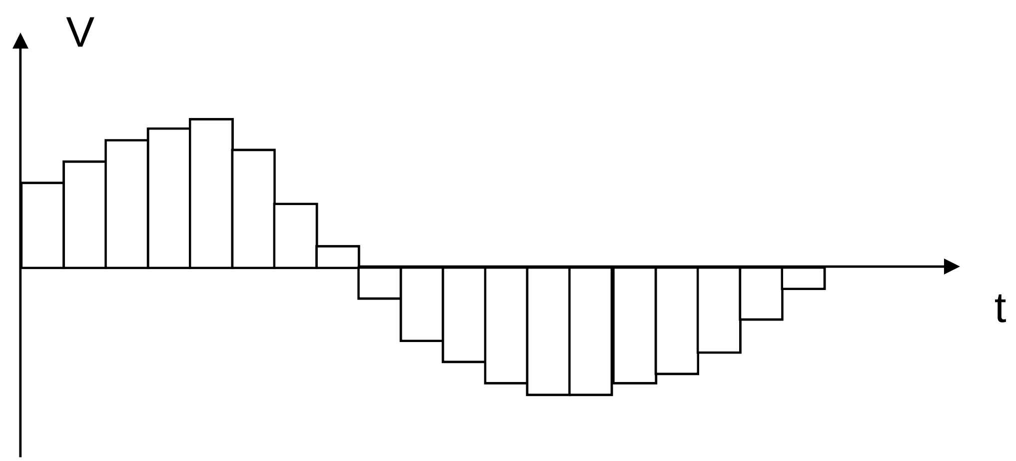
If the frame rate is a bit faster, the next spoke will not have reached the same position in the subsequent frame. The apparent spoke location will be recorded in a location that makes it appear that the wheel is slowly rotating backwards.

Interpolation Example – Digital Audio

CDs are recorded with a samplig frequency of 44.1 kHz per channel.

The Nyquist frequency is then 22 kHz.

The digital signal is restored to an analog signal with a D/A converter:

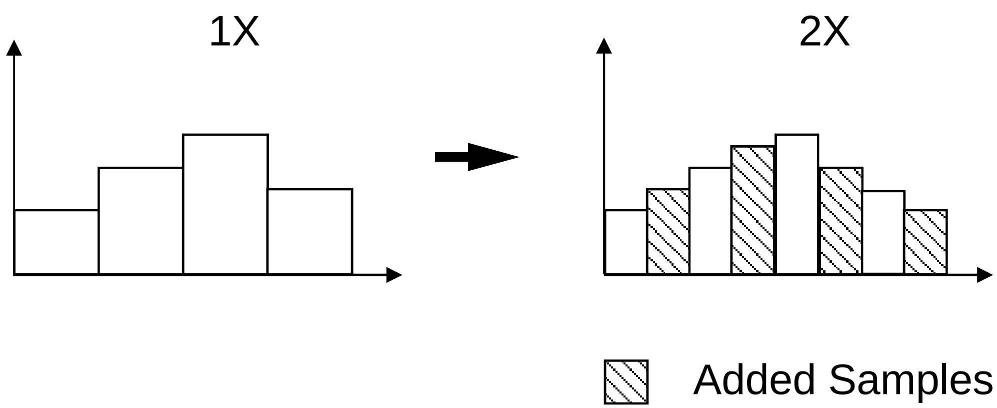


The stair steps at the sampling frequency can be heard, and must be smoothed.

Digital Audio – Oversampling

Create a new digital data stream with twice as many samples.

Linear interpolation (averaging) between existing samples is used to create the new samples.



This process can be repeated any number of times: for example, 8X or 128X oversampling.

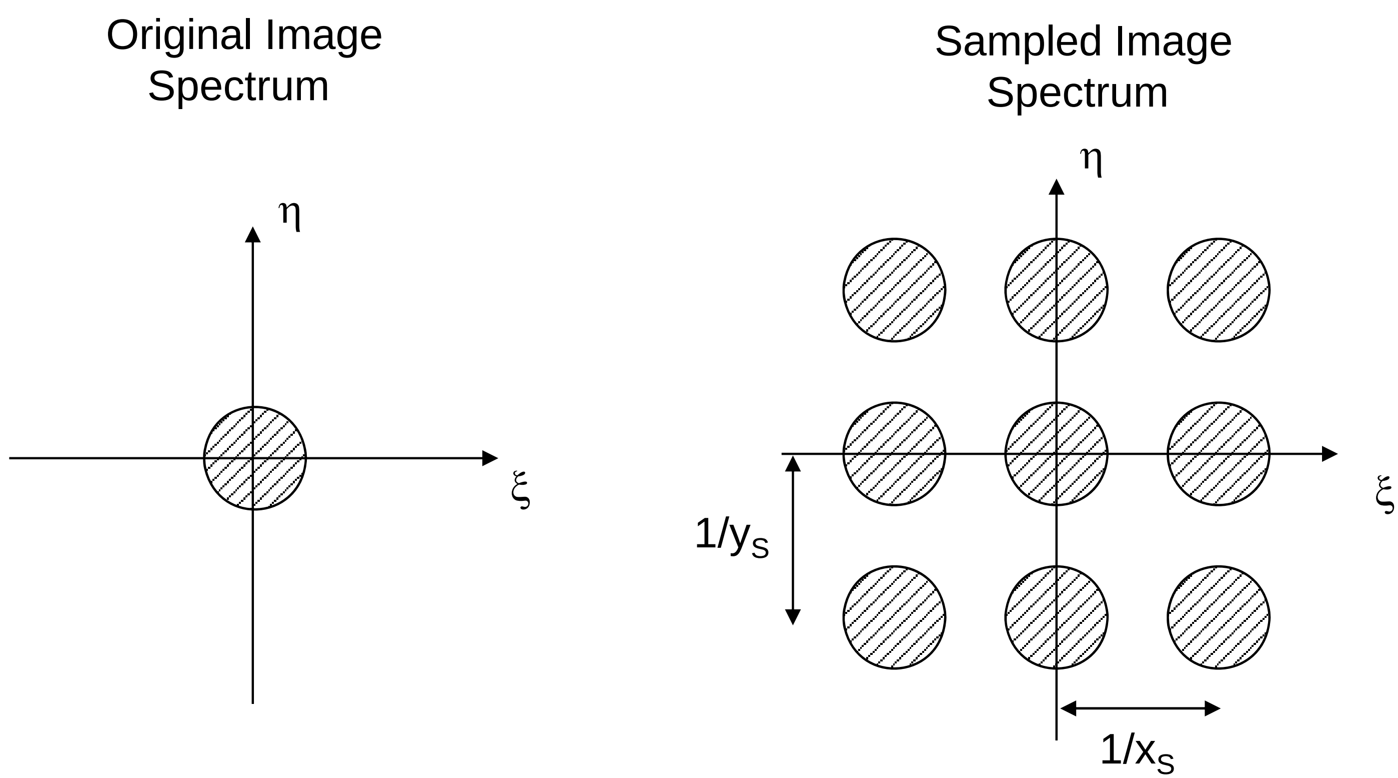
Note that with oversampling, the original sampling frequency has not changed. This is an interpolation technique.

Two-Dimensional Sampled Images

The two-dimensional filtered image spectrum is replicated at all of the delta functions in the Fourier transform of the two-dimensional sampling grid.

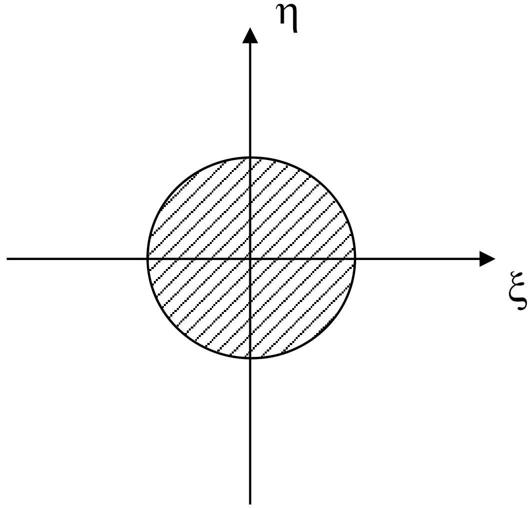
This grid is referred to as the reciprocal sampling grid or lattice.

Aliasing is prevented if the replicated spectra do not overlap.

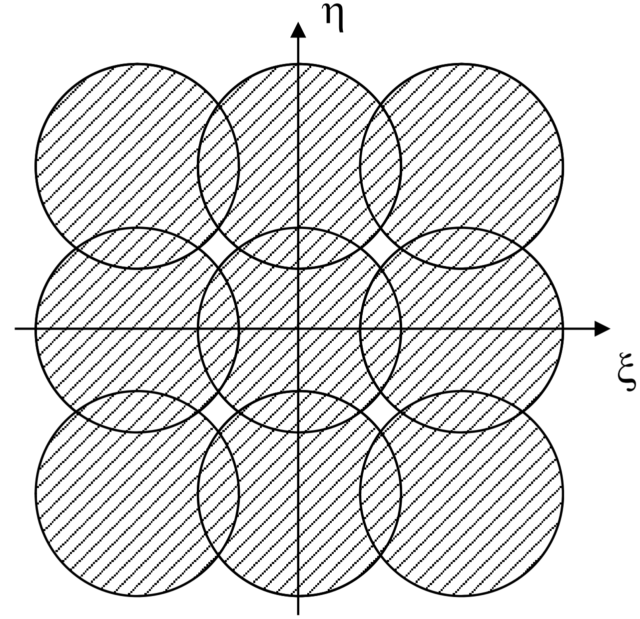


Two-Dimensional Aliasing

Original Image Spectrum



Aliased Image Spectrum



Nyquist Domains

The maximum area that the filtered image spectrum can occupy without aliasing is called the Nyquist domain.

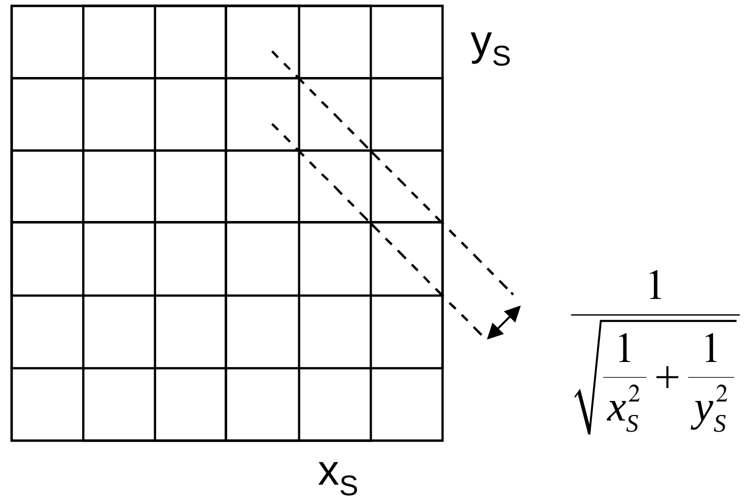
It is exactly analogous to the one-dimensional Nyquist frequency.

The one-dimensional Nyquist frequencies of the sensor are found at the edge of the domain.

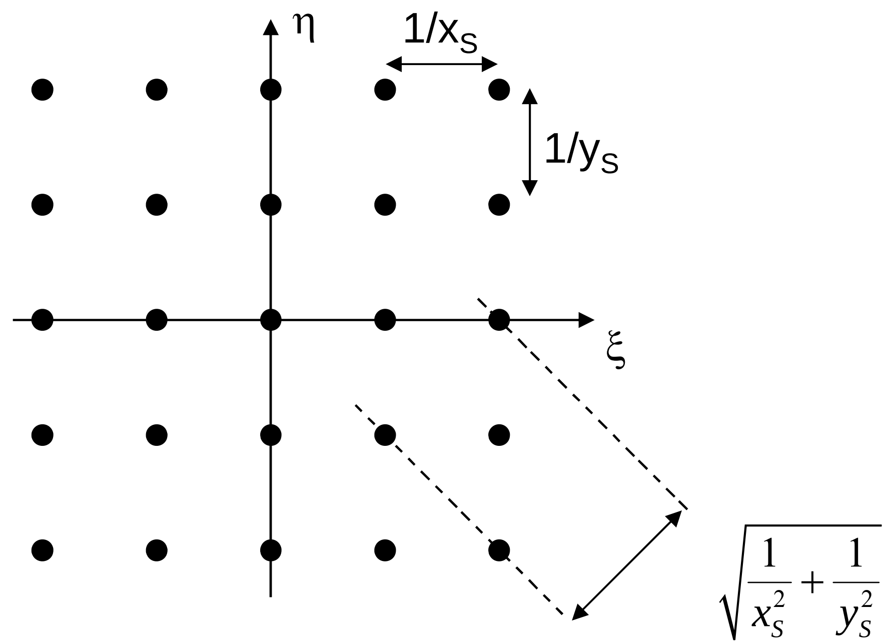
The collection of Nyquist domains will "tile" all of frequency space.

Reciprocal Sampling Grid

Sensor

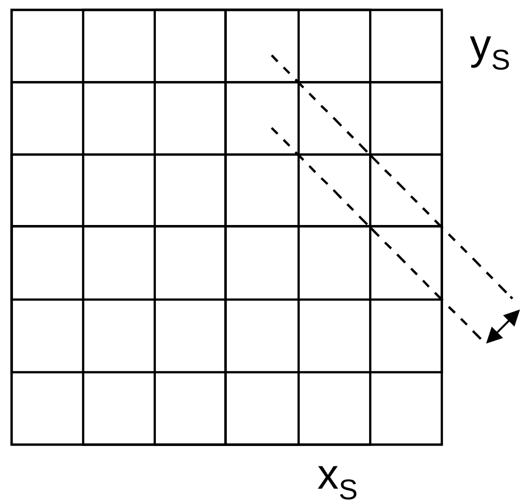


Reciprocal Sampling Grid



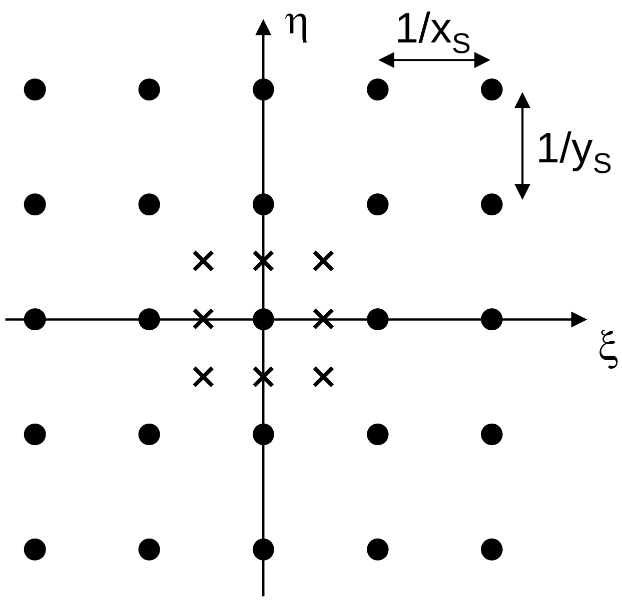
Nyquist Domains

Sensor

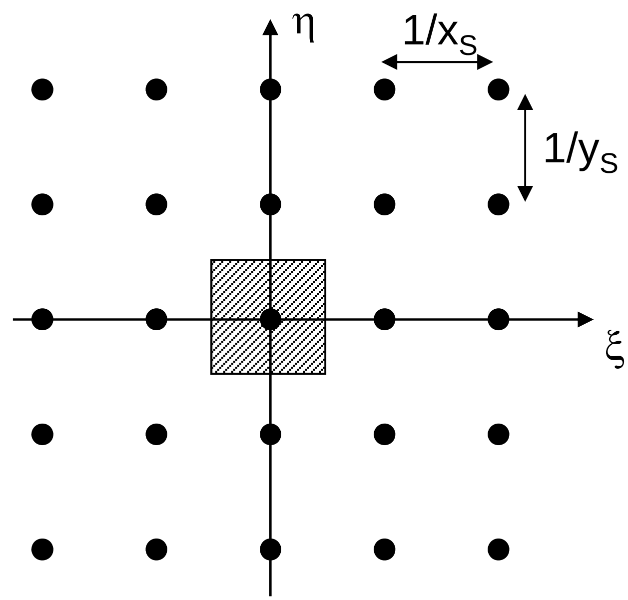


$$\frac{1}{\sqrt{\frac{1}{x_S^2}+\frac{1}{y_S^2}}}$$

One-Dimensional Nyquist Frequencies



Nyquist Domain



Resolution, Sharpness and Aliasing

For a rectangular sampling grid, the maximum resolution (largest Nyquist frequency) occurs along the diagonals.

The two-dimensional pixel MTF within the Nyquist domain defines the image sharpness.

The amount of the pixel MTF that extends beyond the Nyquist domain is a measure of the susceptibility of the system to aliasing artifacts.

The eye is more sensitive to horizontal and vertical frequencies, so the rectangular Nyquist domain is not optimum.

To change the shape of the Nyquist domain, non-rectangular sampling grids are used.

One example is a staggered array where every other row is shifted by a half pixel spacing.

