Why do stars of different brightness have different diameters in an electronic image?

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http://www.narrowbandimaging.com/incoming/star_diameters_crisp.pdf

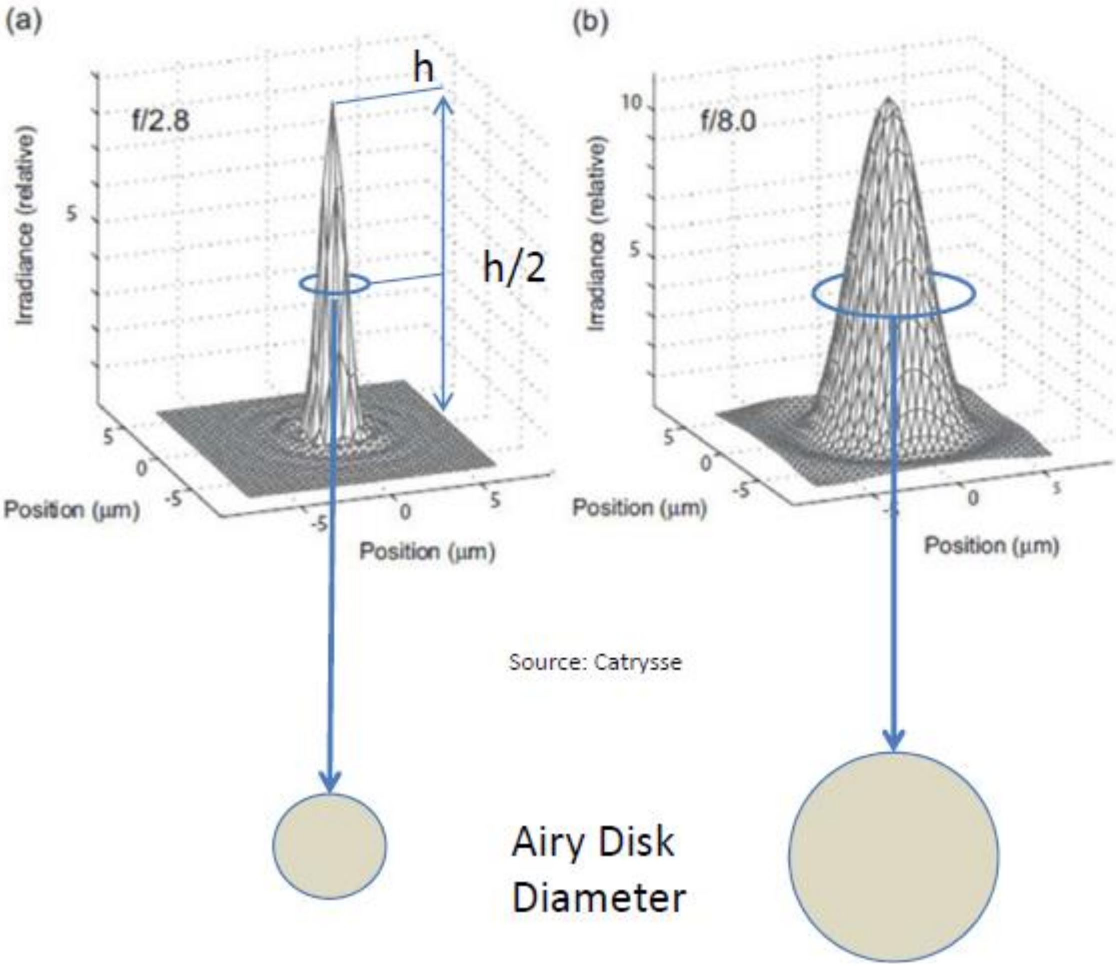
Questions

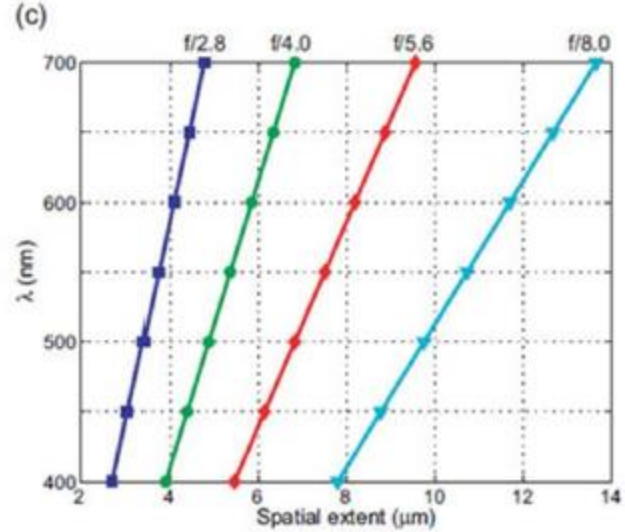
- Why do stars of different brightness have different diameters in a CCD / CMOS image even if all are unsaturated?

Airy Diameter

- Applies ONLY to diffraction limited case
