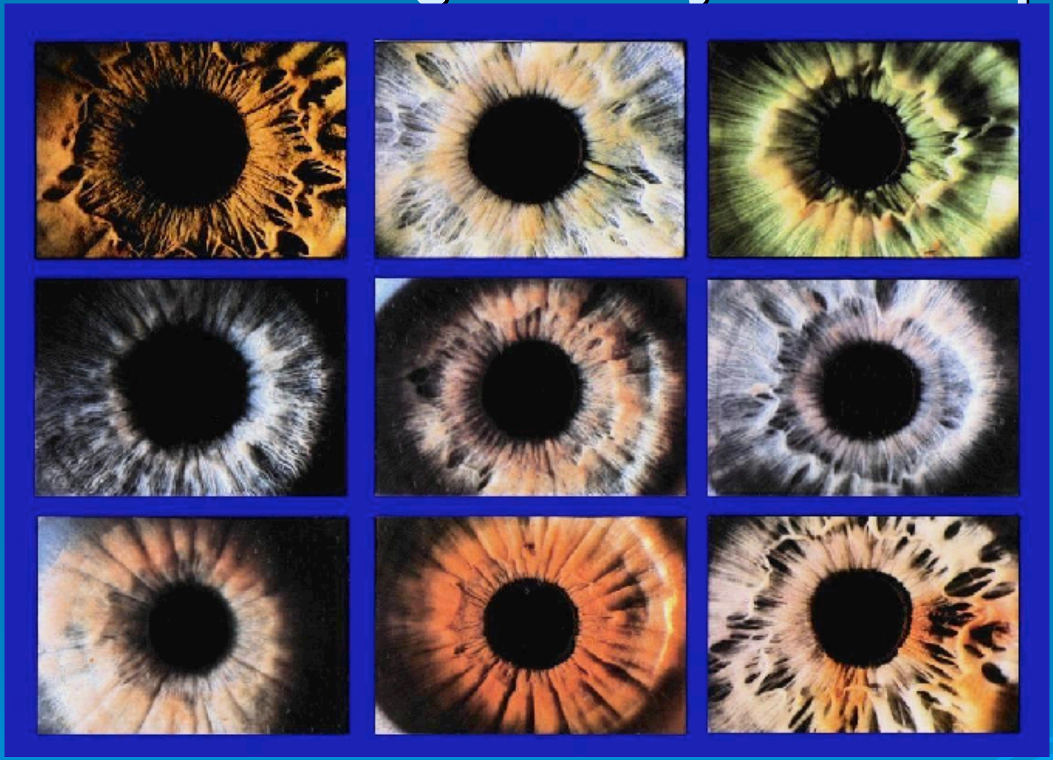
Digital Image Quality for Iris Recognition

Biometric Image Quality Workshop



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Images courtesy of Dr. John Daugman

Abstract

- Different studies show large variations in reported error rate
- Imaging platform differences may account for difference

Objectives

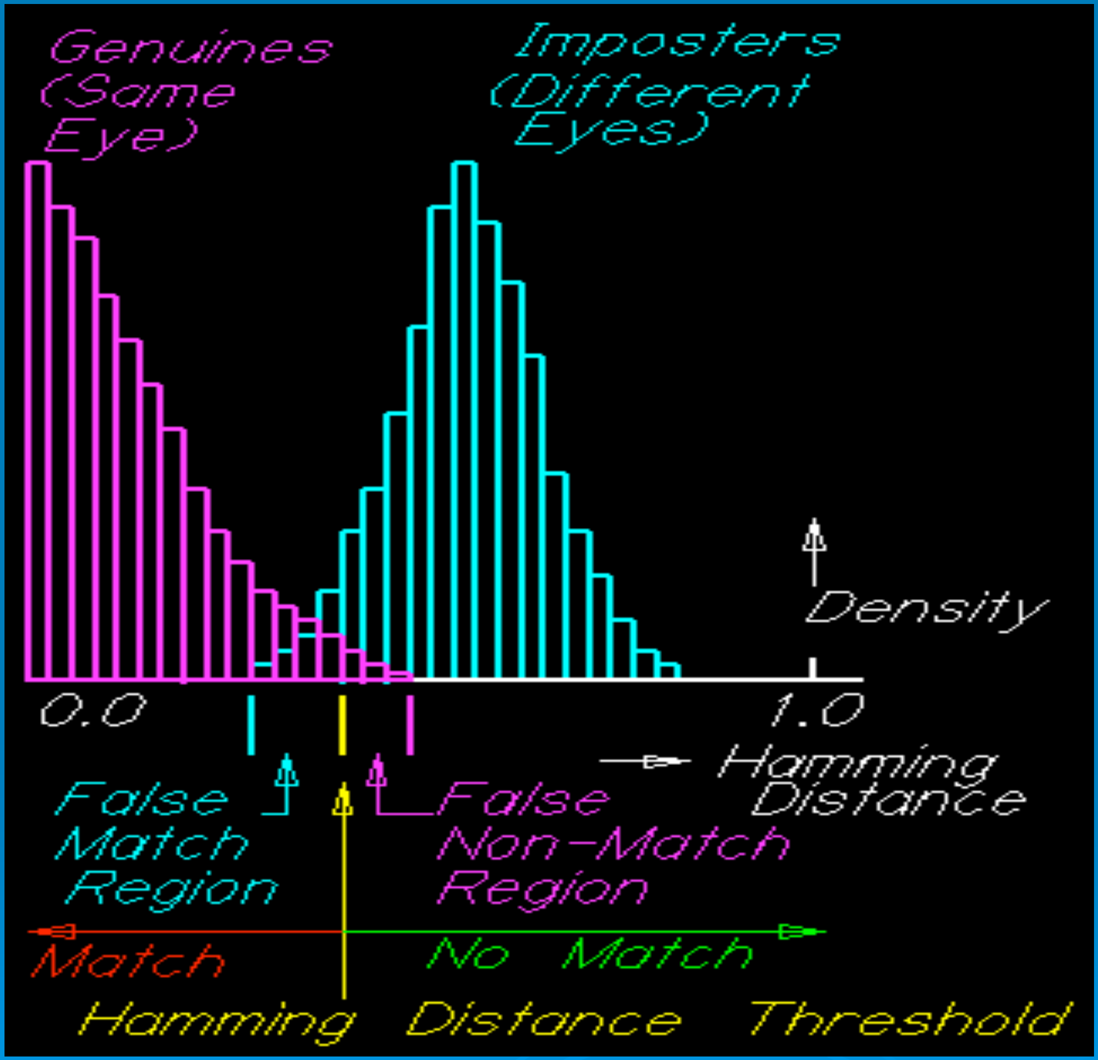
- Show accuracy results from [Daugman] and [IBG] reports.
- Suggest that imaging platform differences may account for the apparent discrepancy between these test results
- Define iris error rate terminology
- Show the components of an imaging platform and their characteristics affecting iris image quality.
- Discuss eye hazard issues with infrared illuminators.

FNMR and FMR Error Rates

- **False non-match rate (FNMR)**
  - Rejection rate of "genuines"
    - Those with valid enrollment on file
  - Passes undesirables in watch-list applications
  - Causes user dissatisfaction, increased workload and delays.
- **False match rate (FMR)**
  - Acceptance rate of "imposters"
    - Those with no enrollment on file
    - Lets known undesirables through