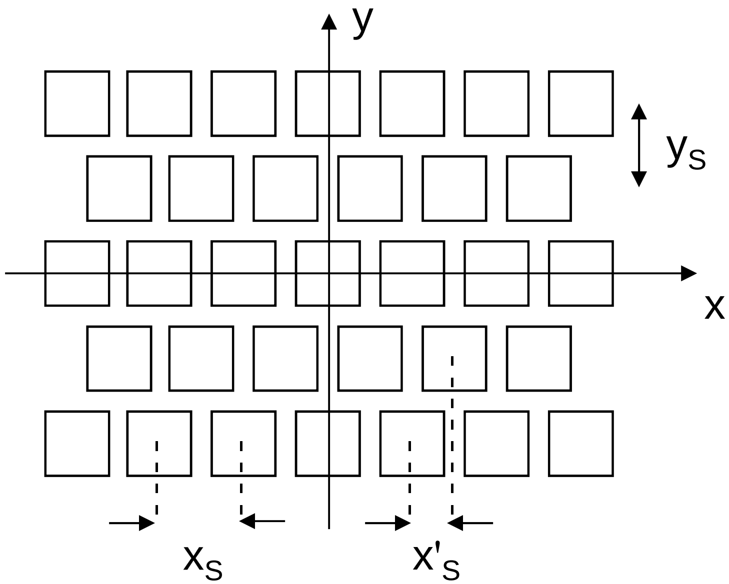
<u>Non-Rectangular Sampling Grid</u>

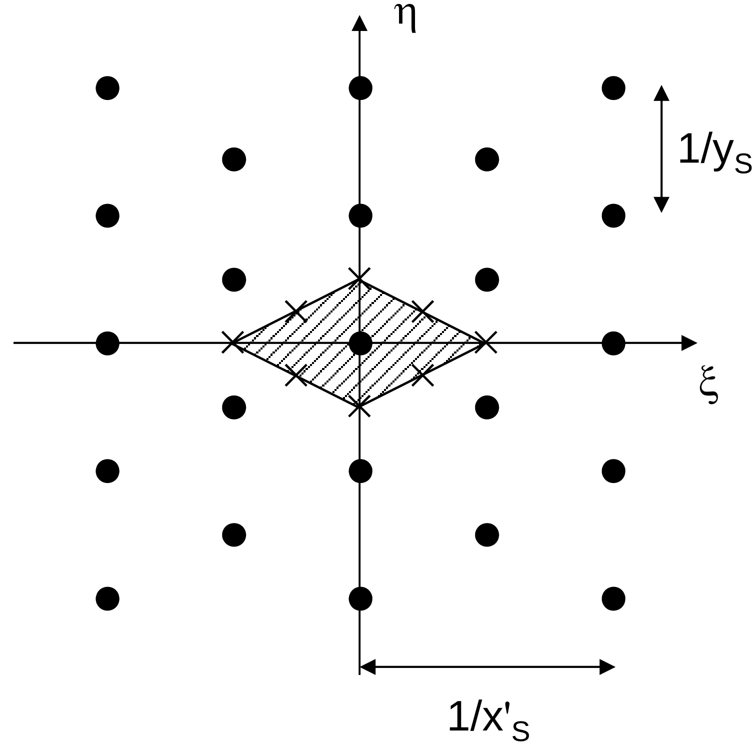
Grid: $$x'_S = \frac{x_S}{2}$$

$$\operatorname{comb}\left(\frac{x}{2x'_S} + \frac{y}{2y_S}, \frac{-x}{2x'_S} + \frac{y}{2y_S}\right)$$

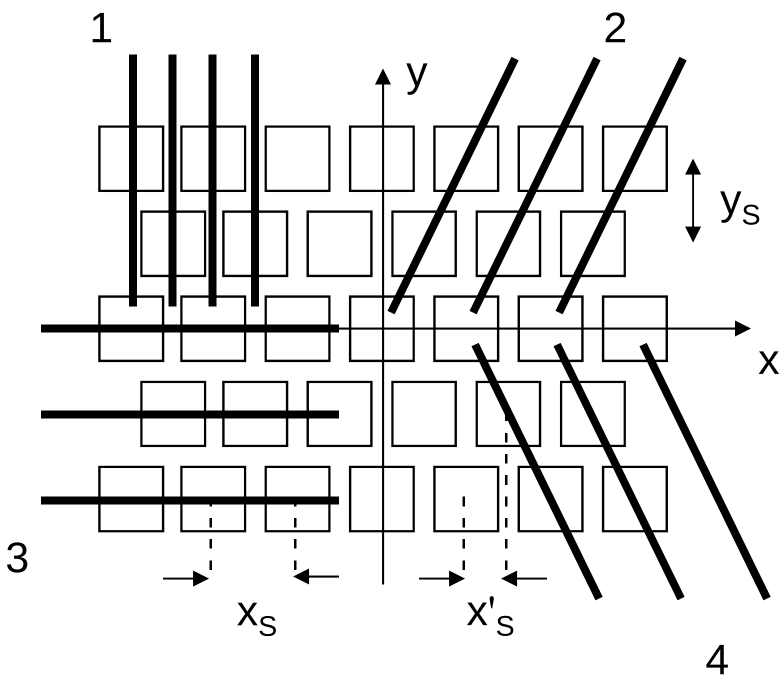
Reciprocal Grid:

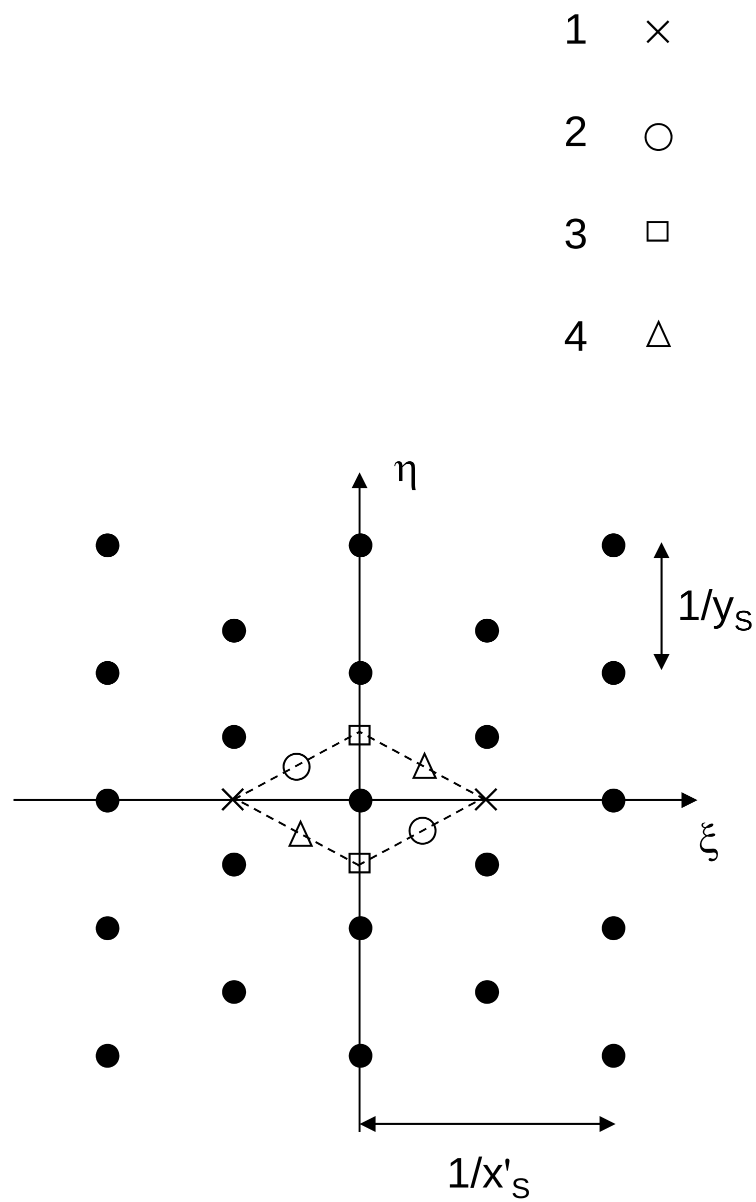
$$\operatorname{comb}\left(x'_S\xi + y_S\eta, -x'_S\xi + y_S\eta\right)$$





Nyquist Frequencies of the Non-Rectangular Sampling Grid





Note that the horizontal resolution has been increased by a factor of two over the vertical resolution.

The vertical resolution is unchanged from the rectangular array.

System Design and Optimization

Two-Dimensional Effective Pivels:

For area sensors:

- The effective pixel is the actual active area convolved with the blur PSF and possibly the lens PSF.

For scanned systems:

- Examples are scanned linear arrays and flying spot scanners.
- The effective pixel is the active area of the scanning spot or detector convolved with the motion of this area during the measurement. The blur PSF and the lens PSF can also be added.

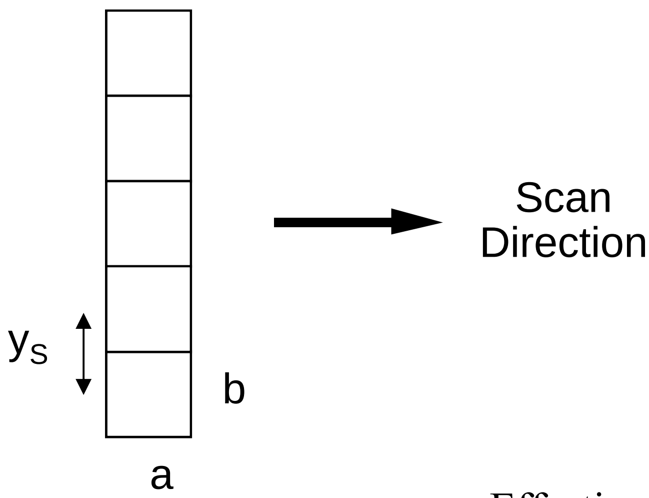
The rules for two-dimensional systems are very much the same as one-dimensional systems.

Once the Nyquist frequencies are chosen, there is a sharpness-aliasing tradeoff that must be optimized for the particular application.

For consumer systems, the optimum situation is approximately $G = 1$ in both directions. The effective pixels would then be contiguous.

Two-dimensional blur filters can be constructed to appropriately filter the image for this goal.

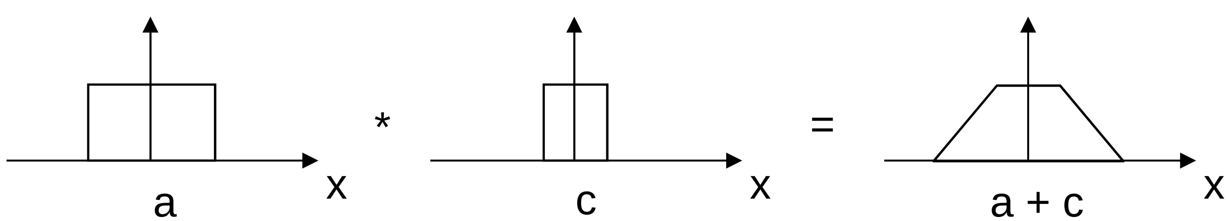
Linear Scanner Array



The detector array or the image moves a distance c during the collection of a sample.

Effective Pixel: $\mathrm{rect}\left(\frac{x}{a},\frac{y}{b}\right) * \mathrm{rect}\left(\frac{x}{c}\right)$

Pixel Width in x: $\approx a + c$



The effective pixel aperture will be non-uniform.

Monochrome Imagers and Blur Filters

For many applications, monochrome video sensors do not require blur filters.

The raw G factors are about 1.

The need can arise in special applications:

- Scanning Text
- Scanning Halftoned Images
- Applications where no aliasing is permitted (medical)

Color Cameras

Broadcast quality TV cameras often contain three video imaging devices that are synchronously operated. The optical system, through dichroic beamsplitters, splits the colors to the three individual sensors.

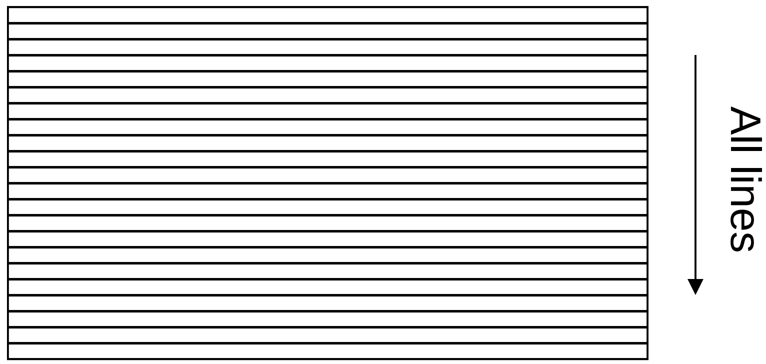
A single-sensor color camera (still or video) can be considered to be three spatially multiplexed sensors in one.

The "three" sensors are produced by the application of color filter arrays (CFA's) to the active area of the sensor. Signals are demultiplexed to R, G and B.

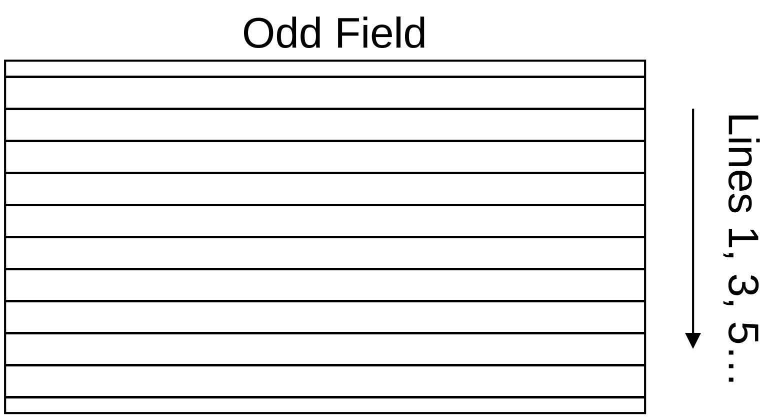
To first order, the image quality of the system can be determined by examining each of the three multiplexed colors independently.

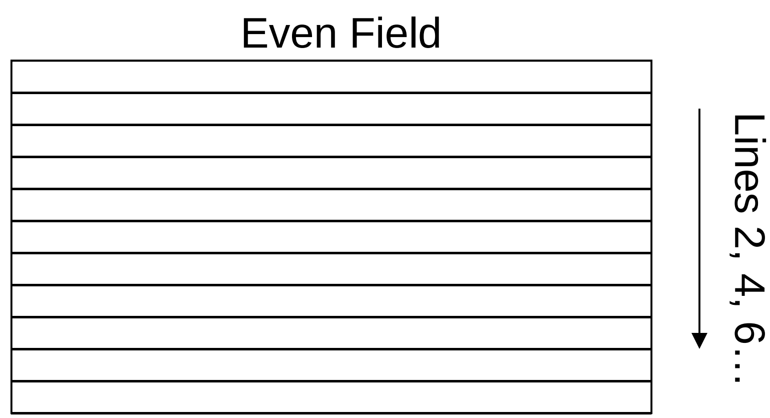
Progressive Scan and Interlaced Video

In progressive scan, all of the video lines are captured and displayed in a single frame. Digital still cameras can be considered in this classification (only a single frame is captured.)



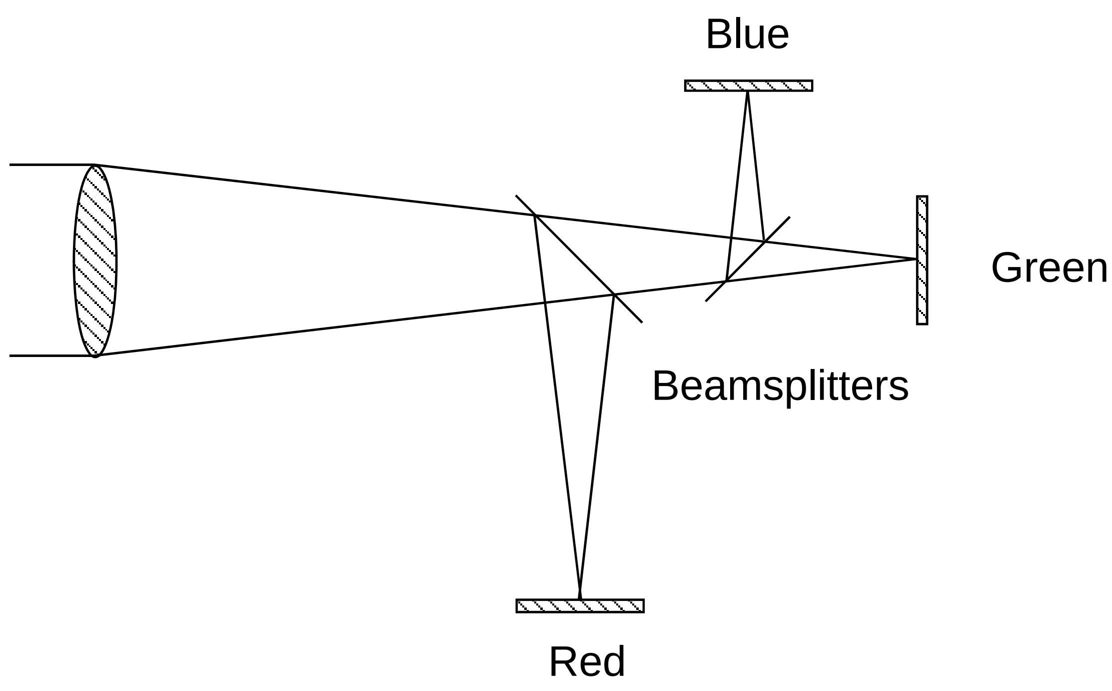
In an interlaced system, the video lines are displayed half at a time in two fields:





For aliasing considerations, both fields must be considered together. They are independently displayed and the eye's temporal response integrated them into a single image.

Three Sensor Camera



Because there is a full sensor for each color, aliasing is usually not severe with this system.

CFAs and Aliasing

The application of the CFA to the sensor reduces the duty cycle of the pixels in each color. The individual G's are now much less than one.

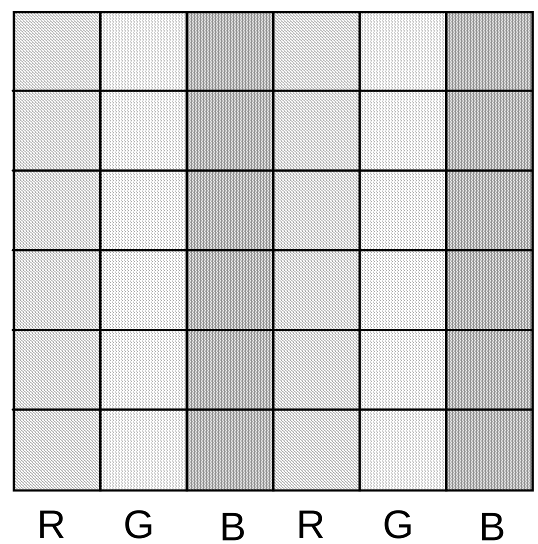
As a result, the sensor is very susceptible to aliasing in each color, and a blur filter is needed to correct this problem.

Birefringent blur filters are common in high-end still digital cameras (DSLRs) and video cameras.

The missing pixel signals in each color must be interpolated to create estimates of the three color signals at all of the pixel locations. The existing signals at the measured pixels are not changed.

An example is the striped pattern, where the three colors are applied to alternate columns of pixels.

Vertical G ≈ 1
Horizontal G ≈ 1/3
(in each color)



CFA's with cyan, magenta and yellow patches are also used.

CFA Nyquist Domains

The effects of various CFA patterns on the Nyquist domains and G-factors of the sensor can be analysed.

A sensor of contiguous pixels (G = 1) is assumed, so that the G-factor in each color must be further modified for the base pixel width-to-pitch ratio of the sensor.

The video interlace complicates the choice of a CFA pattern. To simplify matters, patterns for still cameras or progressive scan video sensors will be discussed first.