- Function of wavelength and focal ratio ONLY
- Sampling point for “star diameter” is DEFINED at half of the maximum value of the star (arbitrary units)

Optics and the Airy Disk:
Focal ratio: Sets spot size for diffraction limited optics





Airy Disk Diameter (microns)

$2.44*f\#*\lambda =$
Airy Diameter

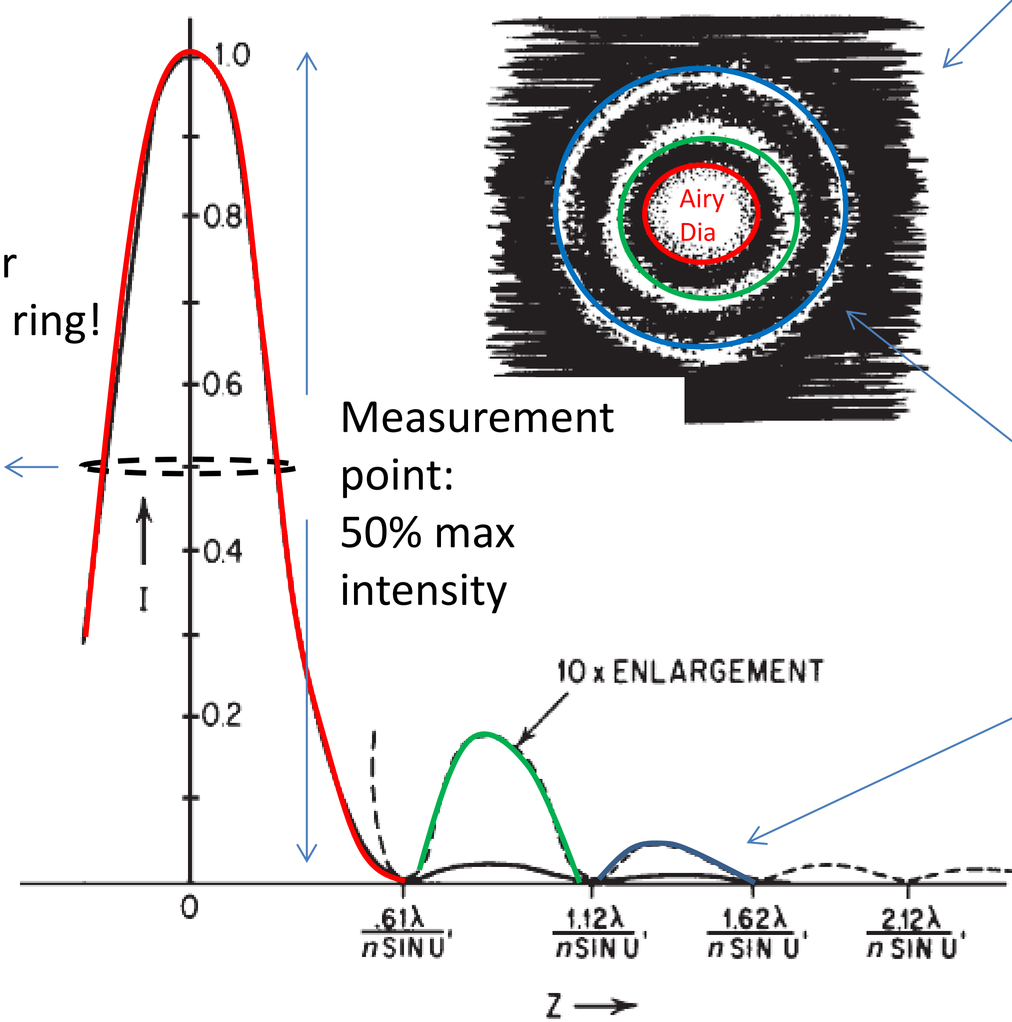
f#	wavelength nanometers	airy diameter (microns)
2.8	550	3.7576
4	550	5.368
5.6	550	7.5152
8	550	10.736