Decision Environment

Discrete Probability Density Curves

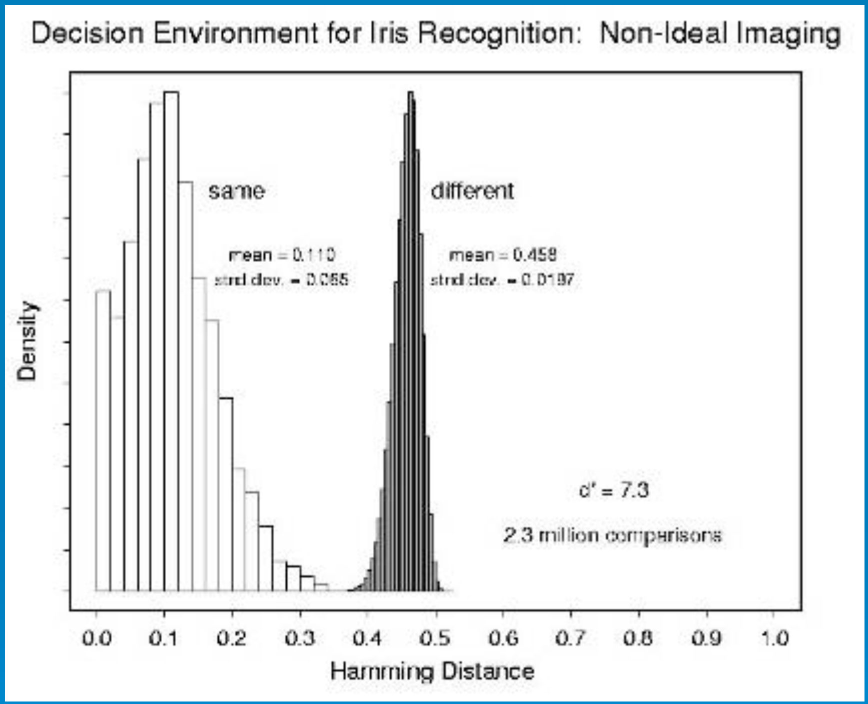


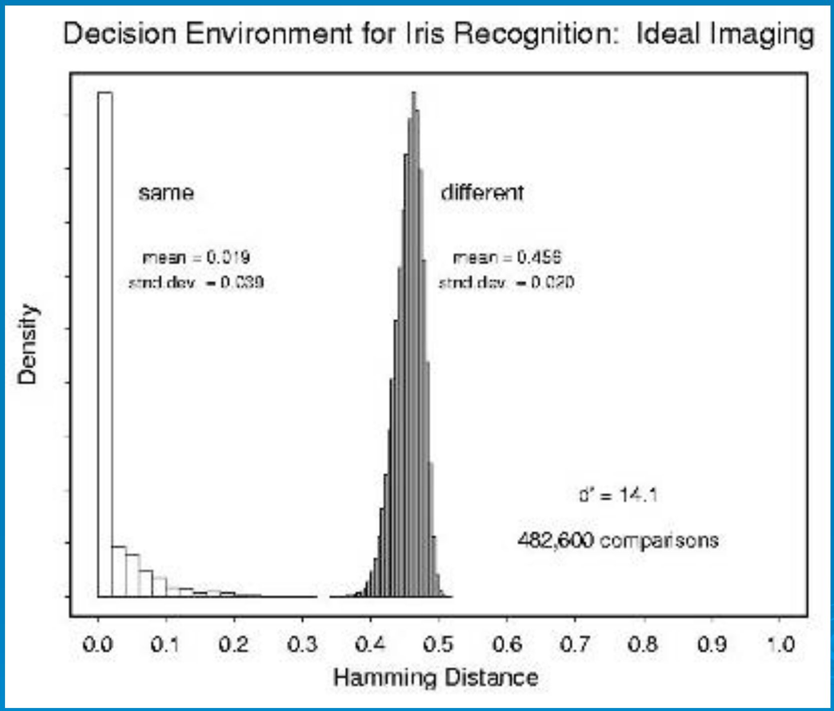
Density curve is histogram normalized to unit area

Hamming distance = number of corresponding bits which disagree in the iris code

FMR = area of blue imposters curve in False Match Region /total area under imposters curve
FNMR = area of red genuines curve in False Non-Match Region / total area under genuines curve

Effects of imaging Platform on "Genuines" Distribution [Daugman]





Poor Imaging

Good Imaging

Differing Error Rate Results

- False Non-match Rate
  - [Daugman] no false non-matches in 7070 comparisons
  - [IBG] one false non-match per 94.339 comparisons
- False Match rate
  - [Daugman] no errors in 9.21 million comparisons
  - [IBG] one false match per 28,902 transactions
- IBG results are at the transaction level, same device, averaged over three devices

The Details

- All suppliers in the IBG test used the same matching algorithm (licensed from Iridian)
  - Each supplier uses their own proprietary imaging platform
  - “the ‘authentics’ distribution [controlling FNMR] depends strongly on the quality of imaging (e.g. aberrations, motion blur, focus, noise, etc.) and would be different for different imaging platforms” [Daugman]
- “the measured similarity for “imposters” [determining FNMR] … is apparently almost completely independent of imaging factors.” [Daugman]
  - It is distributed equivalently to runs of 249 tosses of a fair coin. (Bernoulli trials with p= 0.5, N = 249)

Reducing FNMR by Increasing HD Threshold

- FNMR can be reduced by increasing the HD (Hamming Distance) threshold
- The cost is high: a small decrease in FNMR produces a large increase in FMR
  - Reducing FNMR by 15.7% increases FMR by approximately a factor of 10.
    - Approximate average from curve [IBG] at attempt level.

Summary

- [IBG] reports that FNMR is much higher than FMR
- FNMR can be a serious problem in watch-list applications
  - Passes known criminals and terrorists
  - Fails to pass “genuines” enrolled in the database
- FNMR is heavily influenced by the imaging platform [Daugman]

Components of an Iris Imaging Platform

- Digital Image Sensor
  - CCD or CMOS chip
- Lens
- Illuminator
- Camera
  - Encloses digital image sensor and lens
- Subject interface

The Digital Image Sensor

Digital Image Sensor

- A digital camera chip converts a light image to digital form
- Solid state sensors: CCD or CMOS
  - CCDs have been the choice for low noise
  - CMOS sensors are approaching the performance of CCDs
- Pixel density does not fully define resolution
  - Pixel spacing controls spatial sampling rate
    - Spatial frequency components must be less than sampling rate/2 (Nyquist limit) to avoid aliasing which roduces moiré patterns
  - Pixel-pixel crosstalk reduces resolution
    - Acts as low pass filter on image
  - Sensor may have built-in filters that make it inappropriate for NIR (Near Infrared) imaging
    - RGB
    - Anti-aliasing (low-pass)
- Sensor spectral sensitivity must extend into the NIR.

Digital Image Sensor (cont.)

- Sensor size affects resolution
  - Analogous to advantage of large film size
- Pixel size affects dynamic range
  - Large pixels capture more light, decreasing noise.
  - Pixels smaller than the diffraction limit do not increase resolution
- Defective pixels
  - always black
  - always white
  - “lazy pixels”, sensitivity differences
  - number and maximum cluster size must be specified

Important Digital Image Sensor Specifications

- Dynamic Range
  - = 20 log (Max Output (p-p) / Read Noise (rms))
- Fixed pattern noise (FPN)
  - = Fixed pixel-pixel offset variations
- Photo Response Non-Uniformity (PRNU)
  - = Fixed pixel-pixel gain variations
- Responsivity
  - = Output in digital numbers / light input in nJ/cm^2
- Read Noise
  - = Random rms noise of the digital output
- Noise Equivalent Exposure
  - Read Noise / Responsivity
- Saturation Equivalent Exposure (NEE)
  - = Maximum Output /Responsivity

The Lens

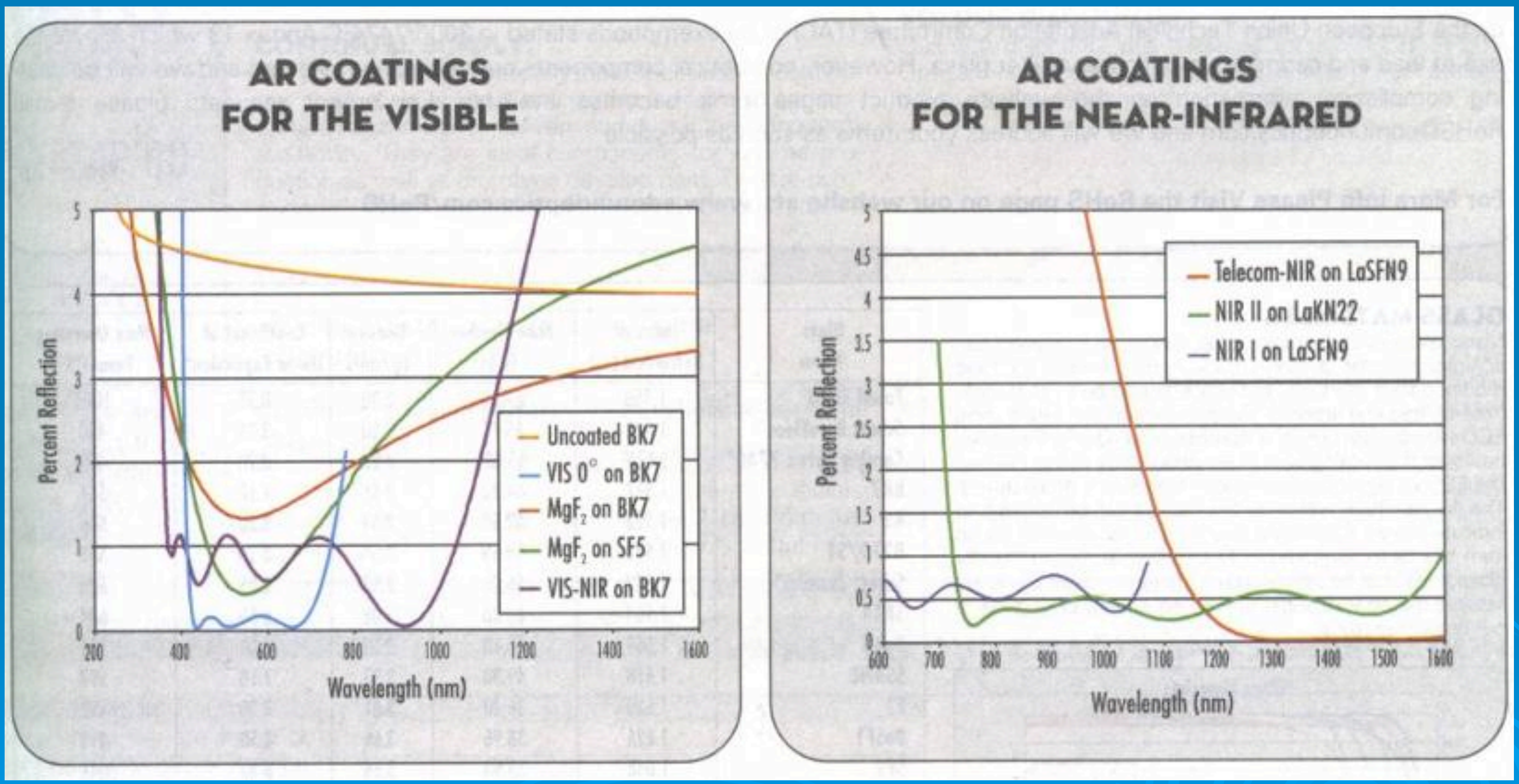
The Lens

- The lens must faithfully project an image of the subject onto the digital sensor.
- NIR imaging places special requirements on the lens
  - Different from those for visual light.
  - High quality lenses designed for visible light can produce serious image degradation in the NIR

NIR Lens Requirements

- High-quality lenses optimized for visible light often perform poorly in the NIR (Near Infra-Red, 700-1000 nanometers)
- Lens design must be optimized for the NIR.
  - Lens coatings must be designed for the NIR
  - Lens elements are coated to reduce reflections and avoid light loss of approximately 4.0 – 5.0% at each surface.
    - 10 – 20 surfaces are common
    - NIR optimized coatings will reduce loss to 0.5-1% per surface
  - Lens coatings not optimized for the NIR will cause:
    - light loss
    - internal reflections
    - ghost images
- Broad-band lenses cover both the NIR and visible range
- Lens must be designed for digital sensor use
  - Cover glass on sensor must be included in lens design
  - Small pixel sizes (3-12 microns) increase requirements for lens quality.