Three Chip Camera

G	G	G	G	G	G
G	G	G	G	G	G
G	G	G	G	G	G
G	G	G	G	G	G
G	G	G	G	G	G
G	G	G	G	G	G

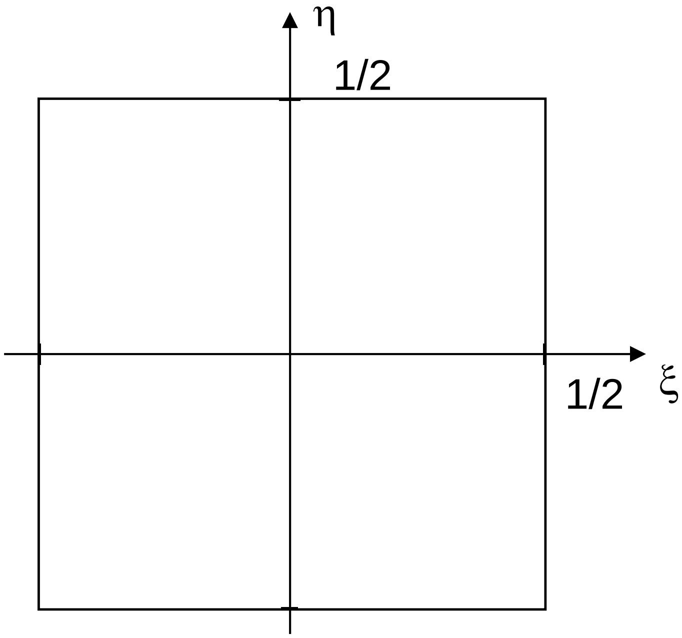
Nyquist frequencies:

Color	H	V
R	1/2	1/2
G	1/2	1/2
B	1/2	1/2

G Factor:

Color	H	V
R	1	1
G	1	1
B	1	1

Nyquist Domains:



Pixel pitch is defined to equal 1

RGB Stripe CFA Pattern

R	G	B	R	G	B
R	G	B	R	G	B
R	G	B	R	G	B
R	G	B	R	G	B
R	G	B	R	G	B
R	G	B	R	G	B

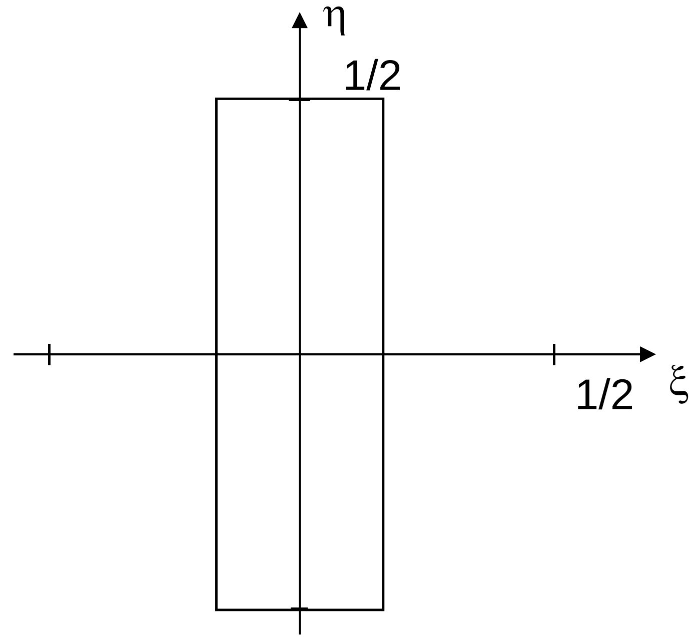
Nyquist frequencies:

Color	H	V
R	1/6	1/2
G	1/6	1/2
B	1/6	1/2

G Factor:

Color	H	V
R	1/3	1
G	1/3	1
B	1/3	1

Nyquist Domains:



Pixel pitch is defined to equal 1

The vertical characteristics are unchanged from a monochrome camera.

Unequal Pixel Densities for R, G & B

Most of the TV detail or luminance signal is generated from the Green samples.

Only low resolution Red and Blue signals are needed to provide color information.

Unequal pixel densities make better use of the available pixels.

RGBG Stripe CFA Pattern

R	G	B	G	R	G
R	G	B	G	R	G
R	G	B	G	R	G
R	G	B	G	R	G
R	G	B	G	R	G
R	G	B	G	R	G

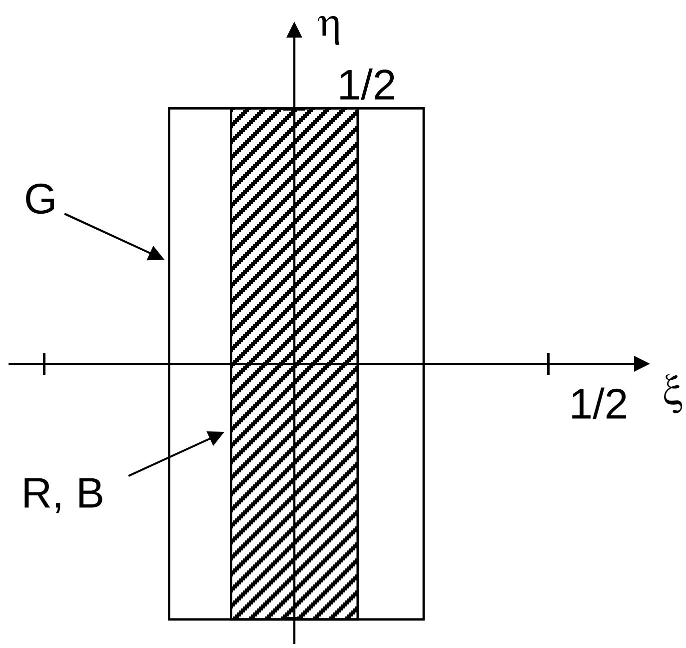
Nyquist frequencies:

Color	H	V
R	1/8	1/2
G	1/4	1/2
B	1/8	1/2

G Factor:

Color	H	V
R	1/4	1
G	1/2	1
B	1/4	1

Nyquist Domains:



Pixel pitch is defined to equal 1

Bayer Checkerboard CFA Pattern

G	R	G	R	G	R
B	G	B	G	B	G
G	R	G	R	G	R
B	G	B	G	B	G
G	R	G	R	G	R
B	G	B	G	B	G

Nyquist frequencies:

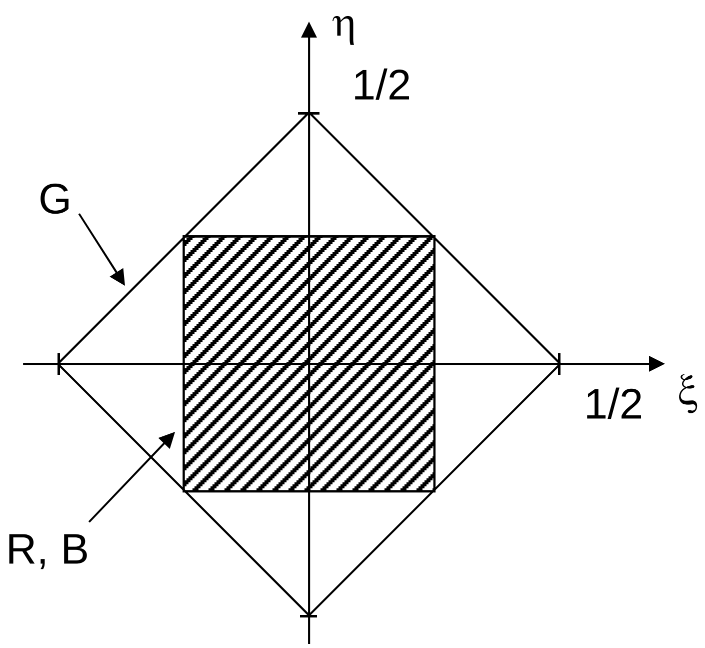
Color	H	V
R	1/4	1/4
G	1/2	1/2
B	1/4	1/4

G Factor:

Color	H	V
R	1/2	1/2
G	1/2 (1)*	1/2 (1)*
B	1/2	1/2

* Line (Sensor)

Nyquist Domains:

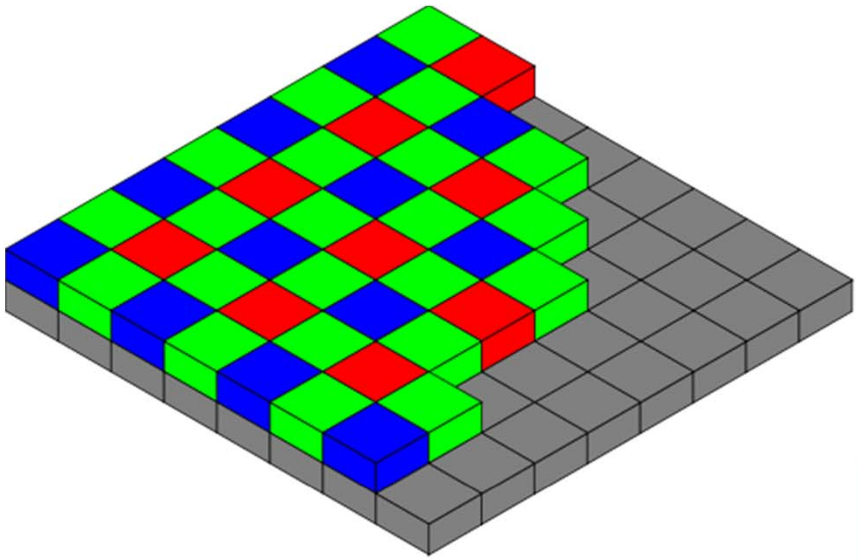


The Green checkerboard provides full vertical and horizontal resolution.

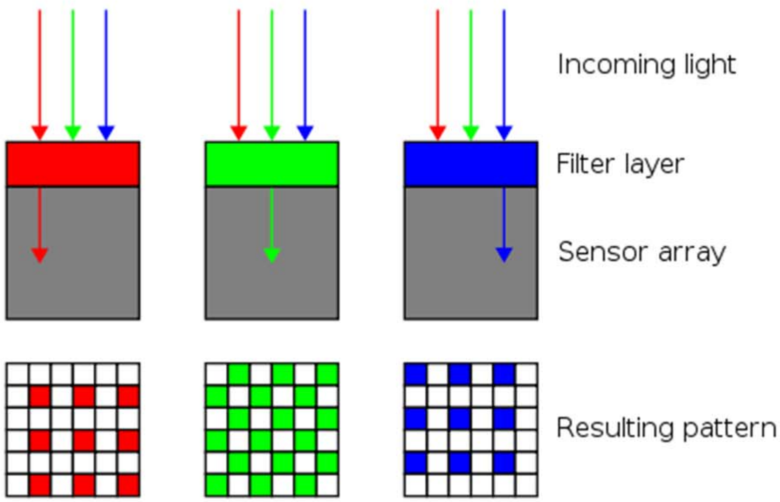
Pixel pitch is defined to equal 1

Bayer Checkerboard CFA Pattern

The Bayer Checkerboard CFA or Filter Mosaic is used on most single-chip digital cameras.



Several variations have been produced including sensors where some of the Green pixels have been replaced by White.



Wikipedia

Bryce E. Bayer
Eastman Kodak Co
U.S. Patent 3,971,065 (1976)

<u>Checkerboard Sampling Grid</u>

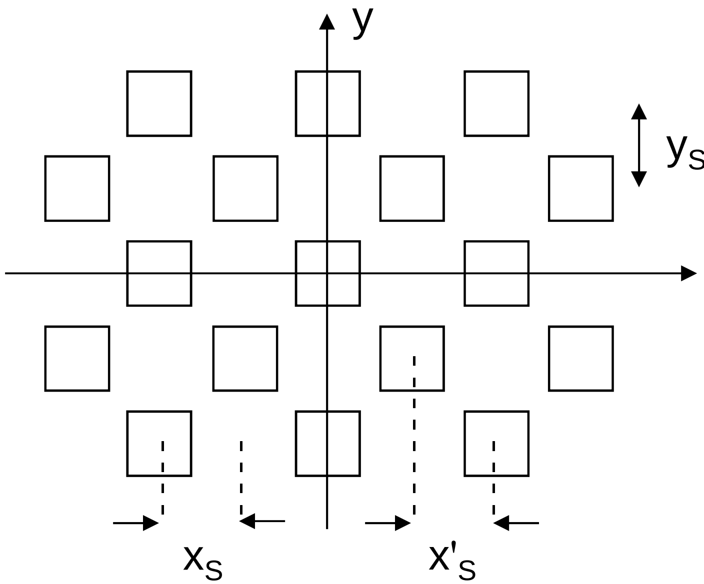
Special case of the non-rectangular sampling grid where the pixel offset $x'_S = x_S$

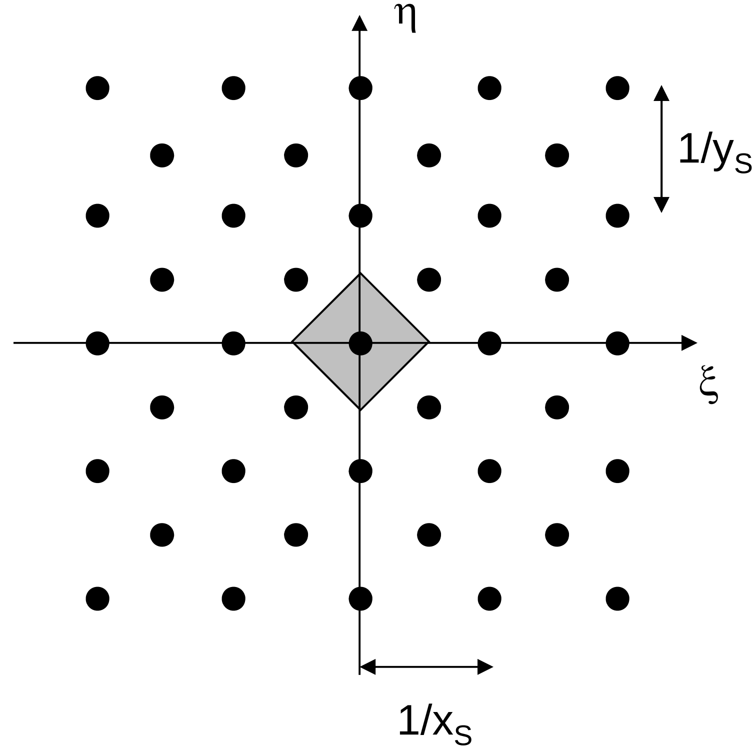
Grid: $x'_S = x_S$

$$\mathrm{comb}\left(\frac{x}{2x_S}+\frac{y}{2y_S},\frac{-x}{2x_S}+\frac{y}{2y_S}\right)$$

Reciprocal Grid:

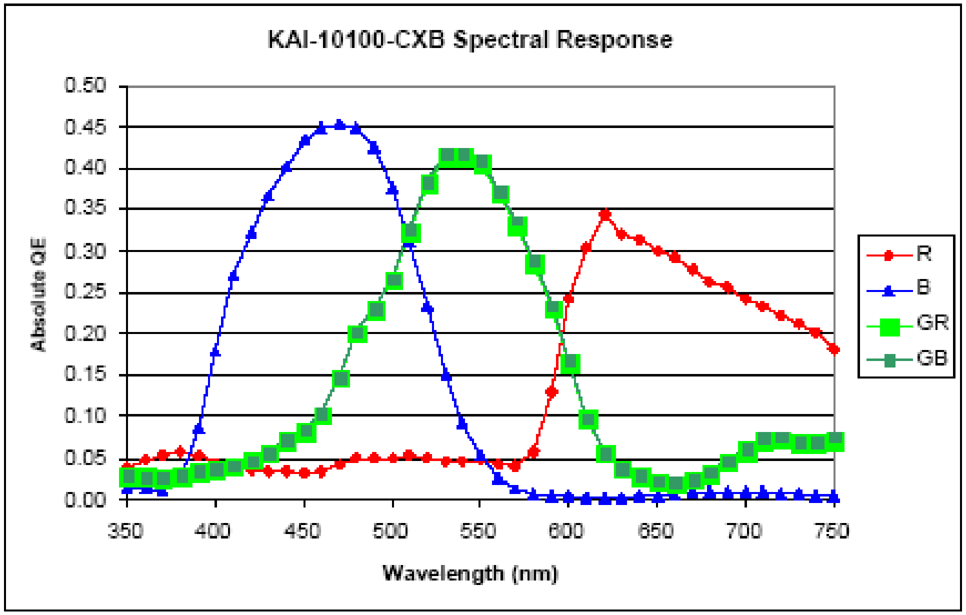
$$\mathrm{comb}\left(x_S\xi + y_S\eta, -x_S\xi + y_S\eta\right)$$





The "missing" pixels add additional points to the reciprocal sampling grid corresponding to the full sensor.

Color Filter Array Response

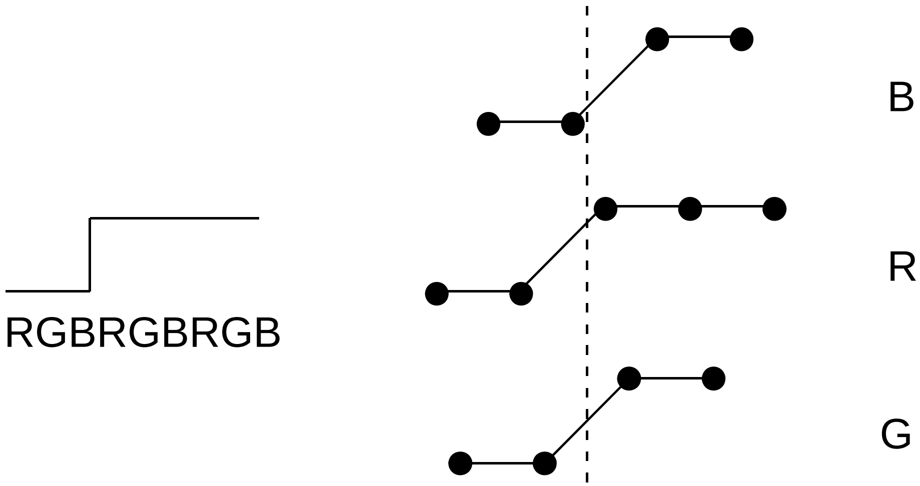


Eastman Kodak Company

Would usually be used with an IR blocking filter.

Color Coincidence

The three colors are measured at different locations on the sensor. A monochrome edge is imaged with colored edge artifacts.



These effects are related to aliasing, and can be explained by including the pixel shift or the phase in frequency space.

Interpolation algorithms are used to evaluate the signal at the "missing" pixels.

Blur filters help to eliminate this kind of artifact and are used with these algorithms.

Checkerboards and Interlaced Sensors

The use of two video fields to complete one video frame greatly complicates the choice of the CFA pattern.

Unless a video field store is used, all data required to interpolate the missing color signals within a field must be present within that field.

This situation usually results in the use of an irregular sampling grid. The sampling pattern cannot be expressed as a simple comb function. The sampling pattern is different for G and R or B.