More details of Diffraction Limited Spot

Diffraction limited Spot

2.44*f#*λ =
Airy Diameter
Only the first ring!

Airy
dia



Periodic Rings
Described by
Bessel Function J_1

Figure 6.16 The distribution of illumination in the Airy disk. The appearance of the Airy disk is shown in the upper right.

Source: Smith "Modern Optical Engineering"

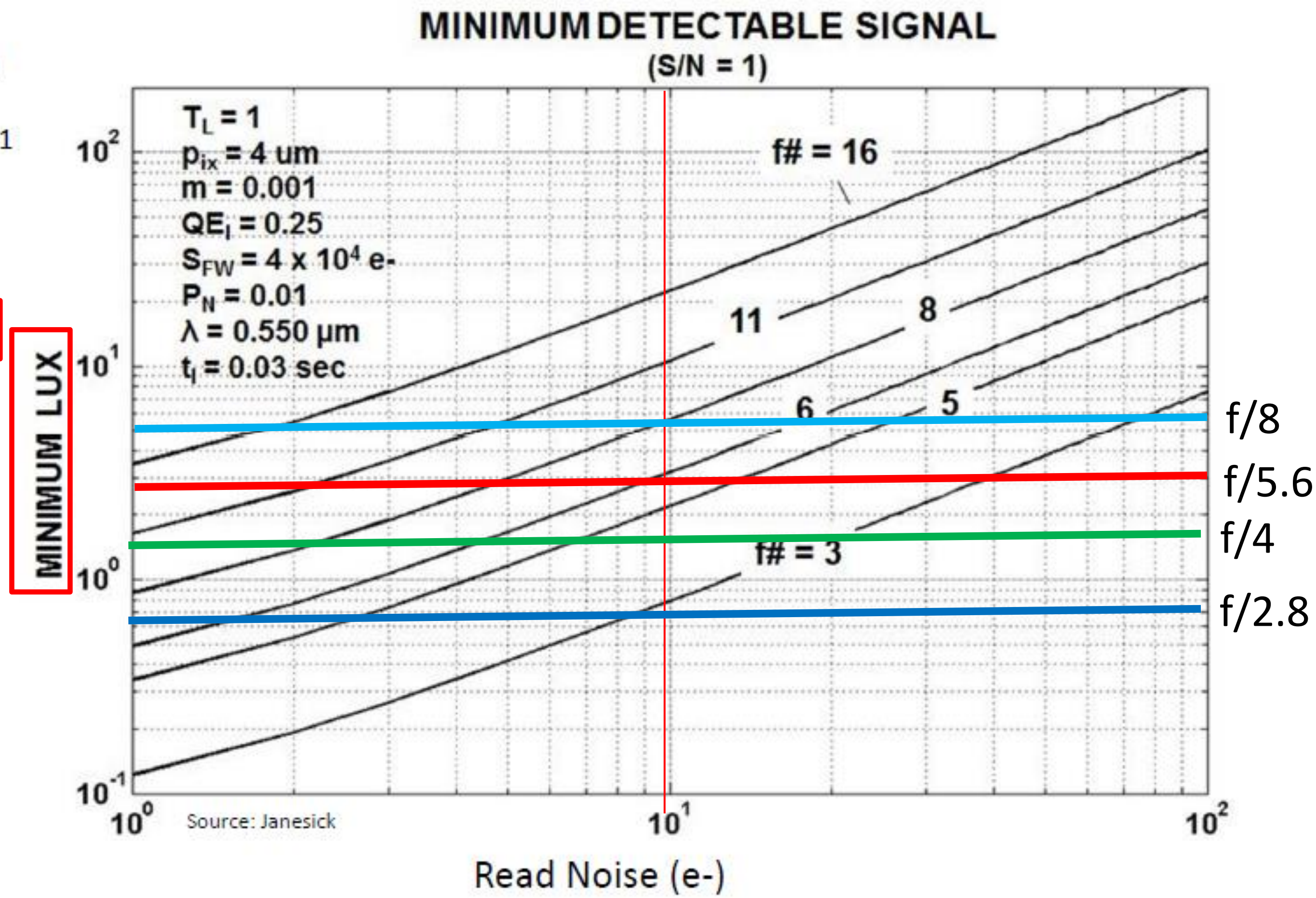
Airy Diameter vs What You See on an Image of a Starfield