AR (Anti-reflective) Coatings



Courtesy of Edmund Optics

Measures of Lens Quality

- Image Sharpness
- Distortion level
- Uniformity of brightness

Image Sharpness

- Sharpness combines effects from several sources
  - Focus error
  - Diffraction
  - Lens aberrations
  - Sensor spatial sampling rate
  - Sensor pixel crosstalk
  - Subject motion
- Overall Image sharpness can expressed as **MTF** (Modulation Transfer Function)

Focus Error

- An out of focus optical system produces a blurry disk when a spot of light is imaged.
  - Called the COC (circle of confusion)
  - Results in blurred images
  - Acceptable diameter depends upon application
- DOF (Depth of Field)
  - The distance range over which subject remains in focus (COC diameter is acceptable)
  - The range is different between front and rear displacements from the ideal focus distance
  - Front DOF
  - Rear DOF

DOF Formula

- DOF =

  $c * N * (1+M/p) / (M^2 * (1 \pm (N * c) / (f * M)))$

  Use + for front DOF, - for rear DOF
- Where:

  c = diameter of largest acceptable circle of confusion

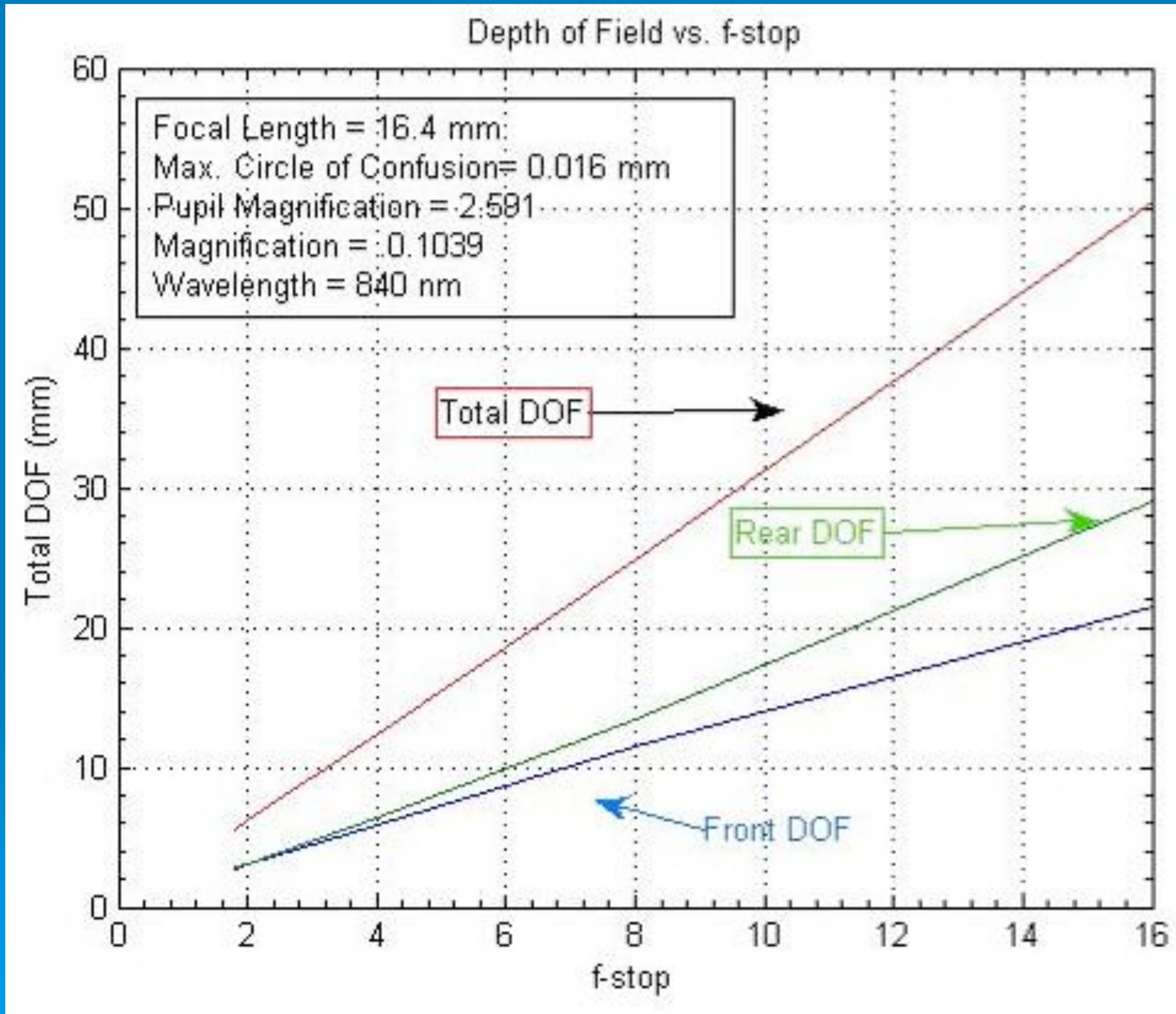
  N = f-number

  M = magnification

  p = pupil magnification

  f = focal length of lens

DOF Curves



Depth of Field vs. f-stop
Focal Length = 16.4 mm
Max. Circle of Confusion= 0.016 mm
Pupil Magnification = 2.591
Magnification = 0.1039
Wavelength = 840 nm
Total DOF
Rear DOF
Front DOF
Total DOF (mm)
f-stop
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16

Diffraction

- Diffraction imposes a fundamental physical limit on image sharpness
  - A point source of light passing through an aperture produces a diffraction pattern of alternating light and dark concentric rings.
  - Called an **Airy disk**
- Radius, R, of the Airy disk from peak to first minimum varies directly as the f-number and the wavelength
  - R = 1.22 * wavelength * f-number
  - N.A. is equivalent measure: N.A. = 1 / (2 * f-number)
  - Airy Disk Simulation (Nikon)