G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

Bayer Pattern

- -Red on odd lines
- -Blue on even lines
- -Requires a field memory

Checkerboards and Interlaced Sensors

G	R	G	R
G	R	G	R
B	G	B	G
B	G	B	G

Modified Bayer Pattern

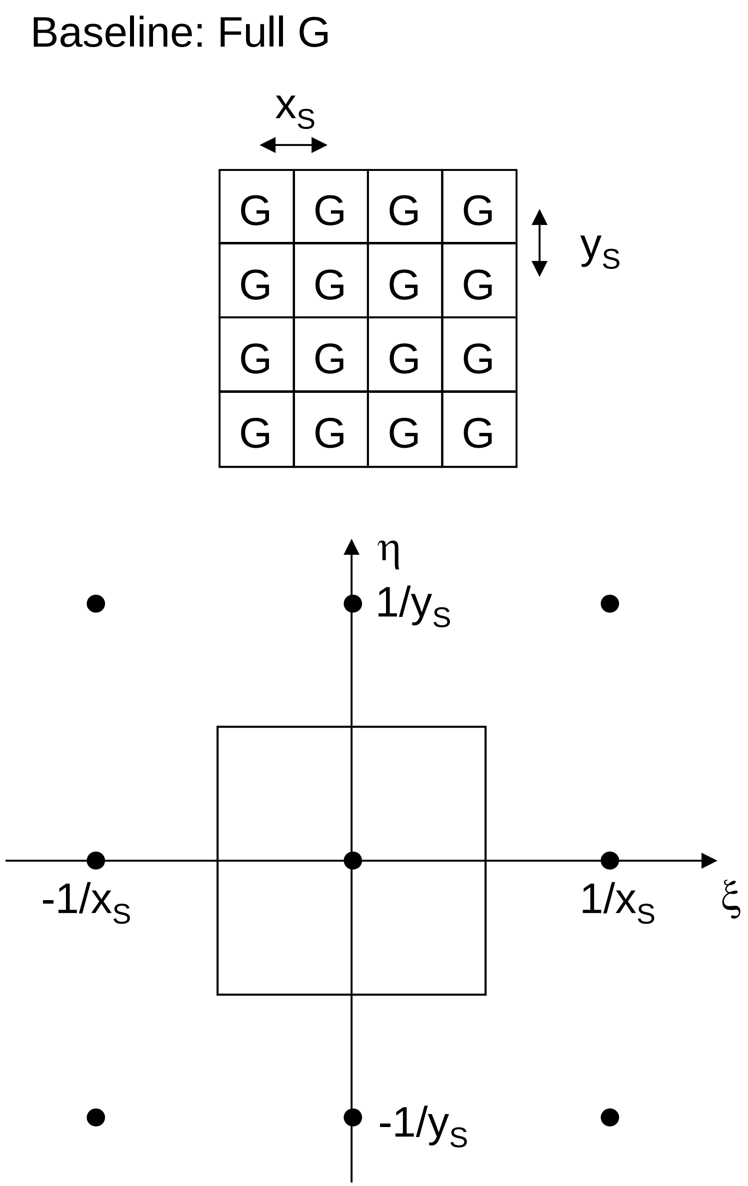
- -Repeats Bayer pattern
- -Red and blue available in both fields
- -Line store needed to interpolate missing R and B lines in each field

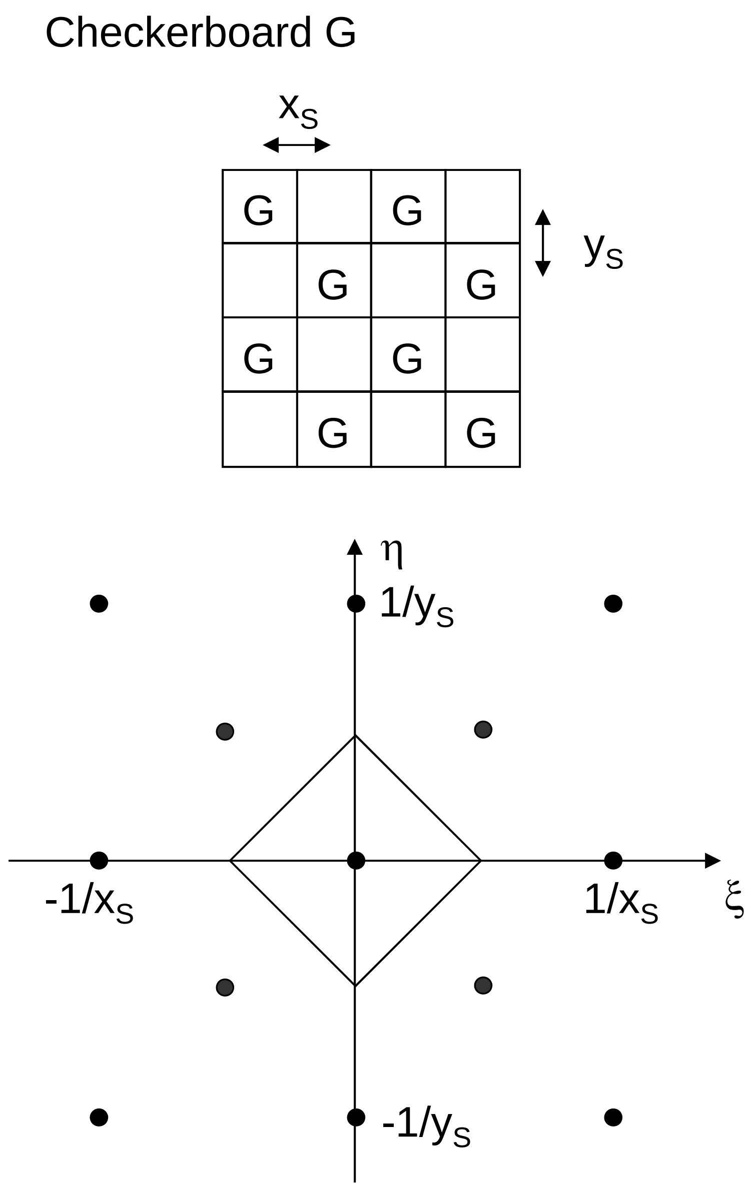
G	R	G	R
G	B	G	B
B	G	B	G
R	G	R	G

Green Checker Field Sequence Pattern

- -Similar to Modified Bayer
- -Each column contains R,G and B pixels

Reciprocal Sampling Grids

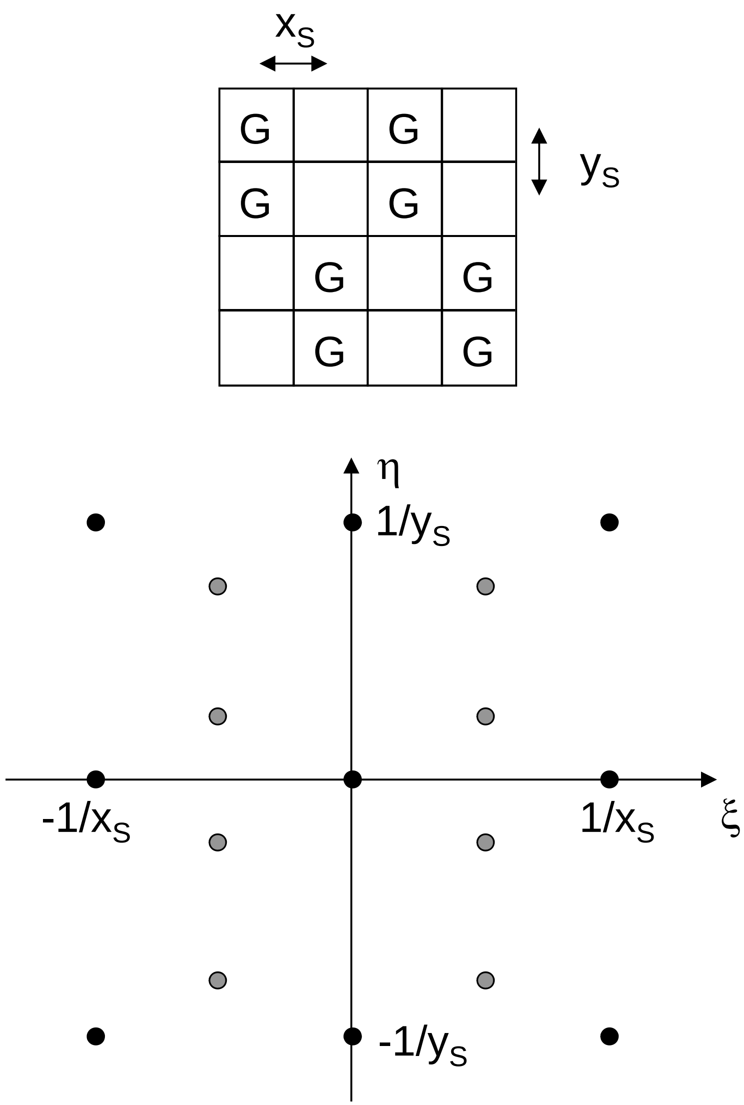




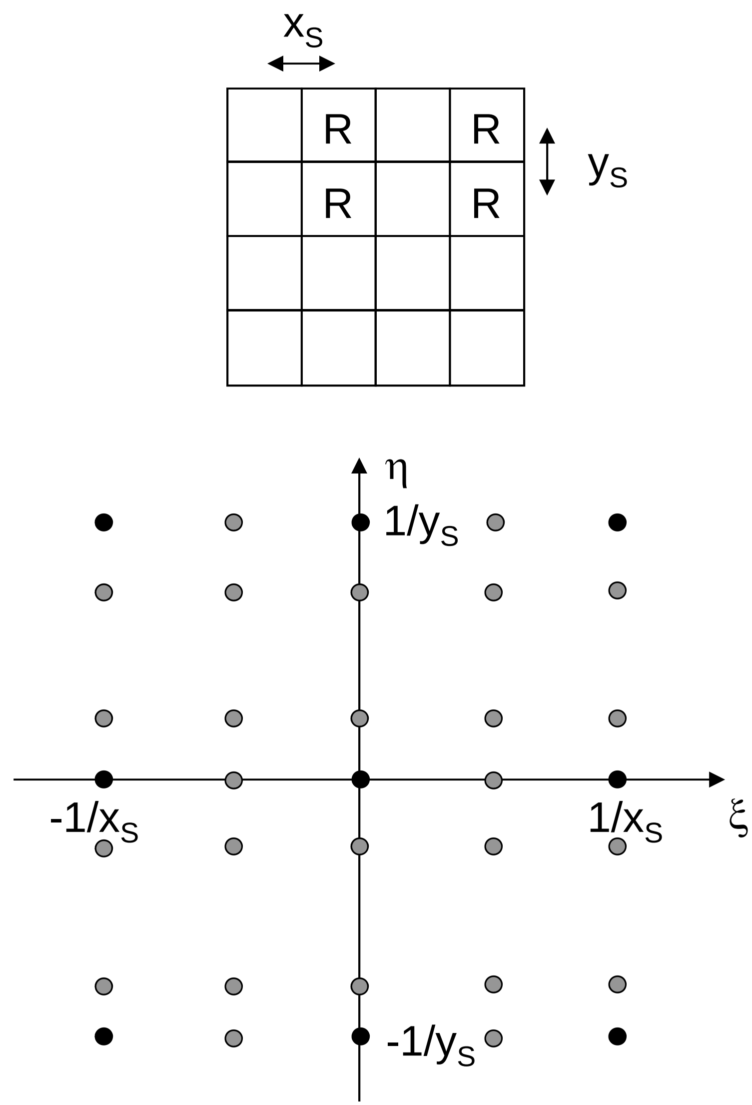
Reciprocal Sampling Grids

Note: The additional delta functions in the reciprocal grid have varying amplitudes.

Repeated G Checkerboard



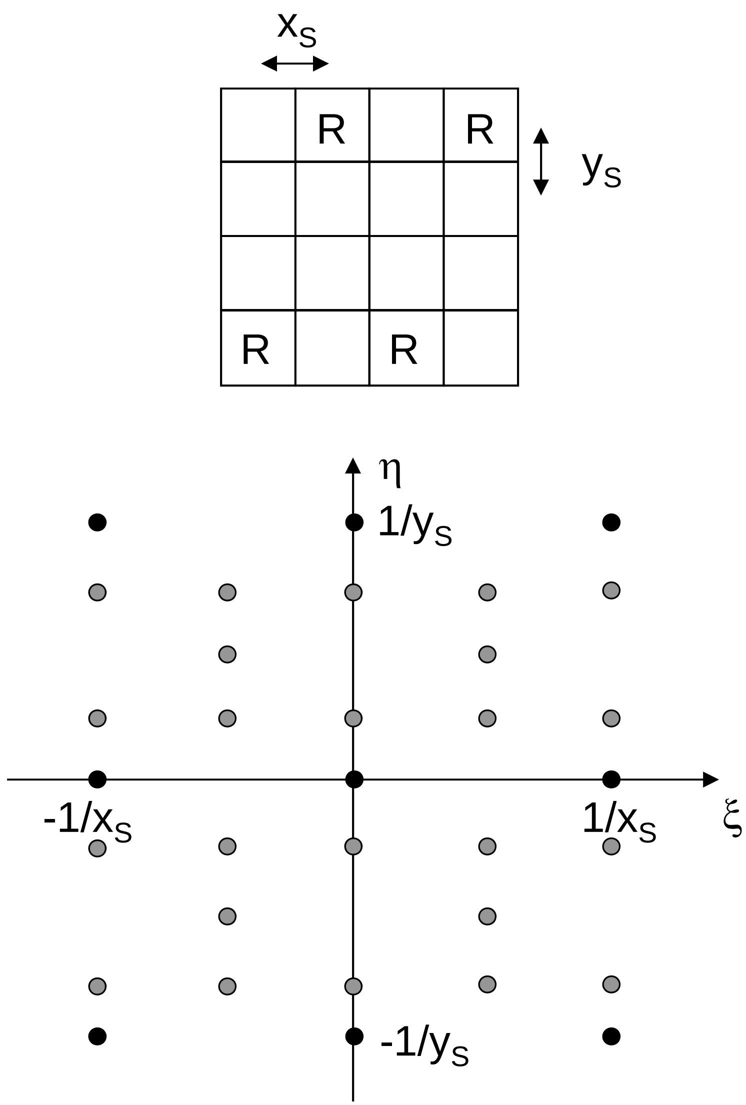
Repeated Checkerboard R Samples



Reciprocal Sampling Grids

Note: The additional delta functions in the reciprocal grid have varying amplitudes.

Green Checkerboard Field Sequence R Samples

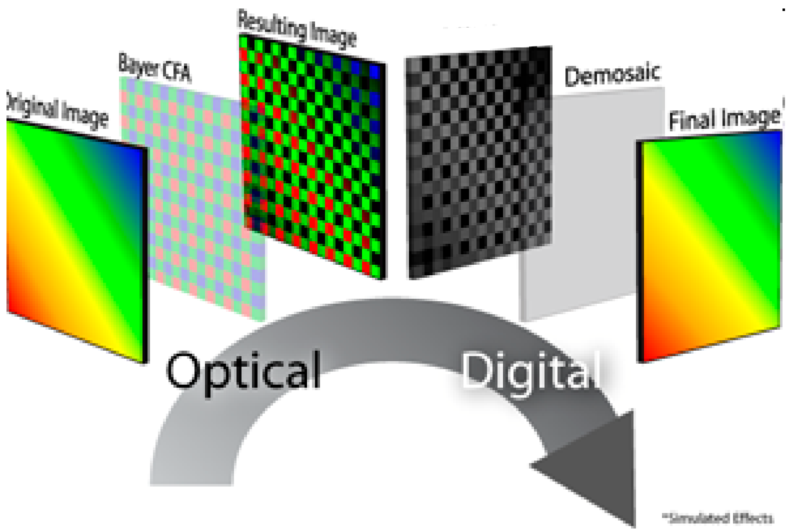


Interpolation and CFAs

The first step in the interpolation process is to create estimates of the three color signals at all of the pixel locations. This process is also know as to demosaic the image.

These signals at the missing pixels are often the averages of the adjacent pixel signals of the appropriate color.

The existing signals at the measured pixels are not changed.

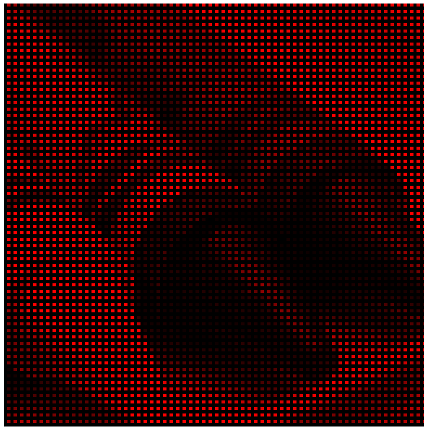


Wikipedia

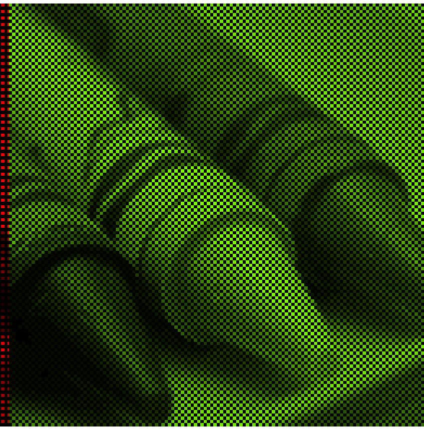
Unless the system has a full field store, the interpolation must use only the data from within a video field.

This is an additional space-variant processing step.