- Airy Diameter: is DEFINED at half of the maximum value of the star intensity (arbitrary units)
- It applies to diffraction limited conditions: seeing-limited is more common but it doesn't change the fact that there's a star profile that is at the root-cause of the bloat issue (read on through the doc)
- This is different than sampling a star field with an electronic imaging system
  - There's a discrete "Detection Limit" for the Electronic Imaging System
    - Signals brighter than Detection Limit will be resolved
    - Signals dimmer than the Detection limit will be obscured in noise
  - Detection Limit is function of many variables including Read Noise, QE, F#, Optical Transmission etc
  - Detection Limit Units: Lux-Sec is common
    (Lux-sec: "light intensity * time of integration"

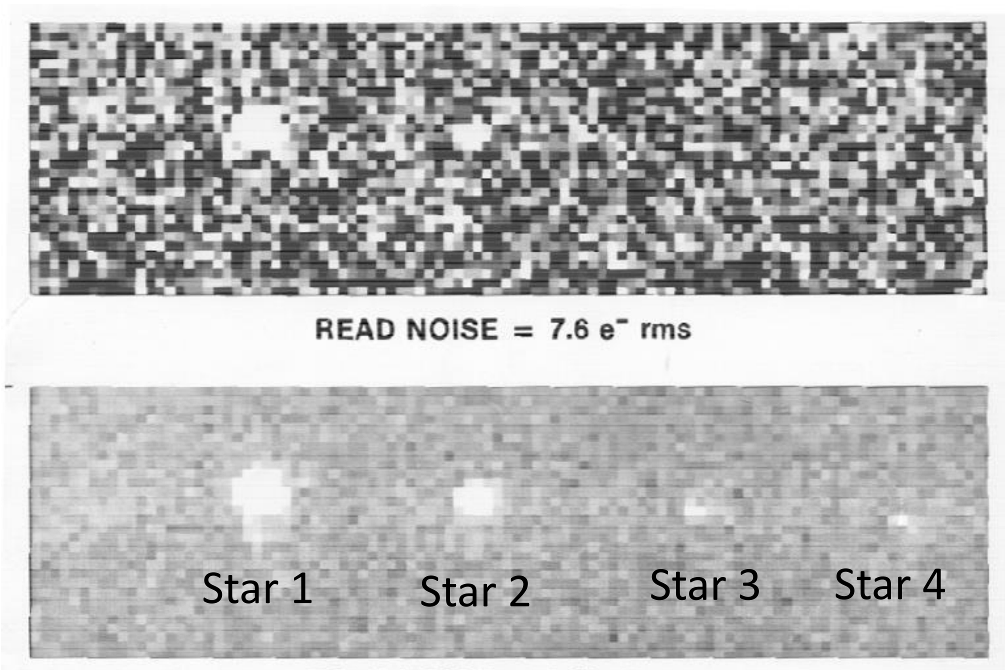
Detection Limit vs Read Noise

100% optical transmission
4 micron pixel
Lens magnification of 0.001
QE = 25%
Full well = 40Ke-
PRNU = 1%
550nm wavelength
Exposure time = 30msec