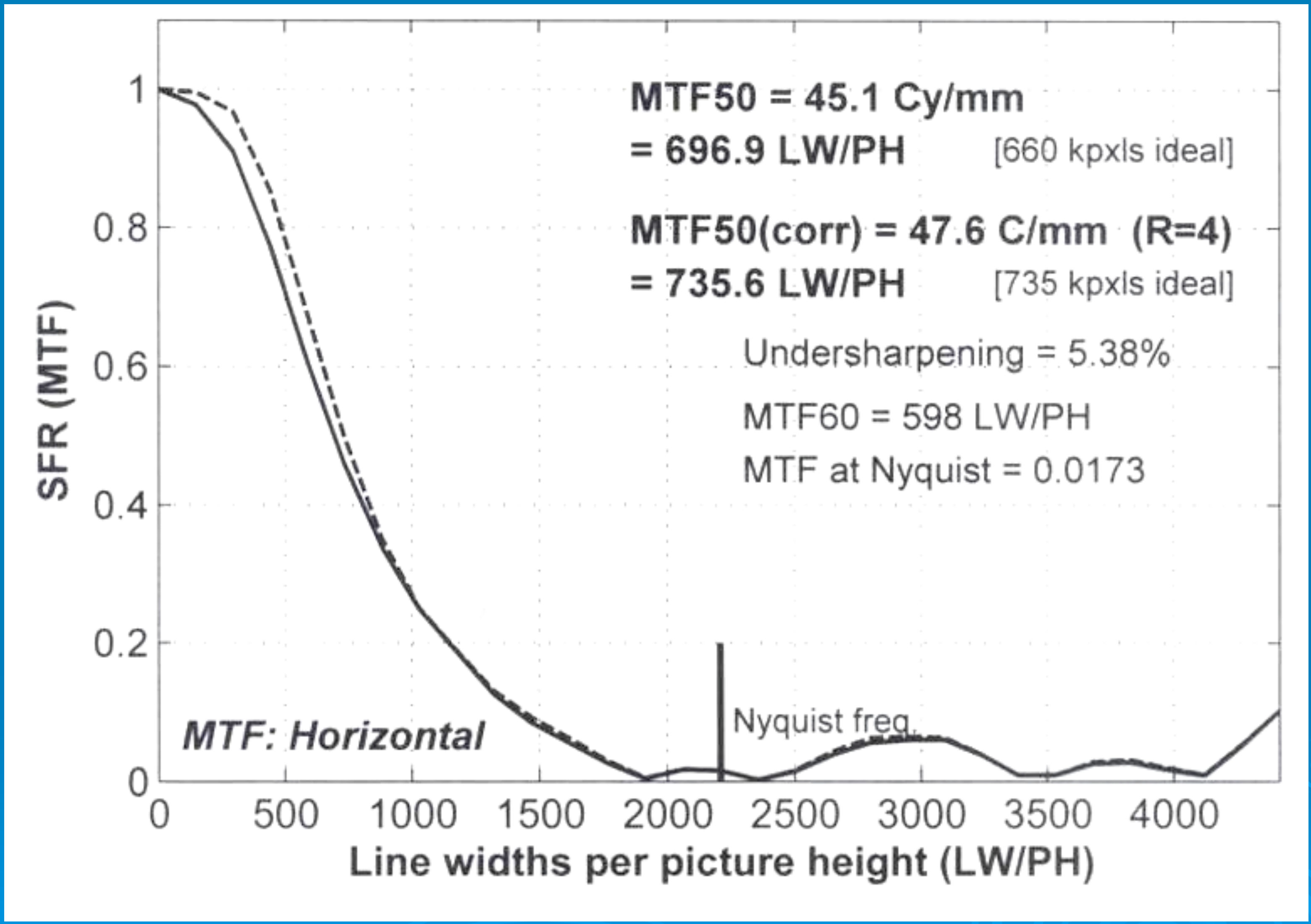
Lens Resolution and f-number

- Lenses are usually aberration limited at low f-numbers (large aperture)
- At high f-numbers, lens resolution becomes diffraction limited.
  - In the NIR, diffraction results in almost a 2:1 reduction in resolution relative to visible light.
- For many high-quality lenses, f-8 through f-11 produces the best balance between aberrations and diffraction

Quantifying Sharpness Using MTF

- Traditional method of measuring MTF is by human observation of a resolution chart image.
  - value is subjective
  - typically yields optimistic MTF at about 2-5% modulation
- MTF can be objectively measured using the slanted-edge method.
  - Requires an image with a sharp, slanted dark/light edge and suitable software [Imatest]
  - ISO 12233:2000 Photography -Electronic still picture cameras – Resolution measurements
- Complete MTF specification must include a modulation level, a wavelength, and overshoot limit. For example:
  - MTF at 60%, 840nm, is 4 line-pairs/mm with edge trace overshoot less than 5%

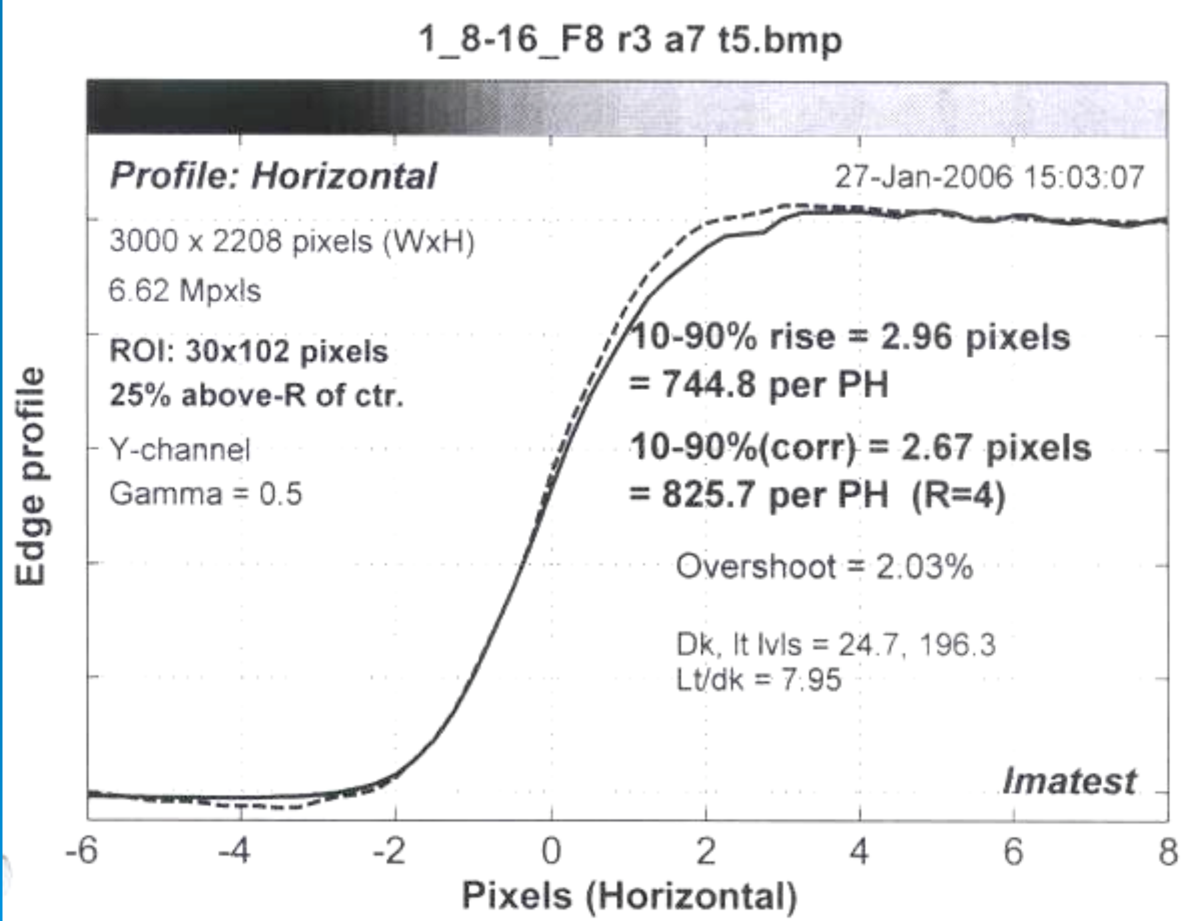
MTF Measured 0n Slanted Edge



lp/mm = MTF60/ (2 * picture height in mm)