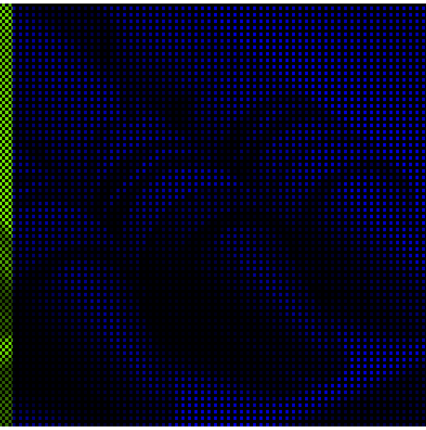
<u>Interpolation and the Bayer Checkerboard Sensor</u>



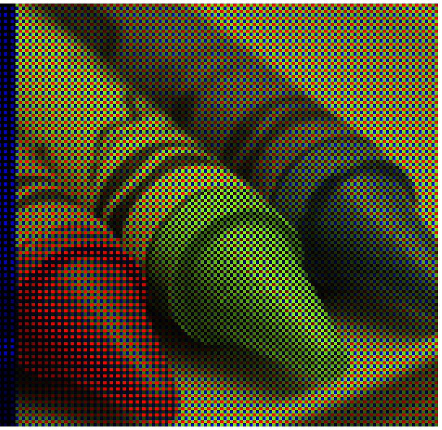
Red (25% of Pixels)



Green (50% of Pixels)



Blue (25% of Pixels)



Combined

Red Interpolated

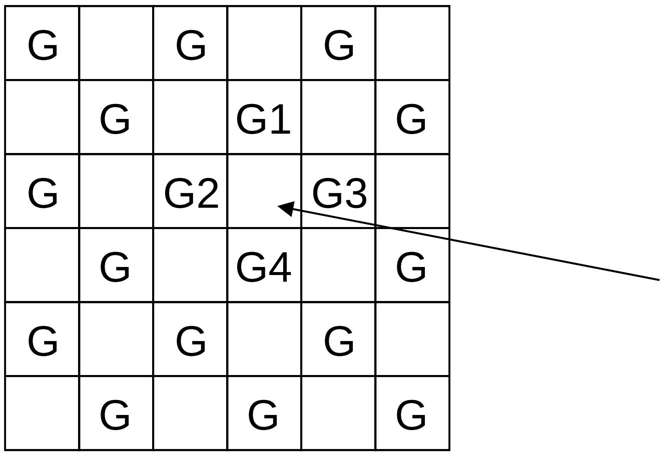
Green Interpolated

Blue Interpolated

Combined

http://www.dpreview.com/learn

Missing Green Interpolation

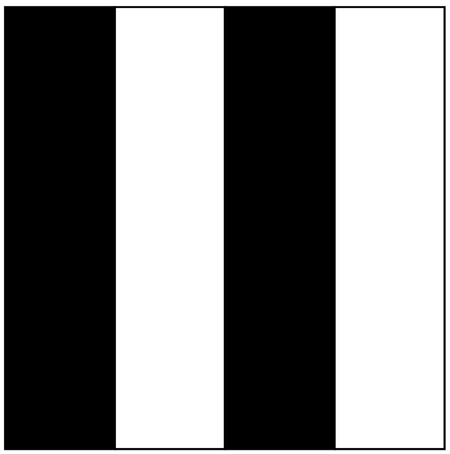


A simple interpolation algorithm for the missing G sample:

Missing G ≈ (G1 + G2 + G3 + G4)/4

Interpolation Example - Checkerboard

Input



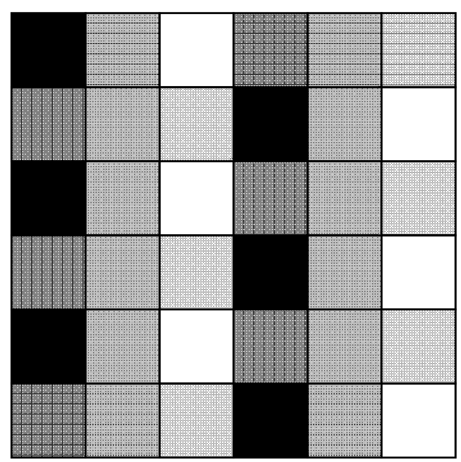
Recorded Samples

	X	1/2	X	0	X	1	
X	0	X	1	X	1/2	X	0
1	X	1/2	X	0	X	1	X
X	0	X	1	X	1/2	X	0
1	X	1/2	X	0	X	1	X
X	0	X	1	X	1/2	X	0
1	X	1/2	X	0	X	1	X
	0	X	1	X	1/2	X	

Interpolated Samples

0	1/2	1	3/8	1/2	5/8
3/8	1/2	5/8	0	1/2	1
0	1/2	1	3/8	1/2	5/8
3/8	1/2	5/8	0	1/2	1
0	1/2	1	3/8	1/2	5/8
3/8	1/2	5/8	0	1/2	1

Display



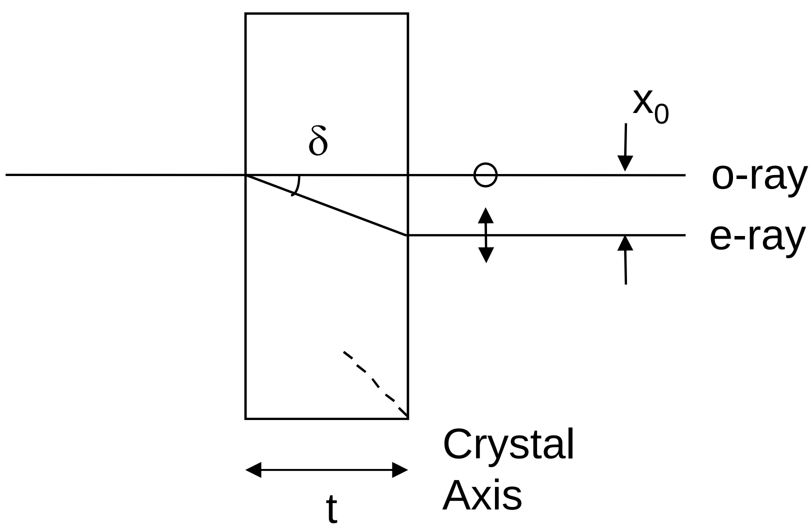
Birefringent Blur Filter Design

Constructed out of stacks of quartz double refraction plates.

The orientation and thickness of the plates determines the blur pattern.

Since the output of each plate is polarized, the orientation of the plates will determine the relative spot intensities.

For n plates, the maximum number of spots in the blur PSF is 2^n.



Crystalline Quartz:

Deviation angle $\delta = 0.34°$

$$x_0 = t\tan(\delta)$$

For a 12 µm spot separation, the plate should be 2 mm thick.

Birefringent Blur Filter Materials

For sensors with large pixel spacings (especially in digital single lens reflex cameras), the quartz plate thickness can be prohibitively thick for mechanical clearances due to the fold mirror and shutter.

An alternative and much more expensive material is lithium niobate $LiNbO_3$.

Crystalline Quartz SiO_2:

$\Delta n = 0.00917$

$n_o = 1.5443$
$n_e = 1.5534$

Deviation angle $\delta = 0.34°$

For a 12 μm spot separation, the plate should be about 2 mm thick.

Lithium Niobate $LiNbO_3$:

$\Delta n = -0.085$

$n_o = 2.272$
$n_e = 2.187$

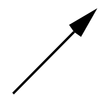
Deviation angle $\delta = -2.18°$

For a 12 μm spot separation, the plate should be about 0.3 mm thick.

$$\tan(\delta) = \frac{1}{2}\left(\frac{n_e}{n_o} - \frac{n_o}{n_e}\right) \qquad x_0 = t\tan(\delta)$$

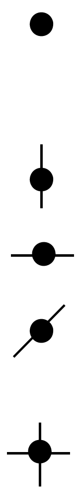
Blur Filter Components

Filter Components:



Double refraction plate:
- Length indicates thickness
- Orientation as indicated
- Arrow indicates deviation of e-ray

Blur Spots:

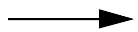


Unpolarized spot

Linearly polarized spot
- Vertical
- Horizontal
- 45° or as indicated

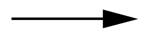
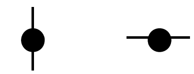
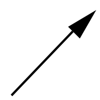
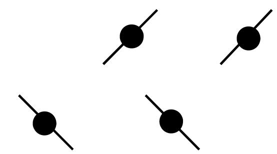
Overlapping linear polarizations

Two Spot Filter

Component	Description	Blur Pattern
	Input	
	Quartz at 0° t=1	 1 - 1

Numbers represent the relative irradiances of the spots in the blur pattern.

Diamond Pattern Filter

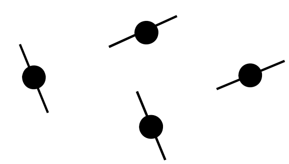
Component	Description	Blur Pattern
	Input	
	Quartz at 0°	
	Quartz at α	

Relative irradiances: $\sin^2\alpha$ $\cos^2\alpha$

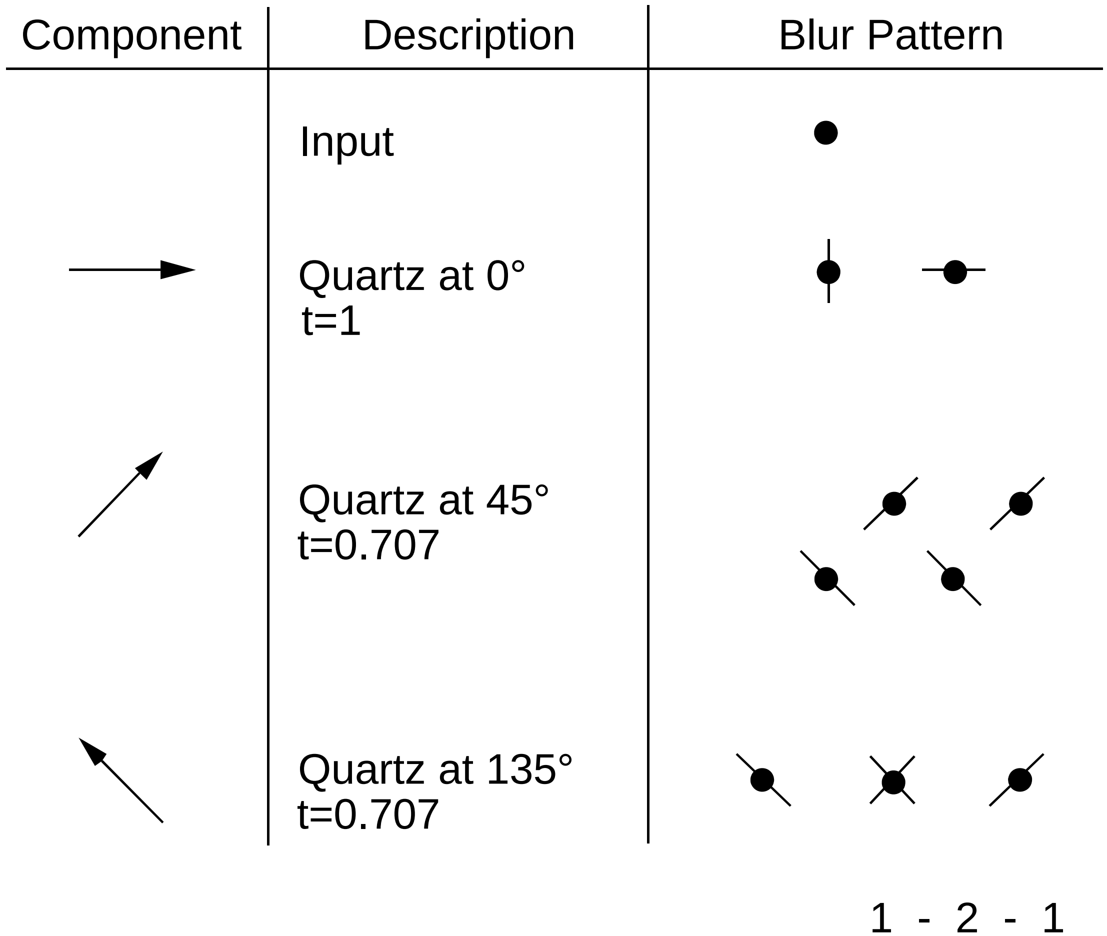
$\cos^2\alpha$ $\sin^2\alpha$

Equal at α = 45°

Orientation at ± $\alpha/2$

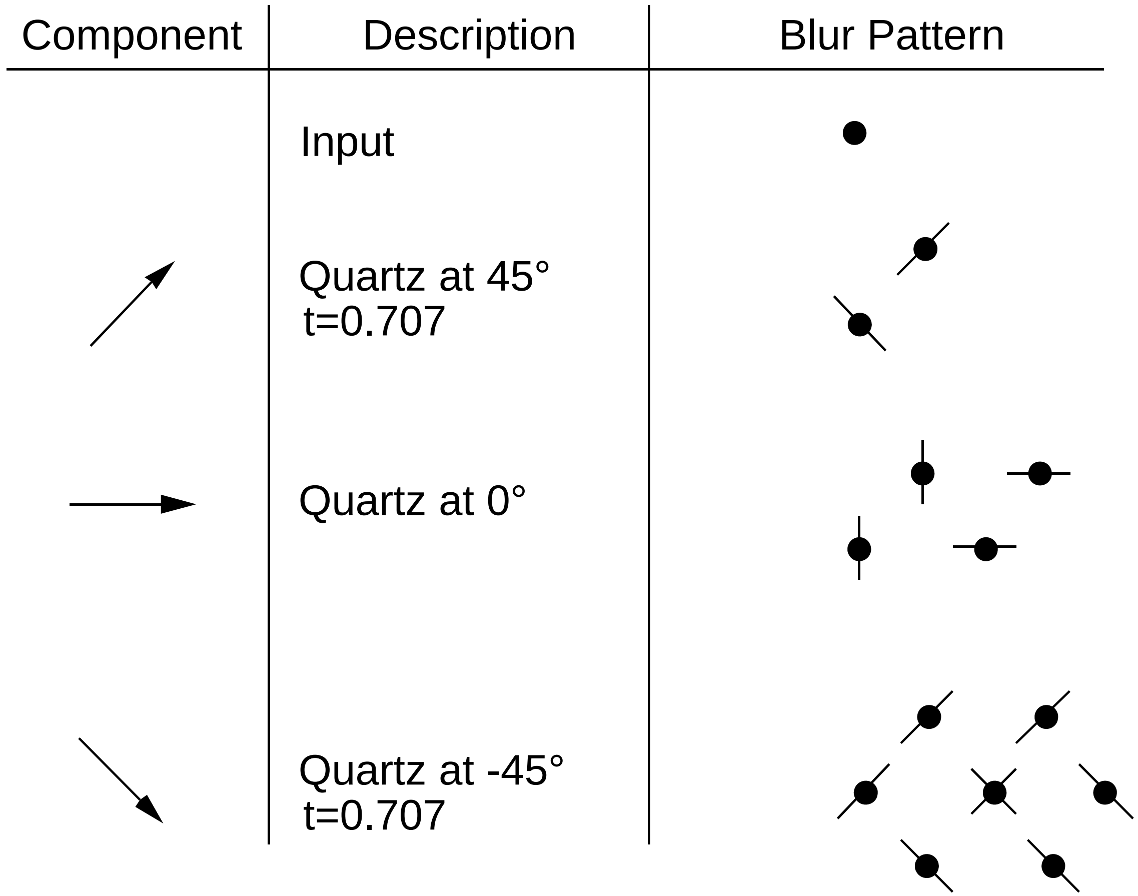


Three Spot Pattern



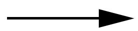
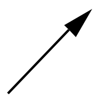
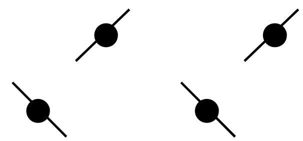
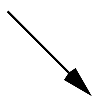
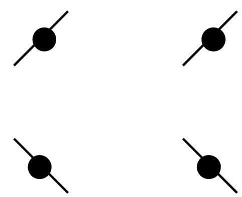
The final plate does not create additional spots.
Four spots are created if the first plate thickness is 2 instead of 1.

<u>Seven Spot Filter</u>



1 - 1
1 - 2 - 1
1 - 1

Four Spot Rectangular Filter

Component	Description	Blur Pattern
	Input	
	Quartz at 0°	
	Quartz at 45° t=0.707	
	Quartz at -45° t=0.707	

1 - 1
1 - 1

A square pattern results when the first plate is t = 1.

Lens Design Issues

For systems that make use of the full sensor resolution:

The lens MTF must support the Nyquist frequencies of the sensor throughout its zoom range. It must do this in all of the spectral bands.

The lens design should compensate for the spherical aberration that is introduced by the plane parallel plates associated with the blur filter and an IR blocking filter. The lens should be designed with these plates as part of the optical system. For the purposes of the optical design, the double refraction of the blur filter is often ignored.

The blur MTF is usually treated separately from the lens design.

For systems that DO NOT make use of the full sensor resolution:

The lens MTF will serve as the limiting factor for anti-aliasing.

The lens MTF must meet the overall system requirements and is now often the limiting factor for the system resolution.

Sensor Sizes

Some typical numbers. Since there is little standardization, the exact numbers will vary.

	Camera Phones		Compact Digital Cameras			
Type	**1/6"**	**1/3.2"**	**1/2.5"**	**1/1.7"**	**DSLR (APS-C)**	**Full Frame 35mm**
Diagonal (mm)	3.00	5.68	7.18	9.50	26-28	43.3
Width (mm)	2.40	4.54	5.76	7.60	22-24	36
Height (mm)	1.80	3.42	4.29	5.70	14.8-16	24
Area (mm²)	4.32	15.5	24.7	43.3	330-375	864

Assuming a 5 megapixel sensor:

Pixel Size (μm)	0.9	1.7	2.2	2.9	8.1-8.7	13

Assuming a 10 megapixel sensor:

Pixel Size (μm)	0.65	1.2	1.6	2.1	5.7-6.1	9.3

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":

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

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

Cell Phone Sensor Sizes

Apple iPhone 5s
- 1/3” Sensor (4.8 x 3.6 mm)
- 8 MP (3264 x 2488) (4:3)
- 1.5 µm pixel size

Samsung Galaxy 5S
- 1/2.6” Sensor (5.95 x 3.35 mm)
- 16 MP (5312x2988) (16:9)
- 1.12 µm pixel size

HTC One M8
- 1/3” Sensor (4.8 x 3.6 mm)
- 4 MP (2688 x 1520) (4:3)
- 2 µm pixel size

Nokia Lumia 1020
- 1/1.5” Sensor (8.8 x 6.6 mm)
- 41.3 MP (7136 x 5360) (4:3)
- 1.2 µm pixel size

All these cameras appear to use lenses between f/2.2 and f/2.5
They have an image quality of a Diffraction Limited Equivalent f/4

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.

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

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

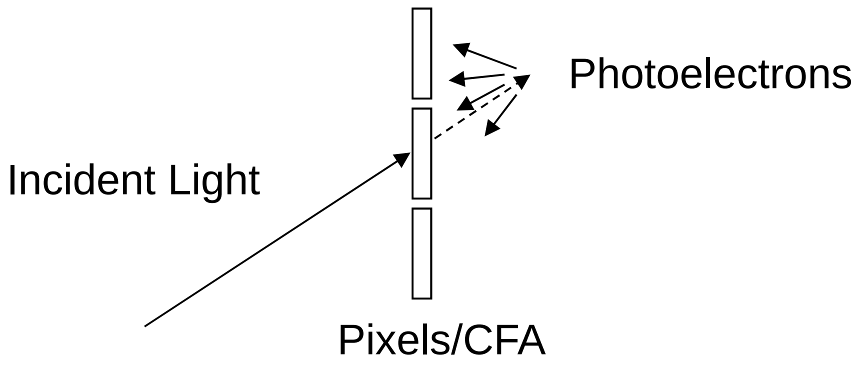
These blur sizes can be scaled by the enlargement ratio from the film to determine a blur requirement for the imaging lens. For a 35 mm negative (24 x 36 mm) enlarged to a 4R print (4 x 6 in), this magnification is about 4X. A blur of 3 mils on the print corresponds to a blur of about .75 mils (19 µm)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

Telecentricity and Pseudo-Telecentricity

The penetration depth for light into the silicon sensor can be several microns (especially for red wavelengths). If the incident light strikes the pixel at an angle (chief ray angle), the location where photoelectrons are produced can be offset from the image plane location.