Exposure: Lux-Seconds



Detection Limit / Read Noise (example)



Source: Janesick

Higher read noise has higher detection limit

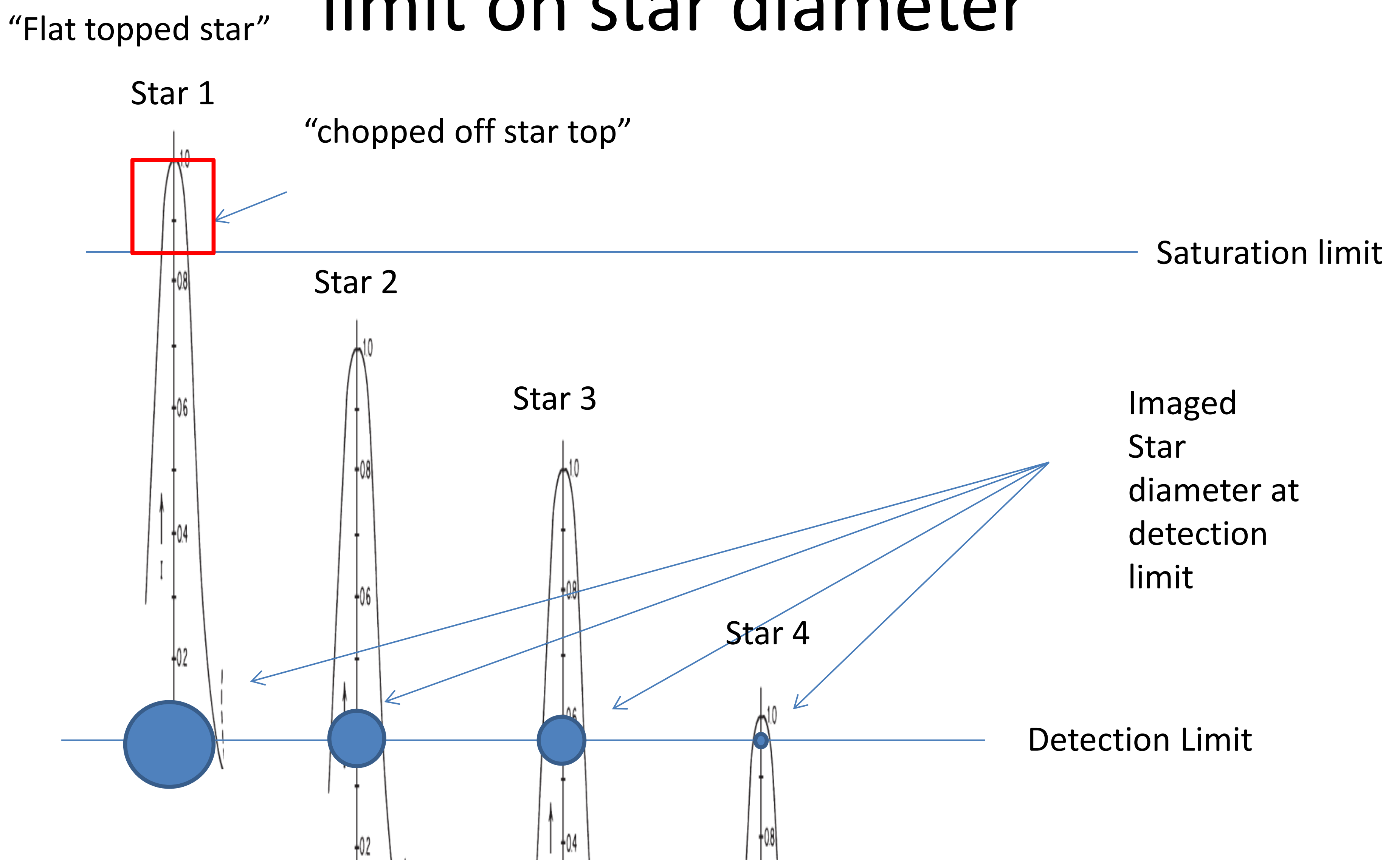
Lower read noise has lower detection limit