For NIST imaging platform, lp/mm = 4.02

Edge Profile



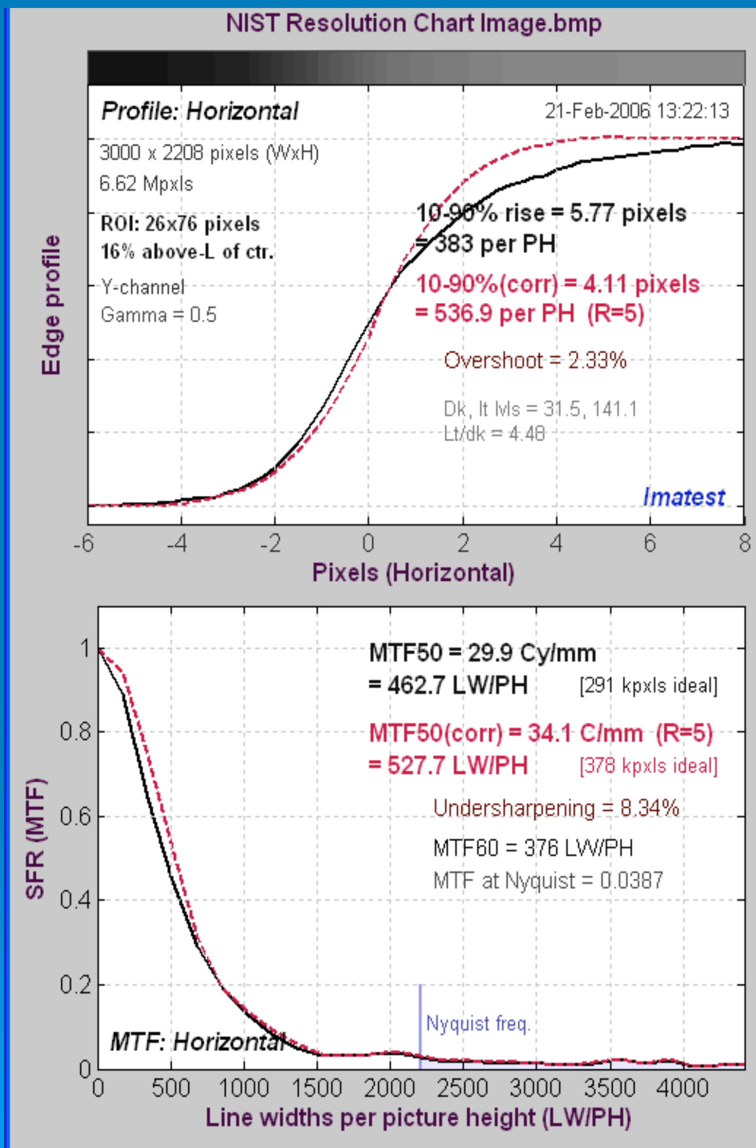
ROI: 30x102 pixels

L R T B = 1807 1836 724 8

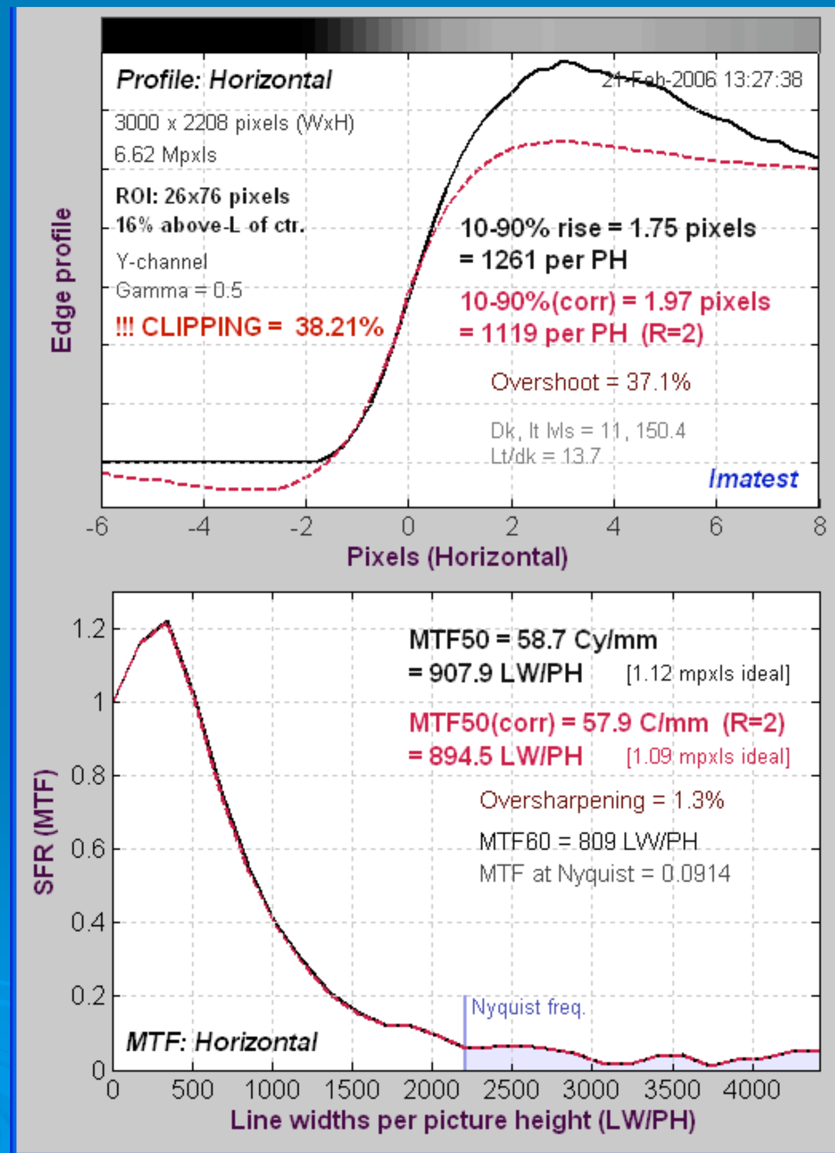
Digital Signal Processing of Image

- MTF can be artificially increased by digital sharpening.
- Excessive sharpening will produce overshoot and ringing on edges.
- Edge profile will show this distortion
- The edge profile can be produced by commercial software [Imatest].

Under-Sharpened
MTF60 = 376 LW/PH



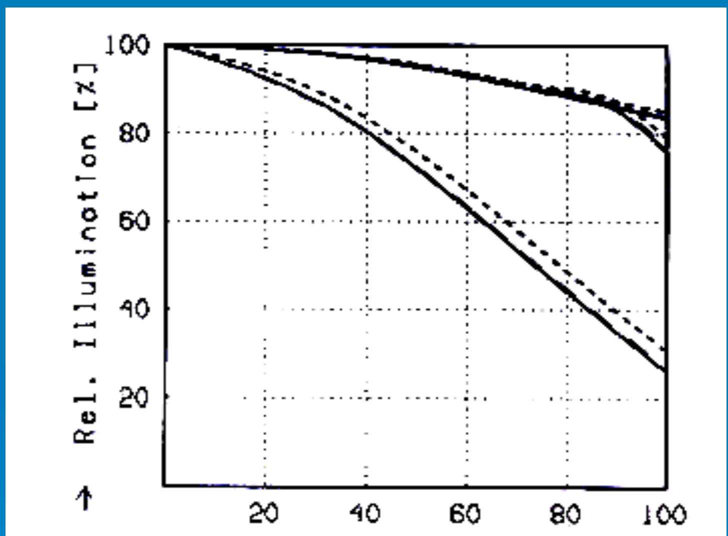
Over-Sharpened
MTF60 = 809 LW/PH



Uniformity

Light is reduced away from center (typical)

- β is magnification (image size / object size)



f/1.8, f/4.0
β = 0.0, 0.02, 0.1, top to bottom

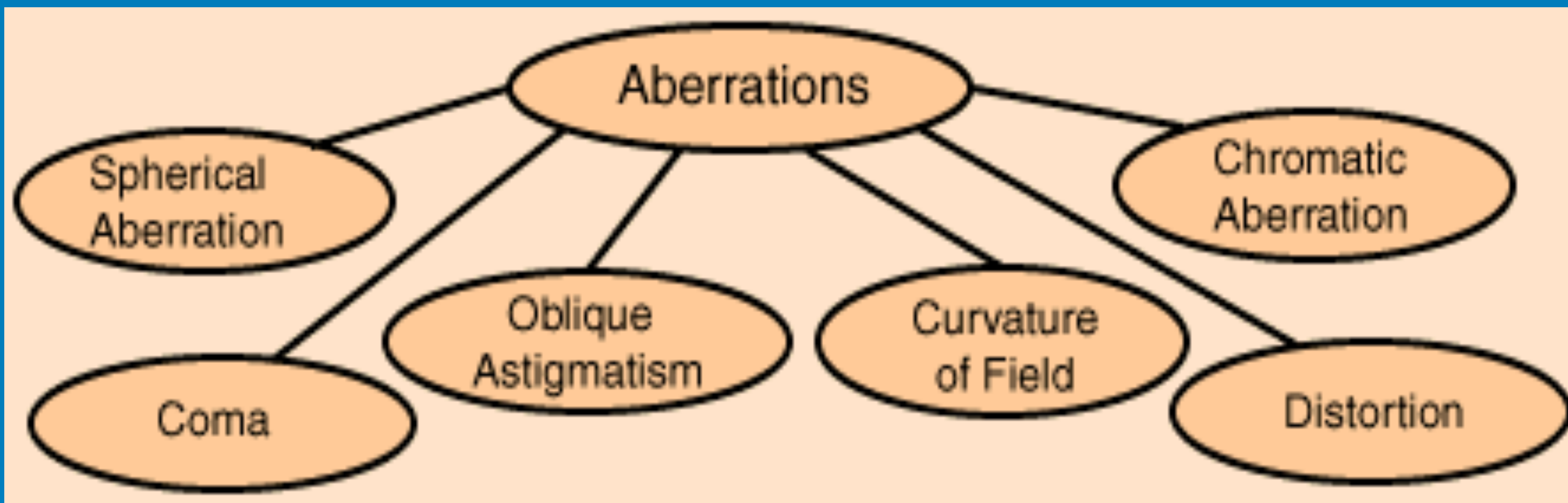
f/8
β = 0.0, 0.02, 0.1, top to bottom

Fraction of maximum image size

Lens Aberrations

- Non-ideal lens characteristics degrade the image in many ways
- Every lens exhibits these aberrations to some degree.
  - The lens designer uses multiple optical elements to reduce aberrations.