In the case of small pixels, this penetration depth can be on the same order as the pixel spacing.



This situation can cause crosstalk between the pixels or recorded color samples.

One solution is to design the lens with the ray bundle at the image plane being at as close to normal incidence as possible. The system should be telecentric or nearly telecentric.

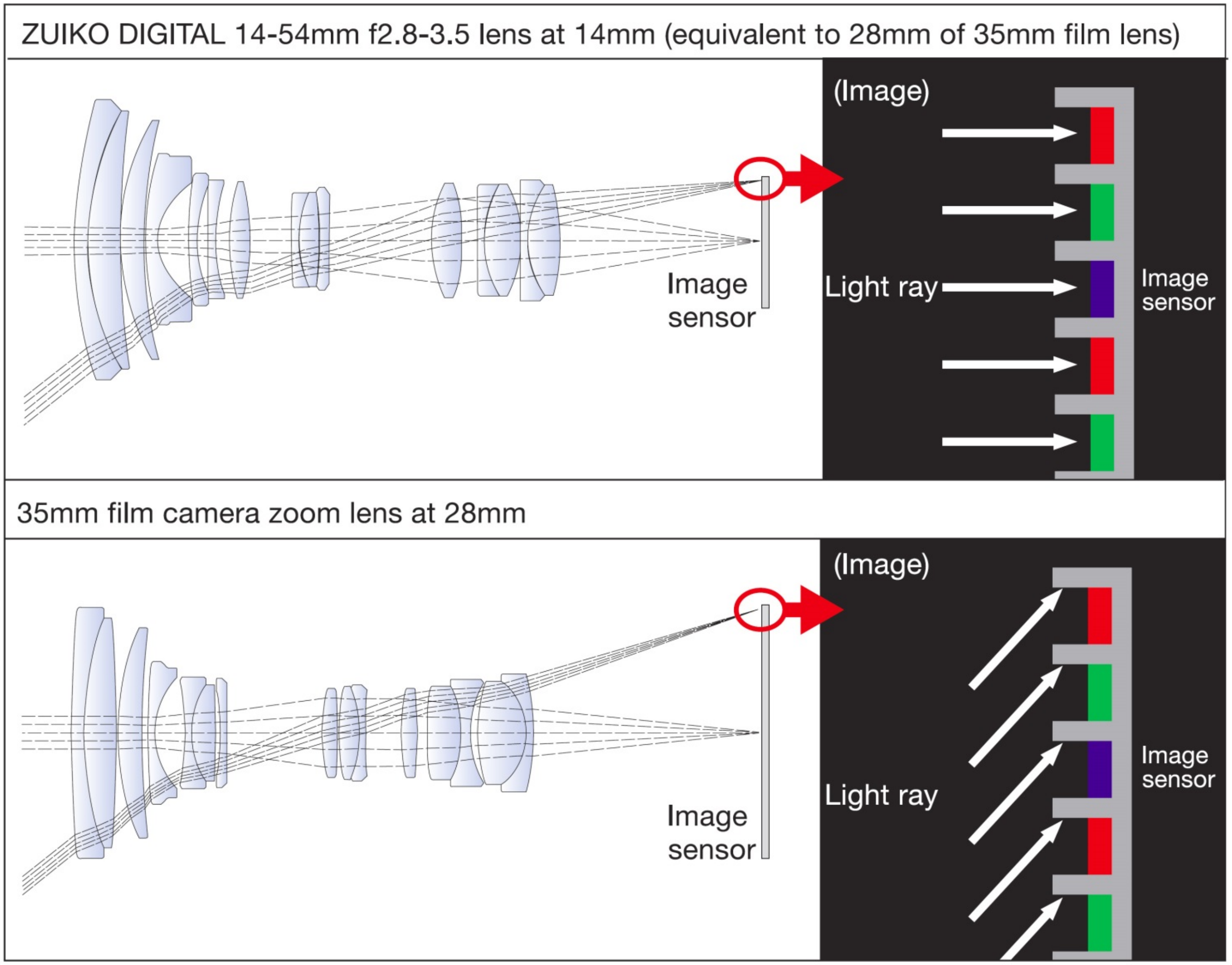
Telecentricity and Pseudo-Telecentricity

Because the stop is the first element of an image space telecentric lens, this configuration is usually not practical in compact systems due to the added length.

Aspheric elements placed near the image plane can introduce pupil aberration and pupil distortion – the pupil shifts with field of view. The system can be made pseudo-telecentric.

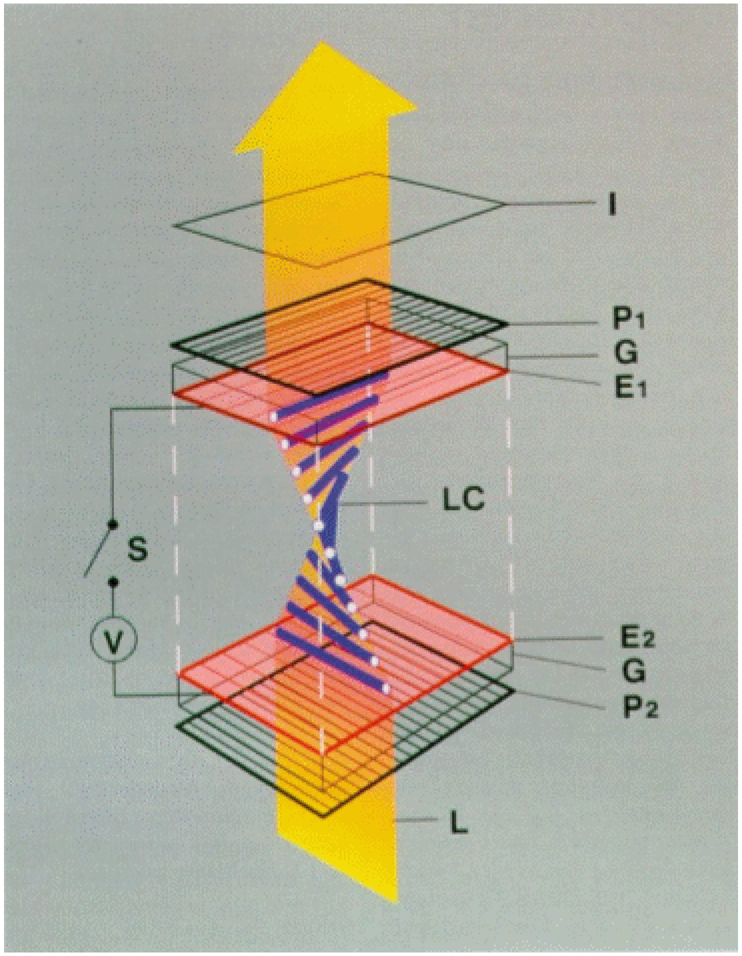
The goal is to move the location of the XP forward.

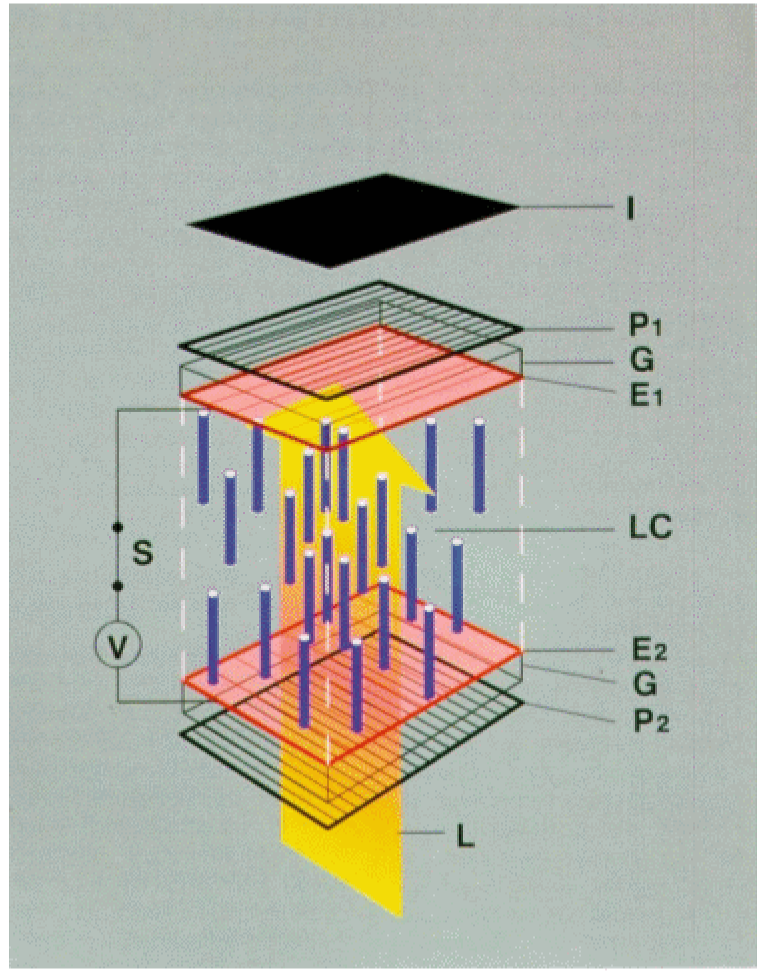
Telecentricity and Pseudo-Telecentricity