Airy Diameter vs What You See in an Image of a Starfield

- In general different brightness stars encounter the detection limit at different percentages of the total "height" of the intensity/distance plot of the star ("cross section")
  - Result is brighter stars have larger diameters than dimmer stars
  - **This is the primary source of "star bloat"**
  - Other factors can contribute
    - Dirty optics
    - Optical scattering
      - External to telescope (dust in atmosphere: transparency)
      - Internal to imaging system
        - » Optics/flocking etc
        - » Reflections
        - » Microlens scattering
    - Image sensor Diffusion MTF
      - Some percentage of photoelectrons will wind up in wrong pixel, but number is very small for visible light wavelength + imagers\
      - For NIR this can be an issue.
      - But image will look smeared if you have Diffusion MTF issues
- And of course Airy Diameters are only relevant to diffraction limited seeing which is rarely encountered in terrestrial sited astronomical instruments

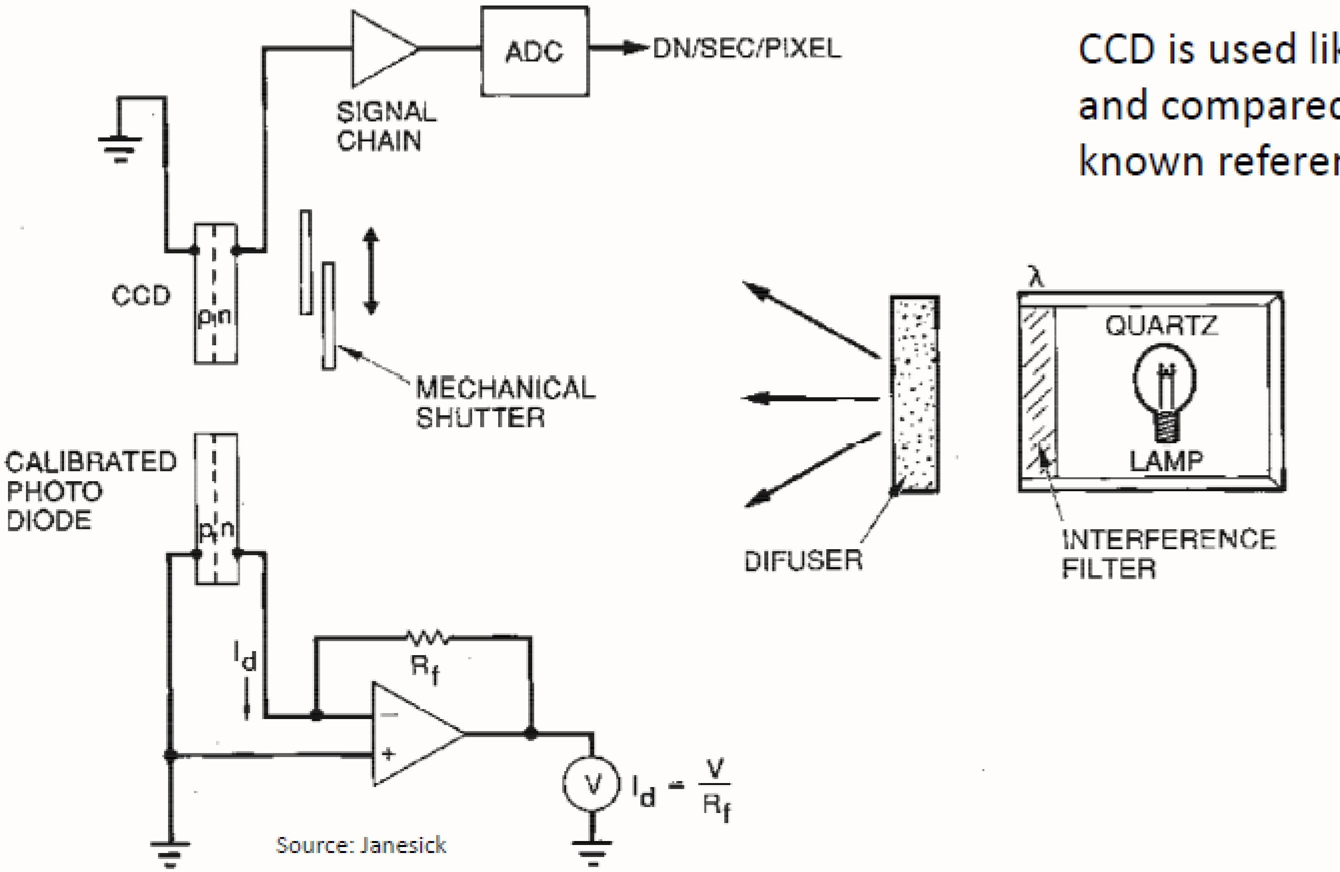
Sampling Starfield with Electronic Sensor: Shows impact of detection limit on star diameter