Common Lens Aberrations



Illustrations courtesy of Dr. Rod Nave
Department of Physics and Astronomy
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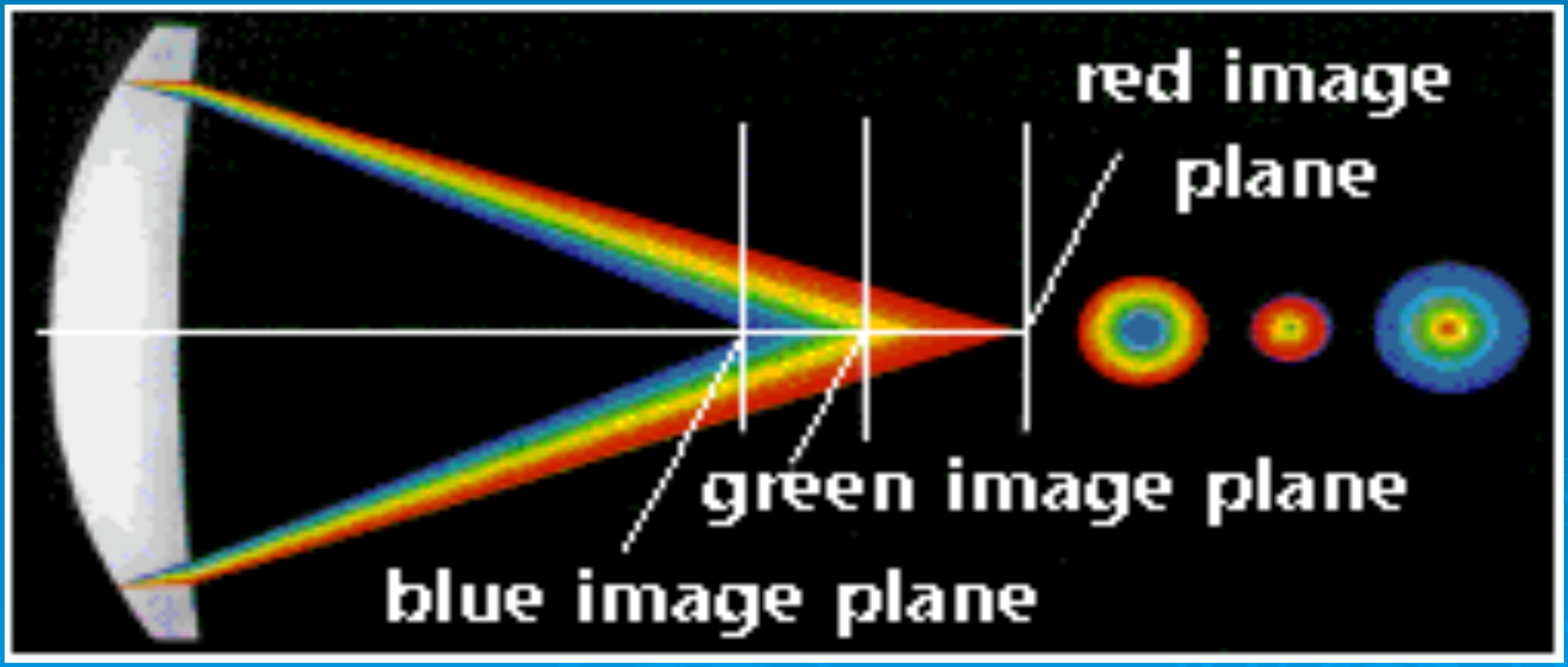
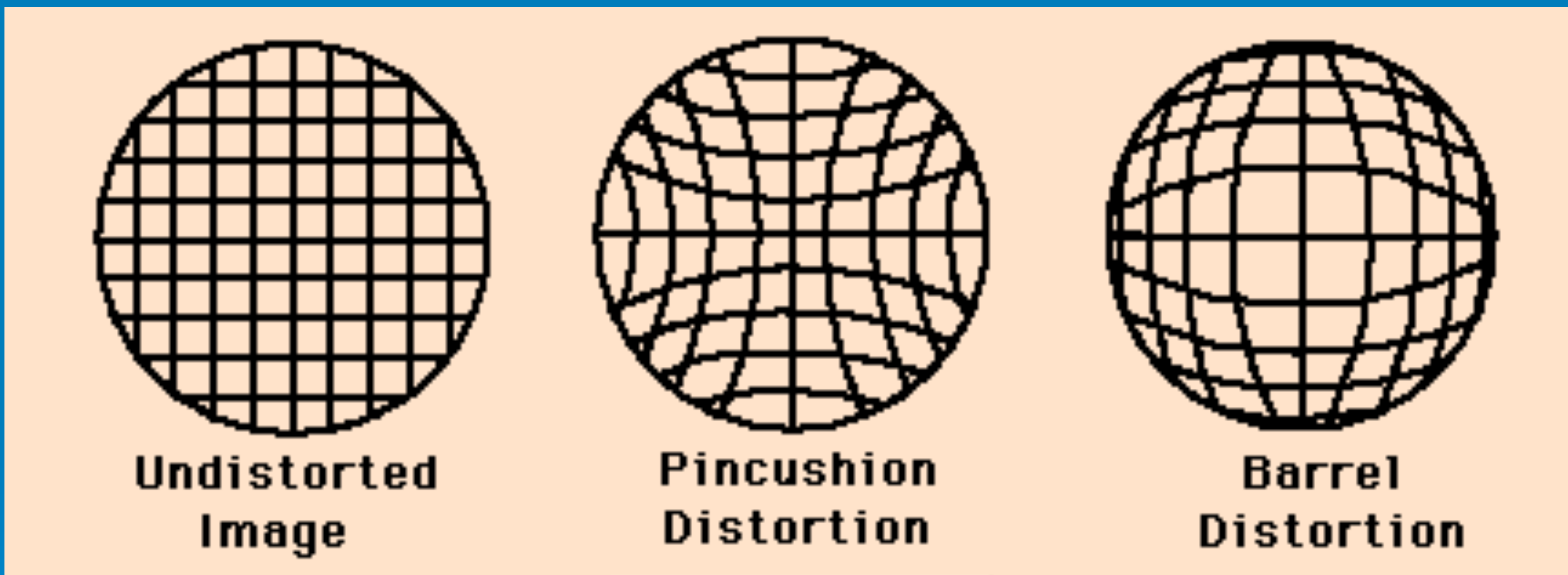
Atlanta, GA 30303-3083

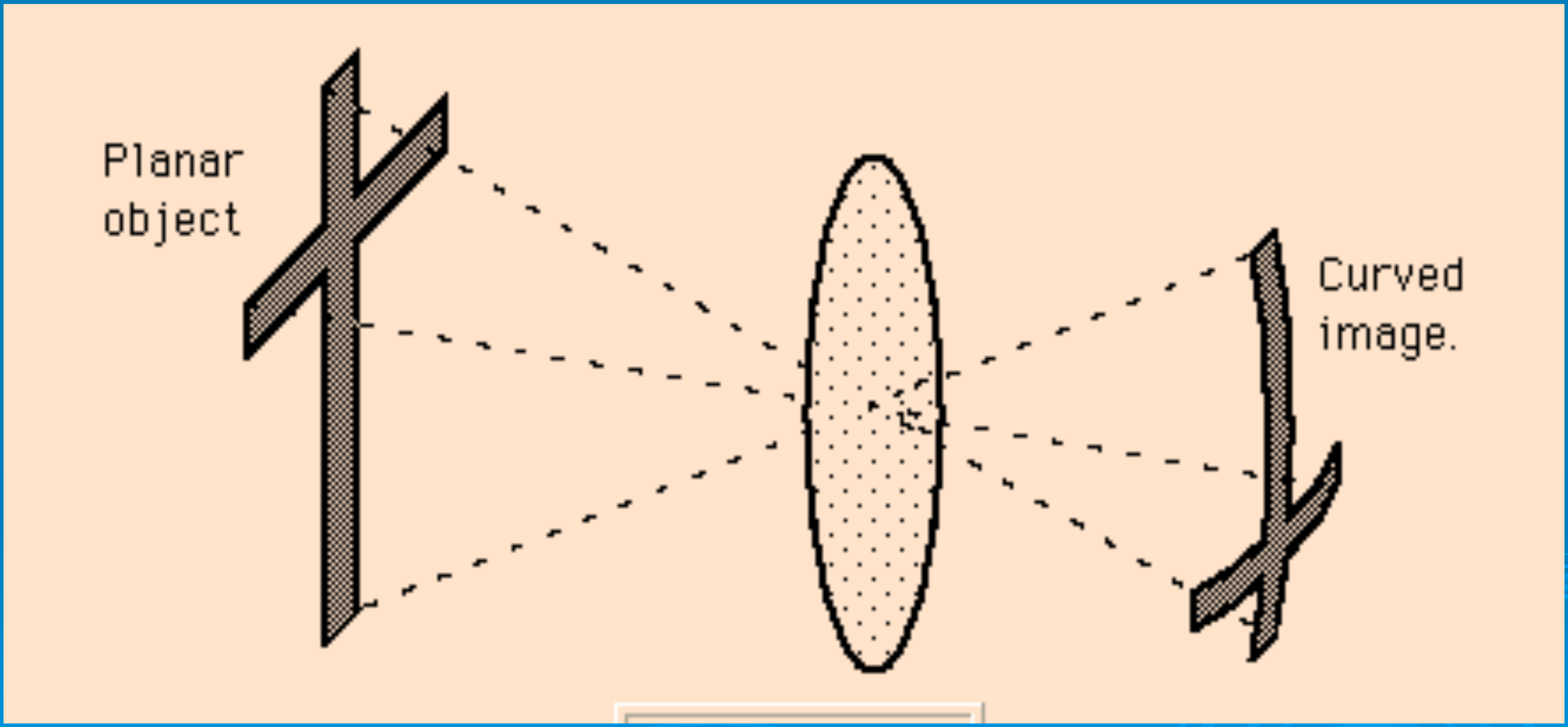
Chromatic Aberration
Light of Different Wavelengths Focus at Different Distances