olympusamerica.com/cpg_section/cpg_support_faqs

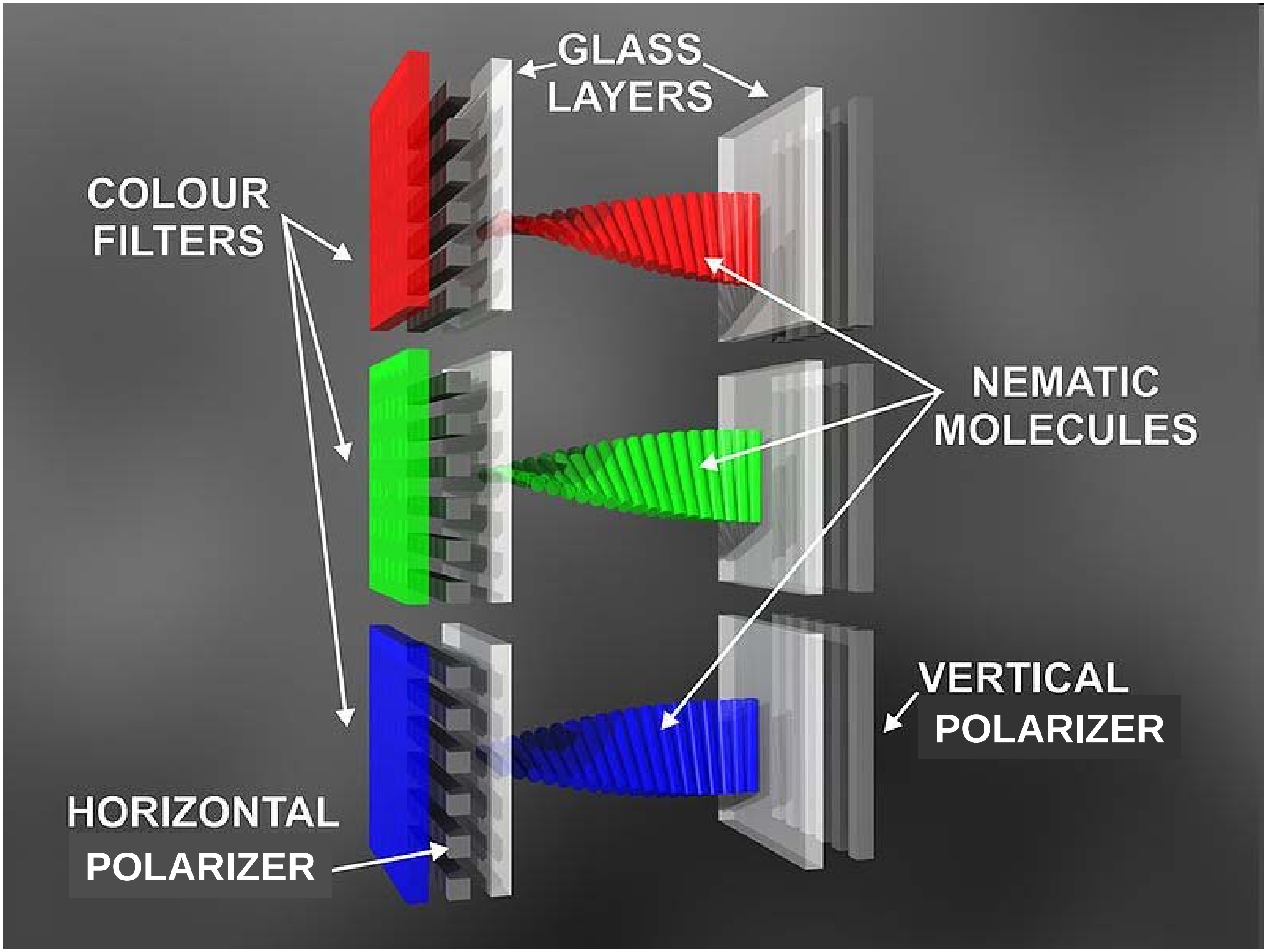
Liquid Crystal Display – Principle



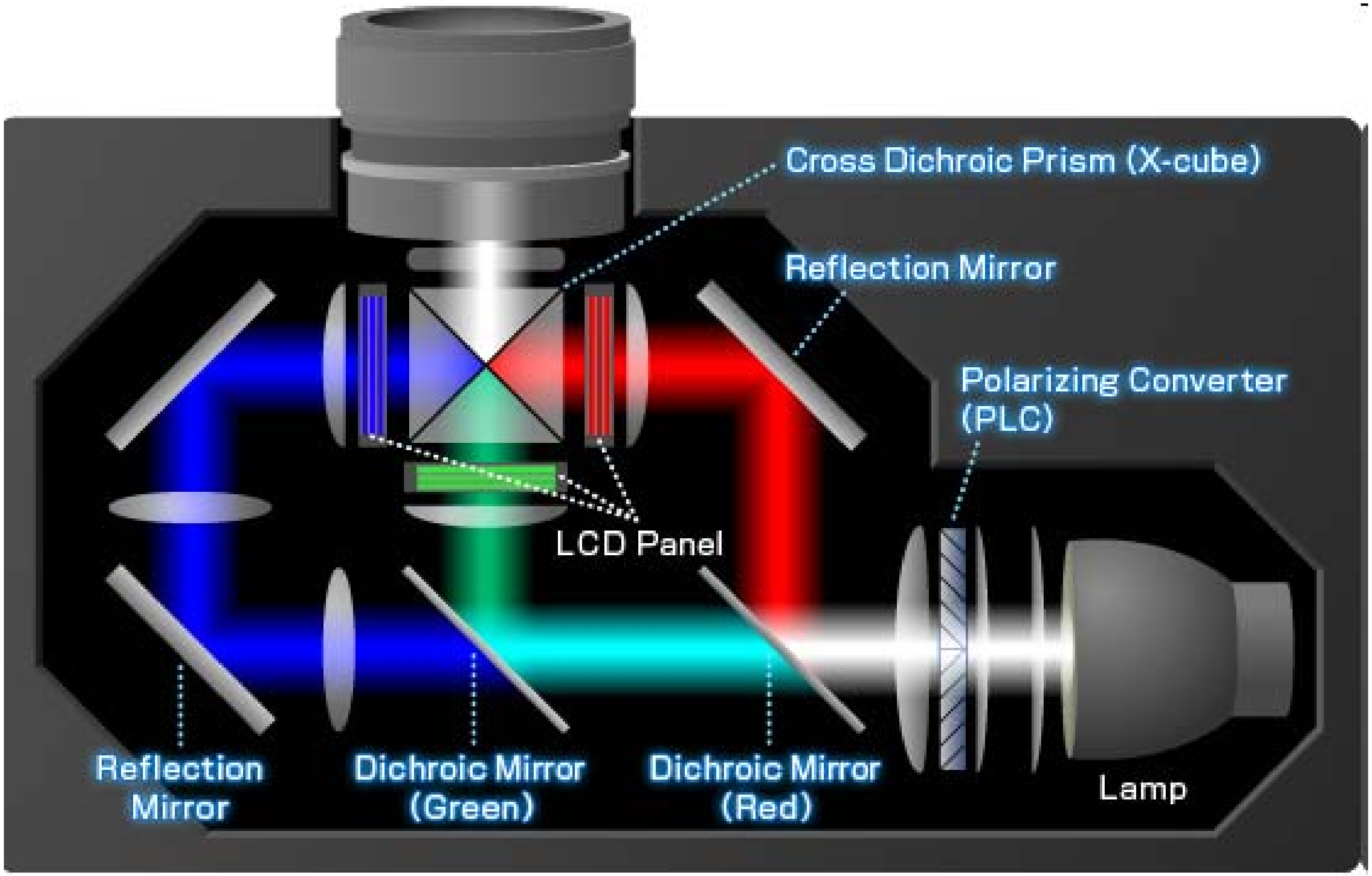


http://www.physics.umd.edu/grt/taj/104a/104anotessupps.html

LCD – Pixels


GLASS
LAYERS
COLOUR
FILTERS
NEMATIC
MOLECULES
VERTICAL
POLARIZER
HORIZONTAL
POLARIZER

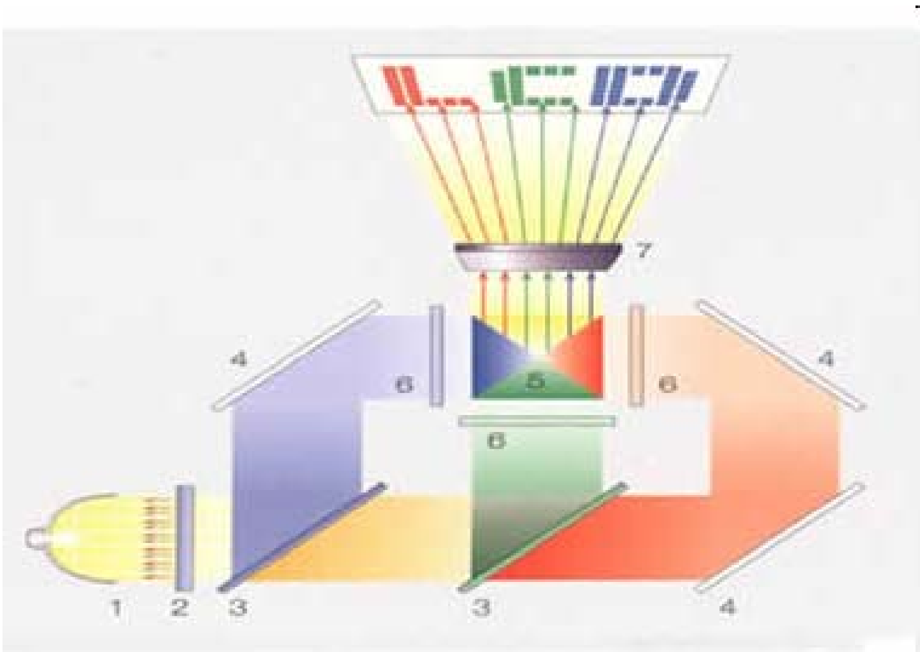
3LCD Projector



http://www.nitto-optical.co.jp

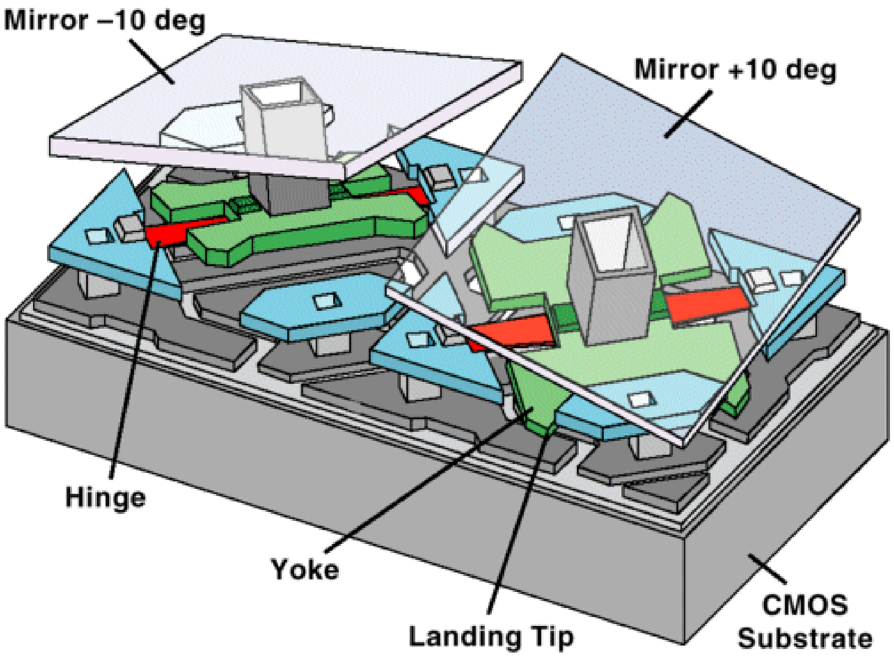
COLLEGE OF OPTICAL SCIENCES
ARIZONA

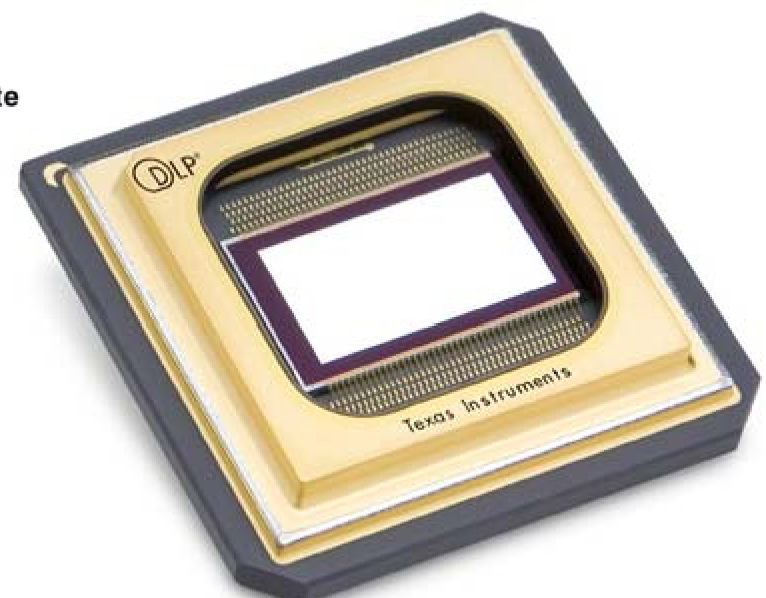
3LCD Projector



http://www.si-cube.com

Digital Light Processing – DLP



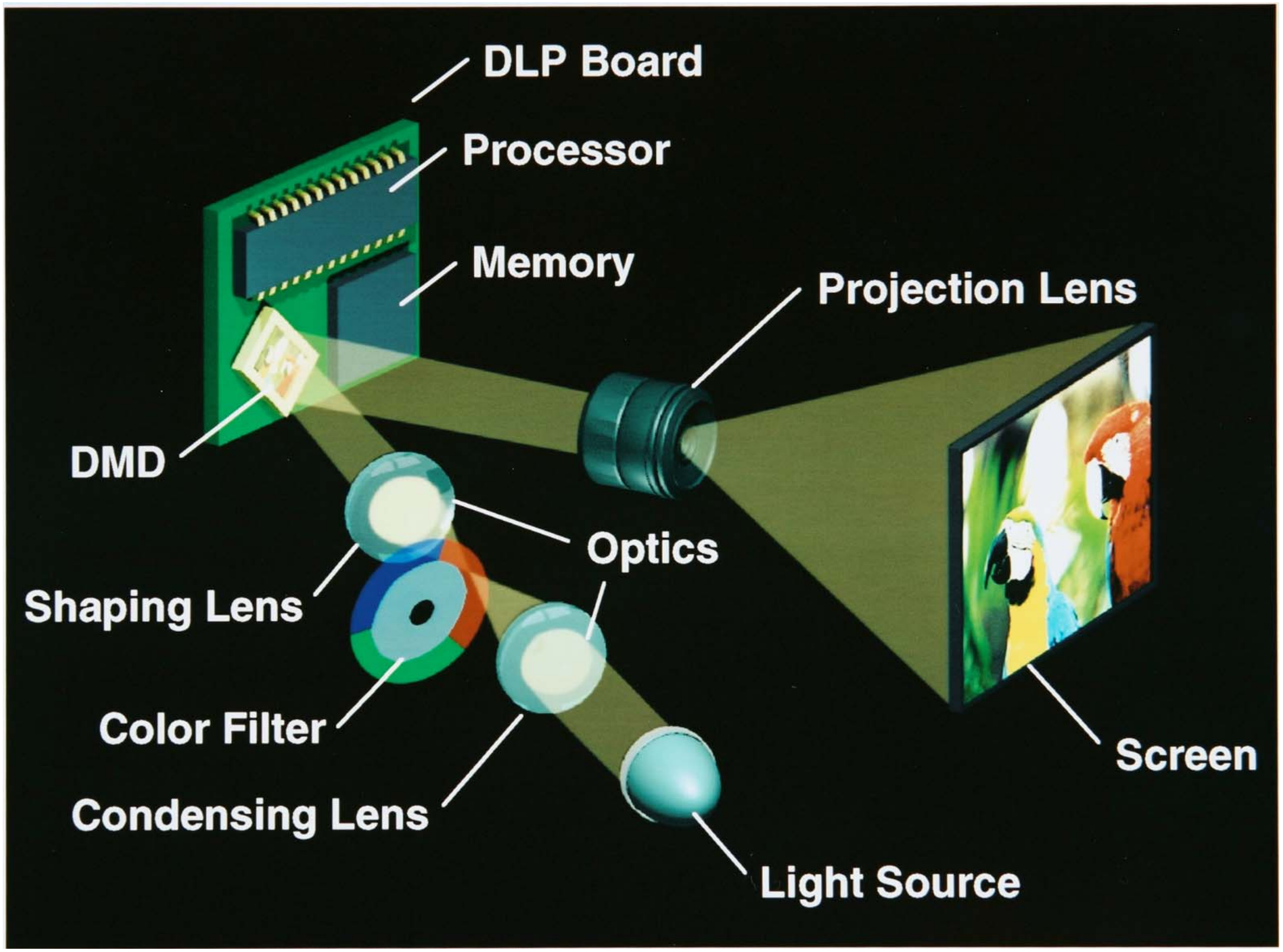


DMD – Digital Micro-Mirror Device

http://www.dlp.com

DLP - Projector

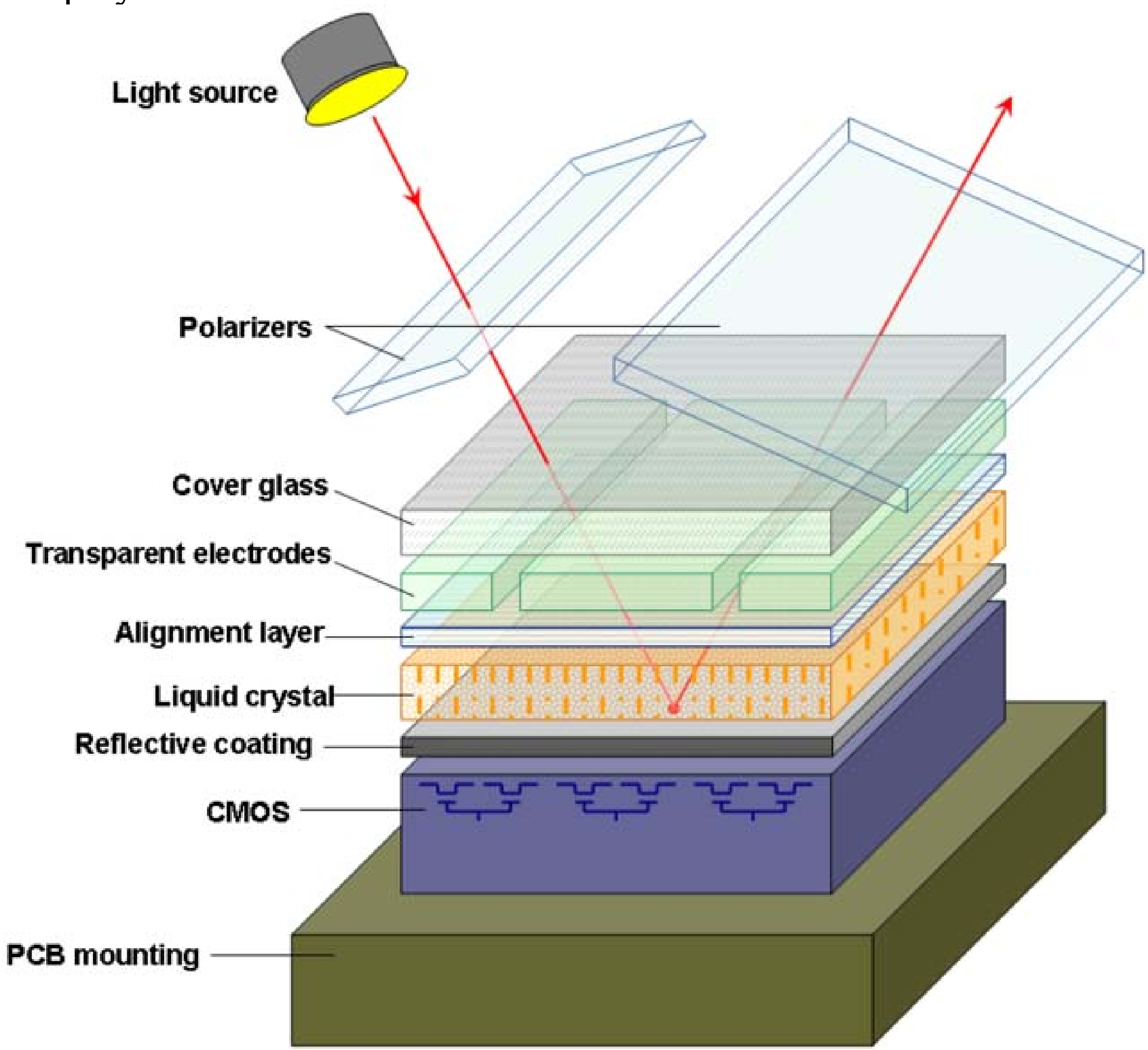
Colors are displayed sequentially in time.
Grayscale is obtained by dithering the individual mirror elements during a frame.



http://www.dlp.com

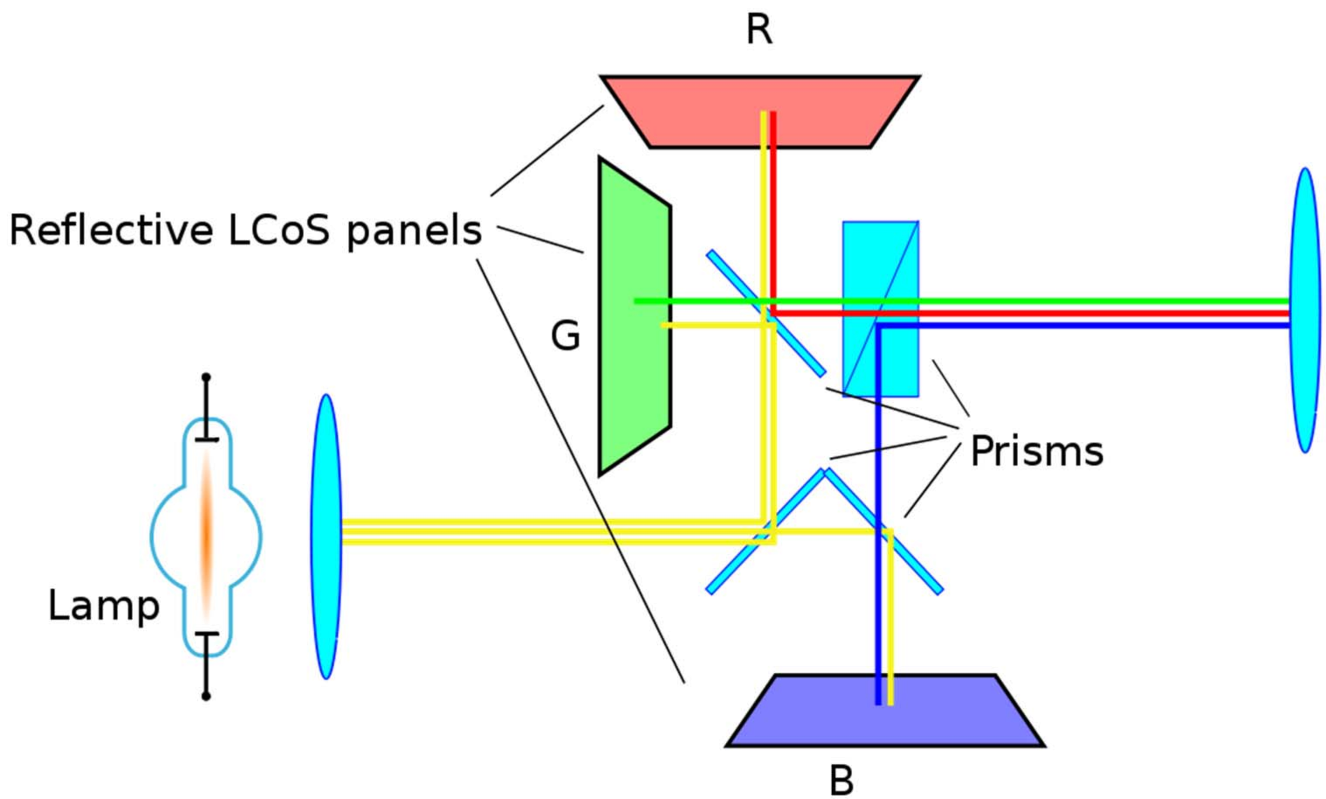
<u>Liquid Crystal on Silicon – LCOS</u>

A reflective LCD display.



Wikipedia

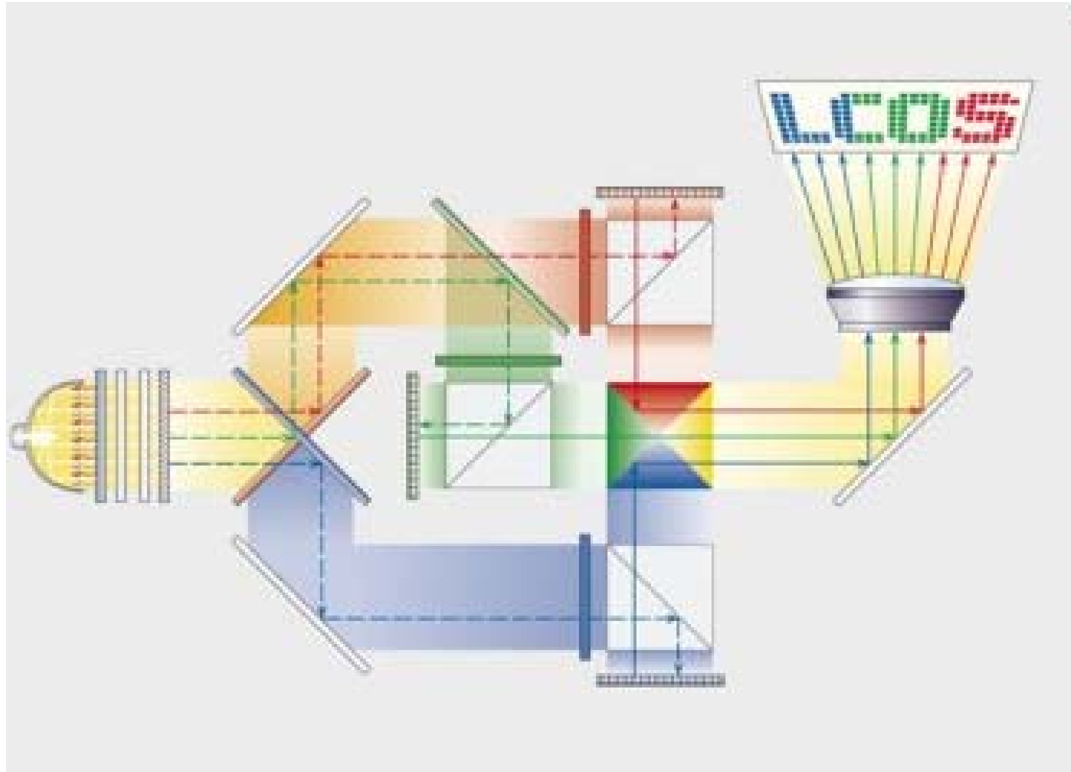
Liquid Crystal on Silicon Projector –



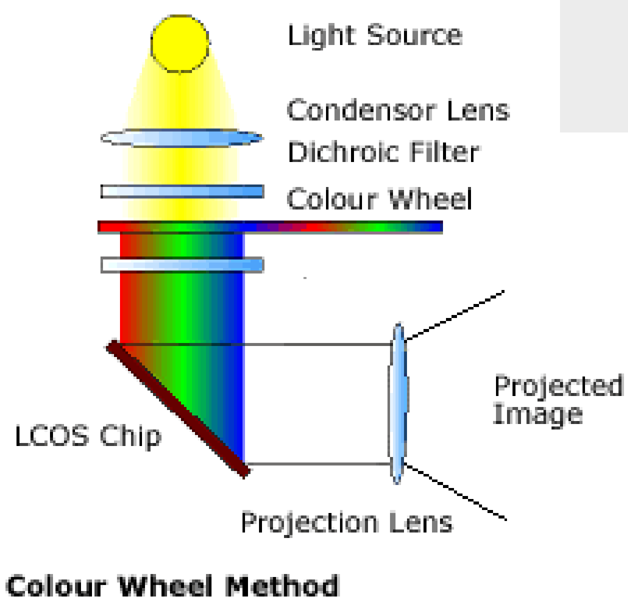
An example is the Sony SXRD system.