Crisp 06/05/2016



Appendix: Diffusion MTF
&
Issues When Imaging at NIR wavelengths

QE Measurement



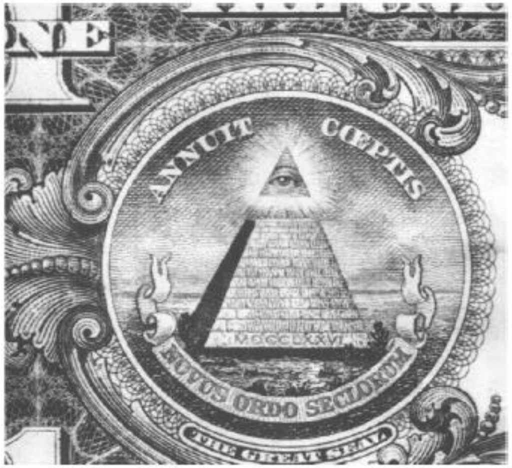
Source: Janesick

CCD is used like a "solar cell" and compared against a known reference diode

QE doesn't tell the whole story

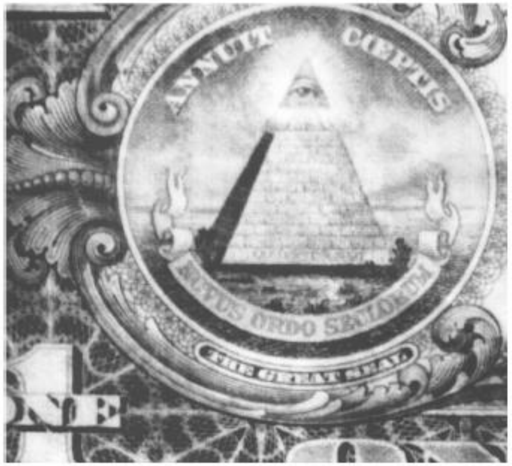
- The entire CCD is used as a single light collector for measuring QE
- If the photoelectrons are collected in the wrong pixels, it makes no difference in the QE value measured
- This can happen when NIR light is used for a CCD