Distortion

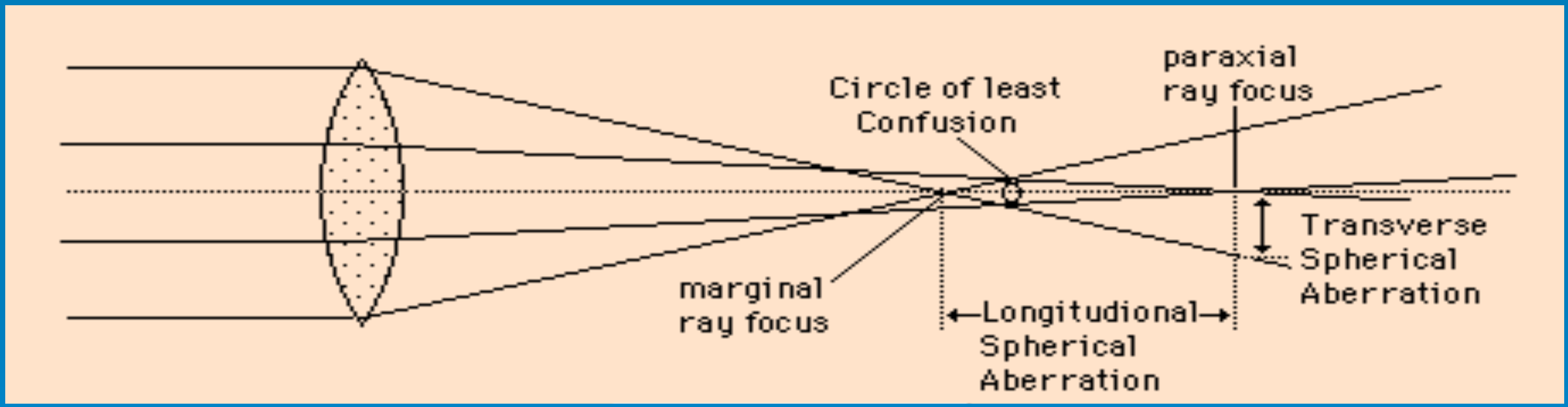

Undistorted Image
Pincushion Distortion
Barrel Distortion

Curvature of Field

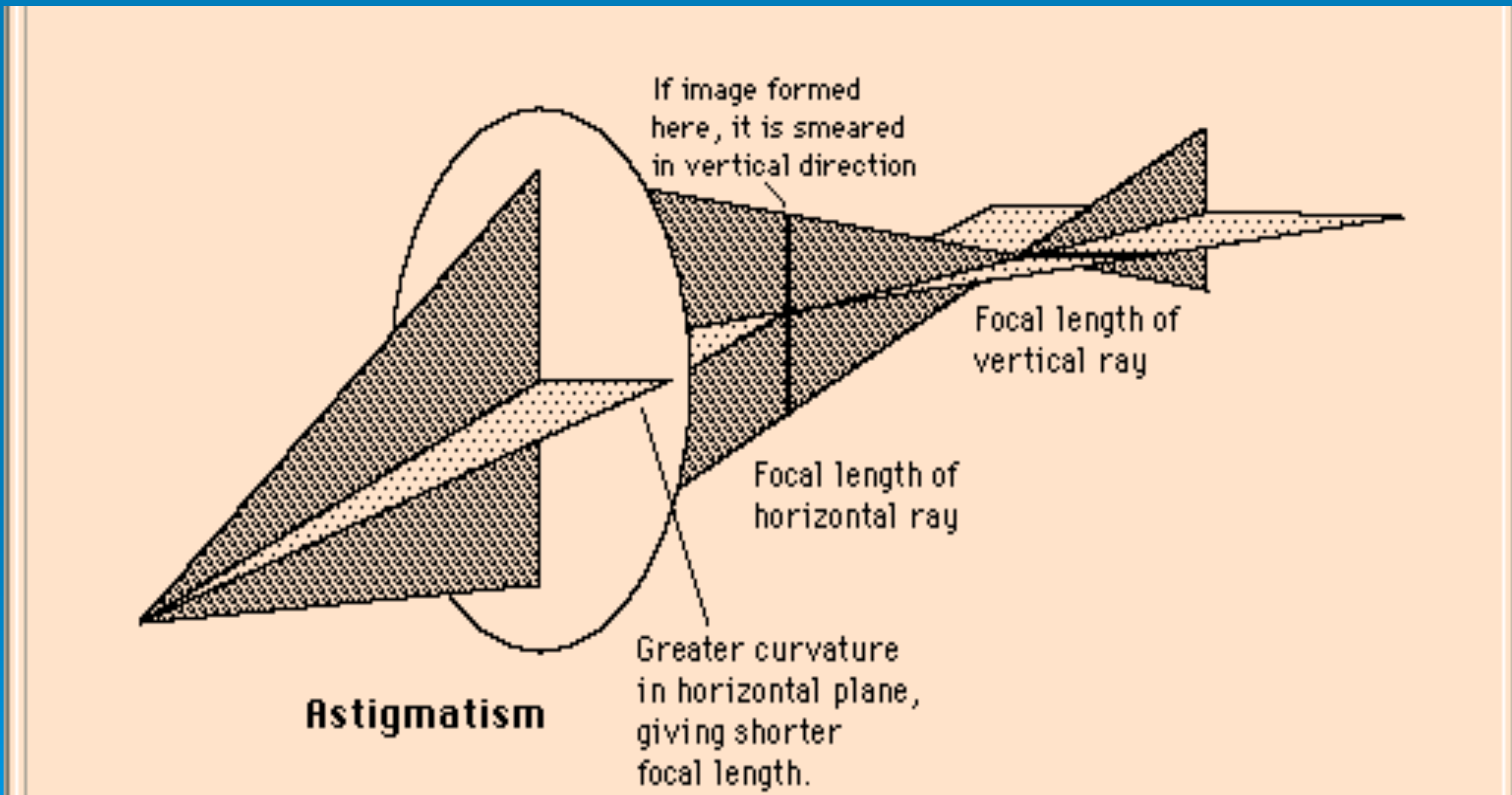


Spherical Aberration

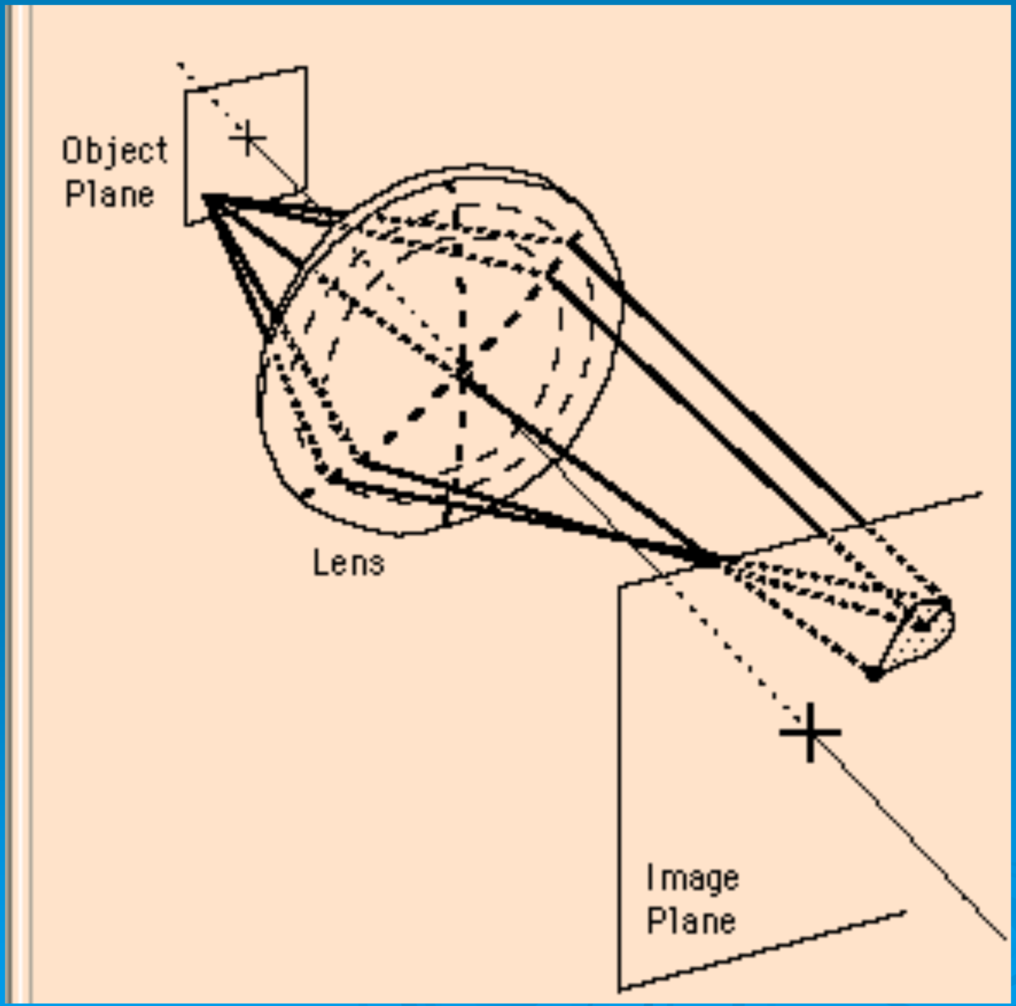
Rays Focus at Different Distances Depending on Position on Lens



Astigmatism

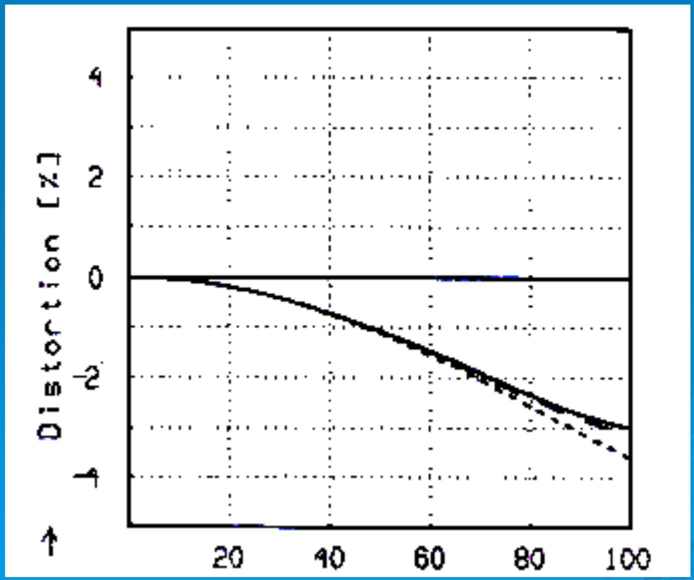


Coma Produces Trailing Comet-like Tail in Image



Lens Distortion Curves (typical)

- Lens distortion increases with the size of the image
- Distortion curve vs. fraction of maximum image size
  - Parameter is magnification: β
  - β = 0.0 (top curve) to 0.1 (bottom curve)



Fraction of maximum image size

The Camera

The NIR Camera

- Controls image acquisition, display, and control.
- Must not have NIR block filter installed
  - NIR block filter is installed on nearly all commercial cameras to reduce blurring caused by non-optimization in the NIR
- Must not have color filter on sensor
  - Installed on most commercial color cameras
- Must not have anti-aliasing diffuser installed
  - Often used to avoid aliasing effects from under-sampling

The Illuminator

Illuminator Requirements

- Sufficient light to produce low-noise images at the desired f-stop
- Uniform coverage
  - Reproducible results require uniform illumination over the object, over the entire permissible positional range of eye locations.
- Illumination must not injure the eye

NIR Imaging

- Iris imaging in the near-infrared (NIR) improves iris detail with dark irises.
  - 700-900 nm range is commonly used
- For blue irises, infrared illumination may produce less iris detail than visible light
  - Broad band sensor and optics can capture both NIR and visible light.