Wikipedia

LCOS Projector



http://www.si-cube.com



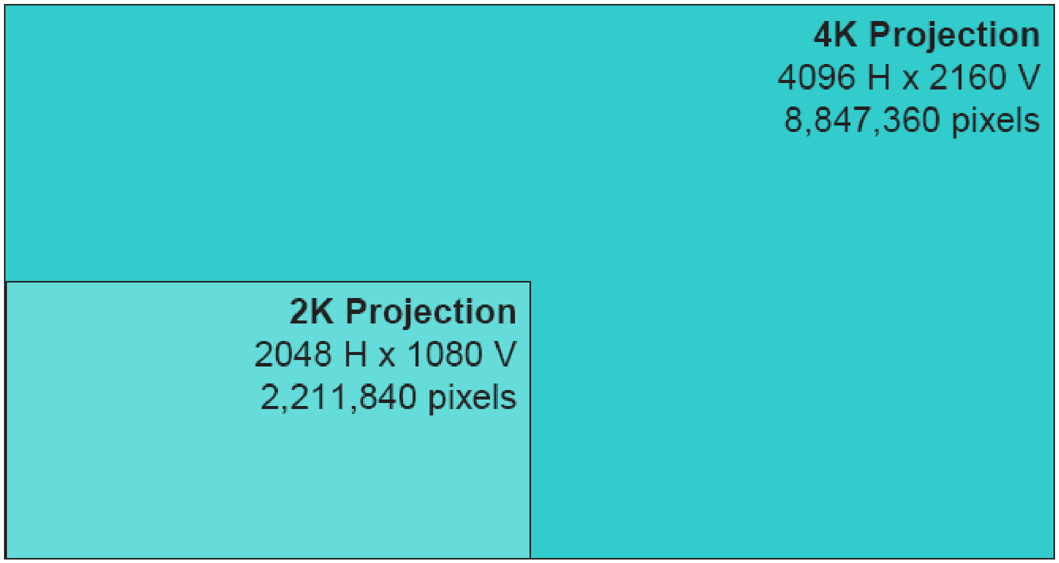
LCOS projectors can be made using a single chip by displaying the colors sequentially in time with a color wheel or by use of a color filter array on the chip.

Digital Cinema

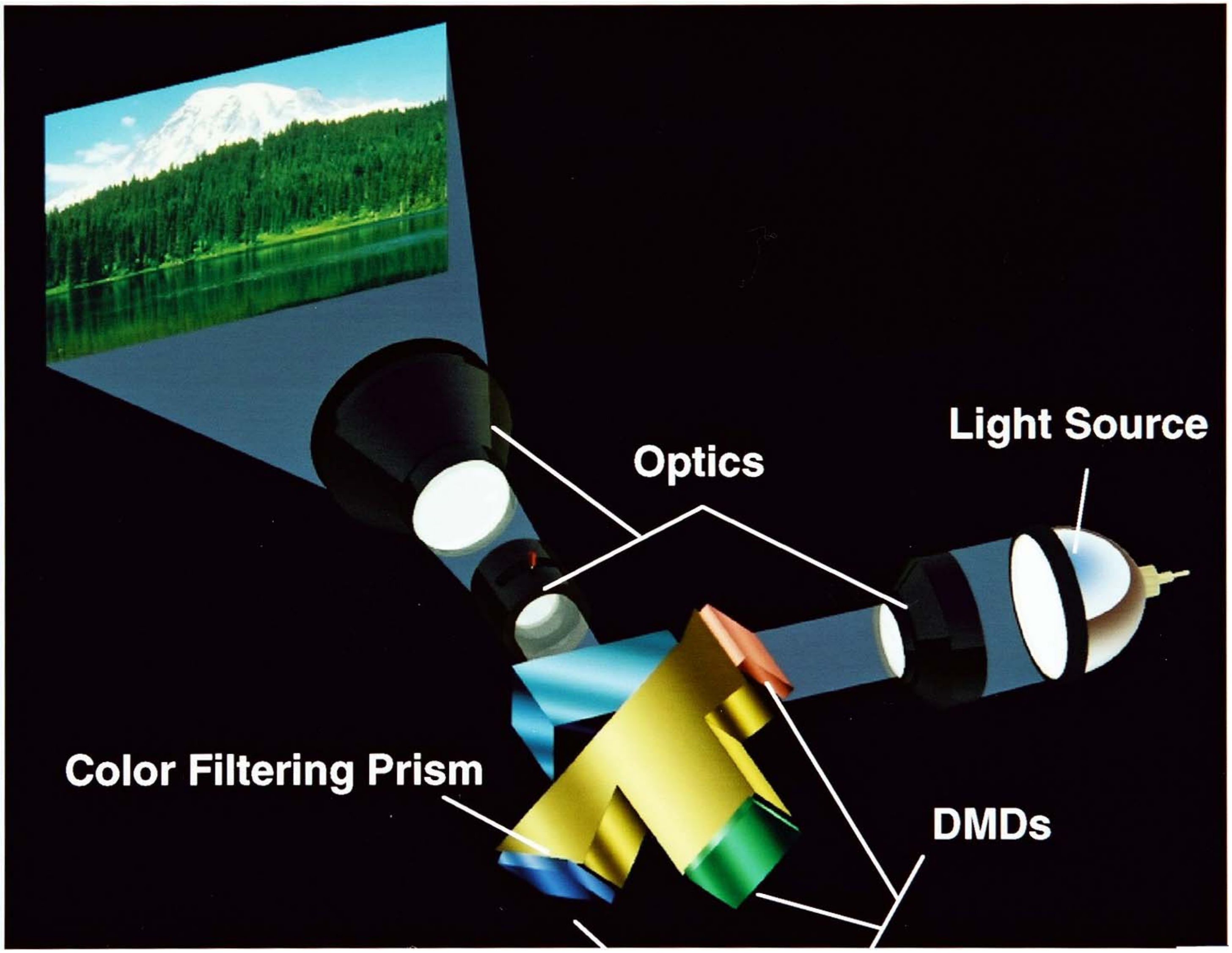
Digital cinema or high-end projectors make use of three chips, and the technology in use today is DLP or LCOS.

Systems are specified by their resolution:

2K at 24 or 48 frames per second (DLP and LCOS)
4K at 24 frames per second (LCOS as of 2010)



DLP Cinema Projector



http://www.dlp.com

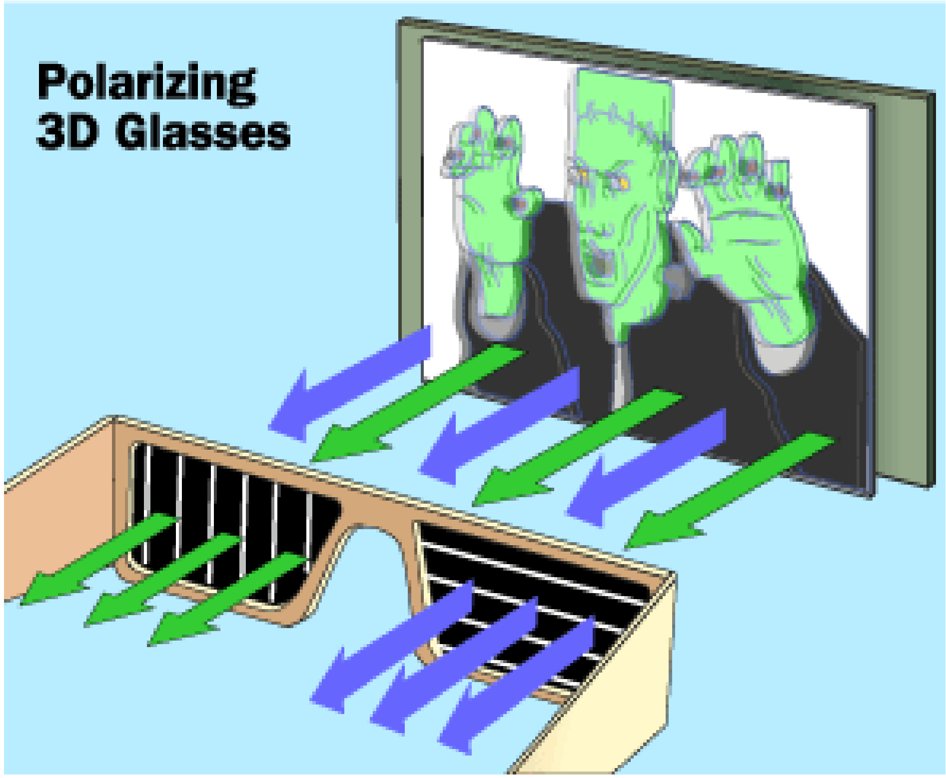
3D Projection

Images are recorded from two different perspectives; the resulting parallax produces the 3D sensation.

The two images are projected, and are encoded:

Color
Polarization
Time

Special glasses are worn so that each eye can only see its respective image.

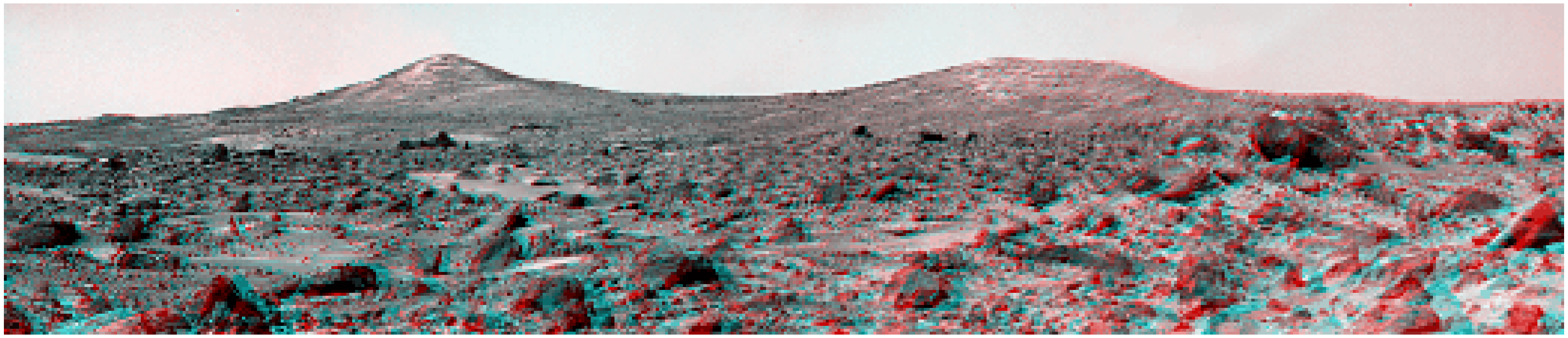


Anaglyph Projection

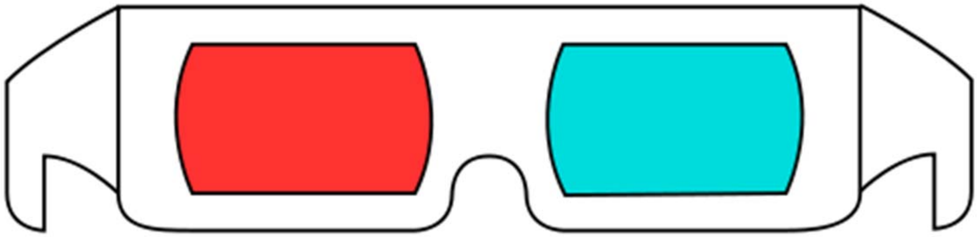
The encoding is by color. Perspective is created because the left eye sees the left or Red image (actually: Image – Blue – Green) and the right eye sees the right Cyan image (actually: Image – Red).

When the two images are fused, not only does the sensation of depth occur, but the colors of the two images merge to produce a full-color image.

This technique is currently in use in 3D TV releases as it is compatible with standard televisions.



NASA – Mars Pathfinder

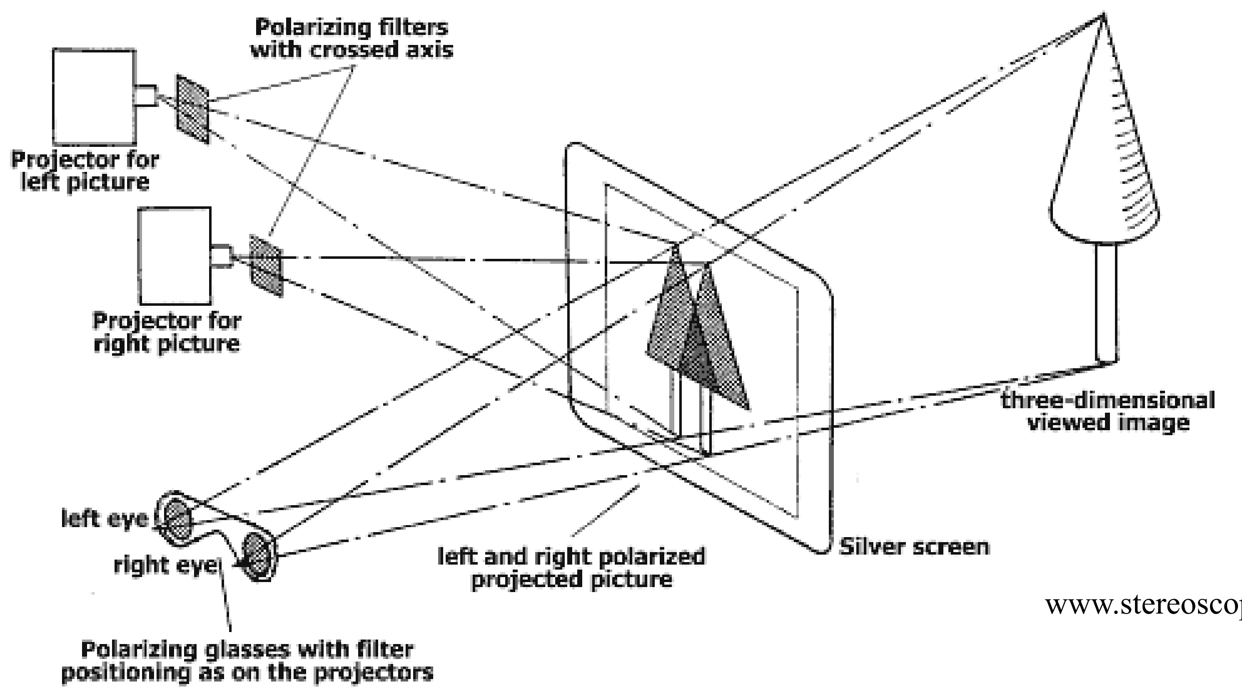


Anaglyph Projection

Wikipedia

3D Projection

The traditional method is to use two projectors running in synchronization. Polarization is used for the encoding. A polarization-maintaining screen is requires (often called a silver screen).



www.stereoscopy.com

The primary issue with this method (aside from needing two projectors) is to maintain registration/alignment of the two images.

Passive Polarization Glasses

Right-handed and left handed circular polarization is used to encode the two images needed for 3D. The eyeglasses worn by the viewer must distinguish between these two polarization states and allow only one to reach each eye.

The required configuration is a RH or LH circular polarization analyzer. It consist of a quarter wave plate (on the projection screen side) followed by a linear polarizer. The transmission axis of the polarizer for one eye is oriented at +45º with respect to the fast axis of the retarder. The transmission axis of the polarizer for the other eye is oriented at -45º.

One lens transmits RHCP and blocks LHCP. The other lens transmits LHCP and blocks RHCP.

Circularly polarized light is used because the angular orientation of the circular polarization analyzer does not matter. It is only the relative orientation of the retarder axis and the linear polarizer that is important.

By using circularly polarized light, the viewer can tilt their head and still fully separate the two images. If linear polarized light were used for the encoding (with linearly polarized glasses), a head tilt would cause cross some of the left image to be seen by the right eye, etc. This is called cross-talk or ghosting and can result in headaches.

Single Projector 3D

The current generation of 3D projectors use temporal switching and alternate between the right eye and left eyes. An electro-optic liquid crystal modulator produces either right-handed or left-handed circularly polarized light.

24 frames per second are required for each eye. To minimize temporal effects between the two eyes, the left and right images are each repeated three times within a frame:

L1 R1 L1 R1 L1 R1 L2 R2 L2 R2 L2 R2 …

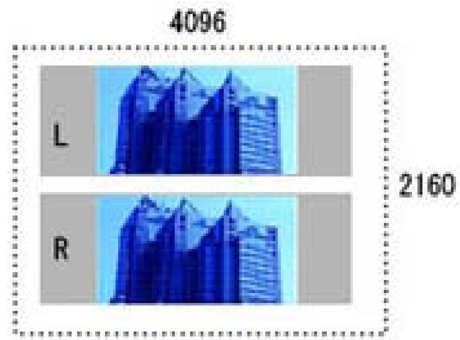
The result is a total projection rate of 144 frames per second.

<u>Dual Projection 3D</u>

The 3D projection standard is 3K per eye. The Sony SXRD LCOS system in the 4K standard has a enough pixels to simultaneously display both the L and R images.

A special dual optical system images each of these two images and provides the polarization encoding. The frame rate only needs to be 24 frames per second.

There is a reduction in flash artifacts.



Sony Dual Image 3D Projection Optics

LKRL-A002

Note the adjustment screws to obtain image registration.

3D TV

Recently, 3D television sets for home use have become available. They are based upon two different technologies:

Spatial Multiplexing

Polarization strips are applied to every other line on the display, and the R and L images are sent only to those respective lines. The images are viewed with passive polarized glasses. Half of the spatial resolution of the display is lost, however the full frame rate of the display is maintained.

Temporal Multiplexing

The L and R images are displayed as alternating frames. Active shutter glasses are required which allow an eye to see only its image. The two lenses alternately darken and become transmissive.

The active shutter glasses use liquid crystal shutters that are run synchronously with the video field rate. Synchronization information is communicated to the glasses by means of a transmitter (IR or RF).

A high video frame rate of 120 Hz is needed (60 Hz for each eye). In addition, relatively expensive active shutter glasses are required for each viewer.