Effects of Illumination Wavelength

Brown Iris

Blue Iris

Visible Illumination

Infrared Illumination

Figure 74 (above). Dark brown irises often record lighter with infrared photography than blue ones, as can be seen in this comparison. The brown eye is on the left, the blue eye on the right; with panchromatic controls on the top and the infrared records below. Notice the detail in the irides of the brown eye with infrared. Image © Williams.

http://msp.pmit.edu.au

Illuminator Safety

- High illumination levels can cause permanent eye damage
  - NIR illumination is particularly hazardous
  - The eye does not respond with protective mechanisms (aversion, blinking, pupil contraction)
- Application requirements call for high light levels
  - Depth of field strongly affects usability
    - Typically achieved by increasing f-number
    - Required light level increases as square of f-number
  - Short exposure time reduces motion artifact
    - Required light level increases with reduced exposure time
  - Signal/noise ratio is improved as light level increases

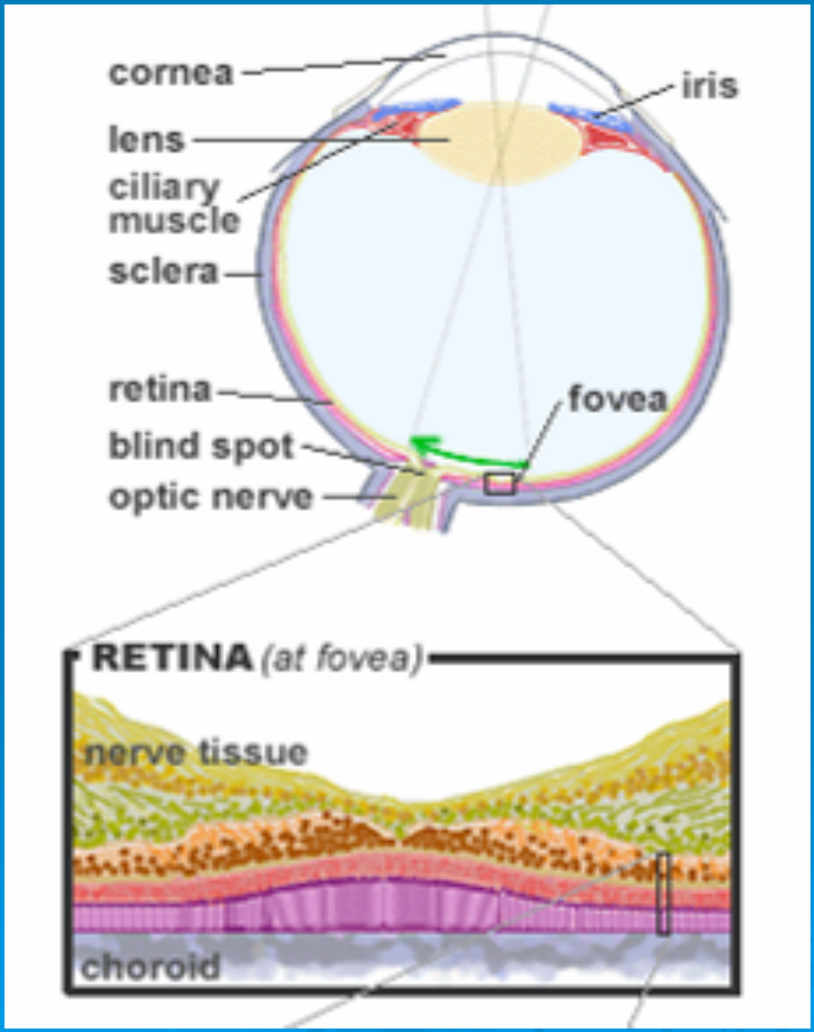
NIR Eye Safety

- NIR (near infrared) illuminators may pose safety issues
  - The eye does not respond to NIR
  - Does not protect itself as with visible light
    - Pupil contraction
    - Avoidance
    - Blinking
- Eye damage from NIR is due to heating
  - Unlike UV, IR does not have the energy to produce photochemical damage

NIR Eye Safety (2)

- Small and extended sources
  - Different safety limits for small and extended sources
  - LED is a small source
    - Eye produces focused image on retina
- Illuminators with multiple LEDs can be hazardous.
- Short duration (flash) illumination is safer for a given watt-seconds/mm^2

Structure of the Human Eye



Geometry of Retinal Exposure [ICNIRP]

D_L is Apparent Source Size through LED lens, specified by some manufacturers
Angular Subtense α is not the Beam Spread usually specified by the LED manufacturer

Extended and Small Sources of NIR

- Extended sources (diffuse light)
  - Can cause damage to cornea, lens and retina
- Small source safety for the retina
  - Small, bright emitters can be imaged onto the retina causing permanent injury.
  - Geometry of the source and eye must be considered
  - Safe level based on thermodynamic model of the retina

Quantities and Units

- **Radiance L_λ** is the source brightness Measured in Watts sr^{-1} cm^{-2}
  - Conserved through lenses
  - Requires knowledge of the apparent source diameter.
    - This is supplied by some manufacturers
    - See Vishay Semiconductors, TSAL5100
- **Irradiance** E_λ is the power density at the eye
  - Measured in Watts cm^{-2}

Protecting Cornea and Lens from NIR Radiation Damage [ACGIH]

For exposures greater than 1000 seconds, irradiance must be limited to less than 10mw/cm^{2}., as well as to:

$$\sum_{770nm}^{3000nm} E_{\lambda} \bullet \Delta\lambda \leq 1.8t^{-3/4}\ W/cm^{2}$$

Where:
λ = Wavelength of incident light
Summation is over λ range where light level is significant
E_{λ} = Irradiance onto eye in Watts/cm^{2}
t = exposure time in seconds
W = watts

Preventing NIR Retinal Damage [ACGIH]

Maximum safe source radiance viewed by the eye for periods greater than 10 seconds

$$\sum_{770nm}^{1400nm} L_\lambda \bullet R(\lambda) \bullet \Delta\lambda \le 0.6/\alpha \quad in\ \ Watt\ cm^{-2} sr^{-1}$$

L_λ = radiance of the source in Watt cm^{2} · steradian^{1}

α = Visual angle of the source at the eye

in radians = source diameter/viewing distance

$\alpha \le$ 0.1 radian, if greater, set it to 0.1 radian

$\alpha \ge$ 1.7 milliradian, not valid for smaller values

Preventing NIR Retinal Damage (cont.) [ACGIH]

- Maximum safe source radiance viewed by the eye for exposure period t ≥ 10 μ seconds, t ≤ 10 seconds.
- For t < 10μ sec, radiance limit is the same as for 10μ seconds

$$\sum_{770}^{1400} L_\lambda \bullet R(\lambda) \bullet \Delta\lambda \leq 5/(\alpha \bullet t^{1/4})$$

R(λ) is a Spectral Weighting Function

- Needed to account for the variation in hazard level as a function of wavelength
- For λ = 700-1050 nm, $R(\lambda) = 10^{(700 - \lambda/500)}$

LED Eye Safety Standards

- See References
  - [ACGIH]
  - [ICNIRP]
  - [ICNIRP 2000]
  - [IEC]
  - [ANSI]

Is This a Real Problem?

- There is no reported case of retinal injury from a single LED.
- "Only because of the extraordinary worst-case assumptions built into some current product safety standards could one reach the conclusion that an LED or IRED poses a safety hazard." [ICNIRP 2000]
- Multiple LED illuminators can easily exceed the 10/mw /cm^2 safety limit
  - Many illuminators use arrays of LEDs.
- New LED technologies are increasing brightness, so the situation bears watching.

The Subject Interface

Subject Interface

- Stability of the eye increases accuracy
  - Avoid motion artifact
  - Position iris uniformly
- Sources of motion
  - The body can move in three dimensions
  - The head can move independently
  - The eye can move independently

Subject Interface (2)

- Both eye and head position must be controlled
  - Cold mirror target with crosshairs
  - Audible feedback
  - Forehead and/or chin rest.
- Eye motion during exposure causes image blurring
- Saccadic motion blur
  - eye moves approximately .001”, 60 times/sec
  - may limit image resolution

References

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