Diffusion MTF/Crosstalk



400nm light

Source: Janesick



900nm light

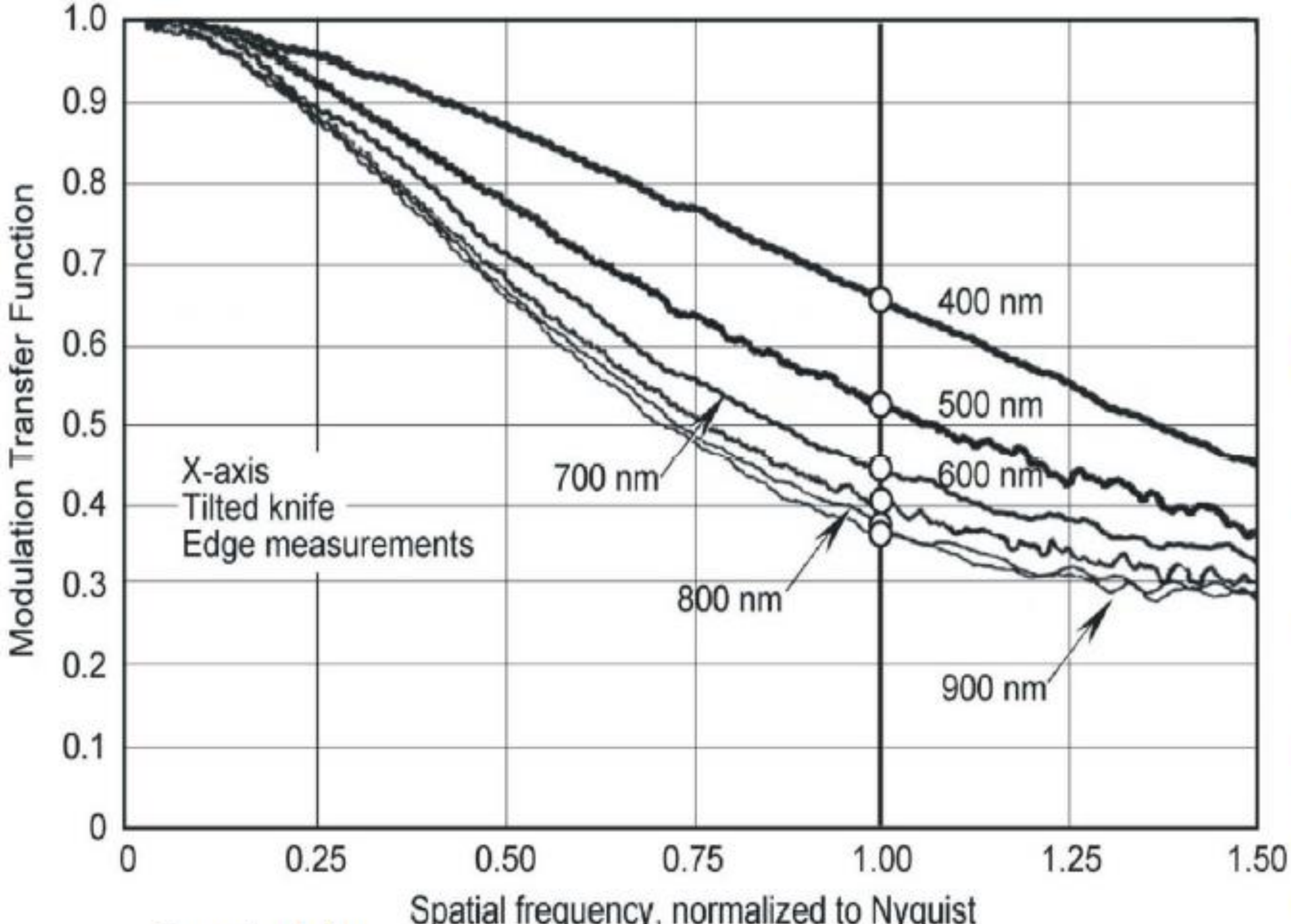
Longer wavelength light penetrates deeper before liberating photoelectrons / holes
If interaction happens outside potential well, then some charge will be captured by the wrong pixel.
CCDs needed for NIR imaging need careful design / fab process optimization to have good MTF.

If Filters without NIR blocking are used it is possible that bright stars will bloat from Diffusion MTF concerns: Stars are broadband and contain significant NIR

The stars are usually the brightest source of NIR in an image and that could cause only bright stars to be effectively impacted by NIR Diffusion MTF

Deep Depletion CCDs such as made by E2V are designed to have good Diffusion MTF at NIR wavelengths

MTF vs Wavelength



Source: Lomheim

Very poor response for NIR wavelengths (>700nm)

At 400nm 65% of charge ends up in correct pixel at Nyquist sampling

At 700nm only 40% does and at 900nm only 35% does

NIR images taken with this sensor will have fine detail smeared

Imaging at NIR wavelengths

- Kodak KAF series sensors have degraded MTF at NIR wavelengths
- Even with all-reflective optics (no chromatic aberration), poor sharpness results due to sensor Diffusion MTF/Crosstalk unless sensors *specifically* designed to work at NIR
- QE is only part of the story, MTF is the big issue for NIR
- Sensors designed for NIR imaging use specialized wafer fab processes and may include high substrate bias voltages to ensure good MTF (to prevent photoelectrons from forming outside of pixel potential wells)

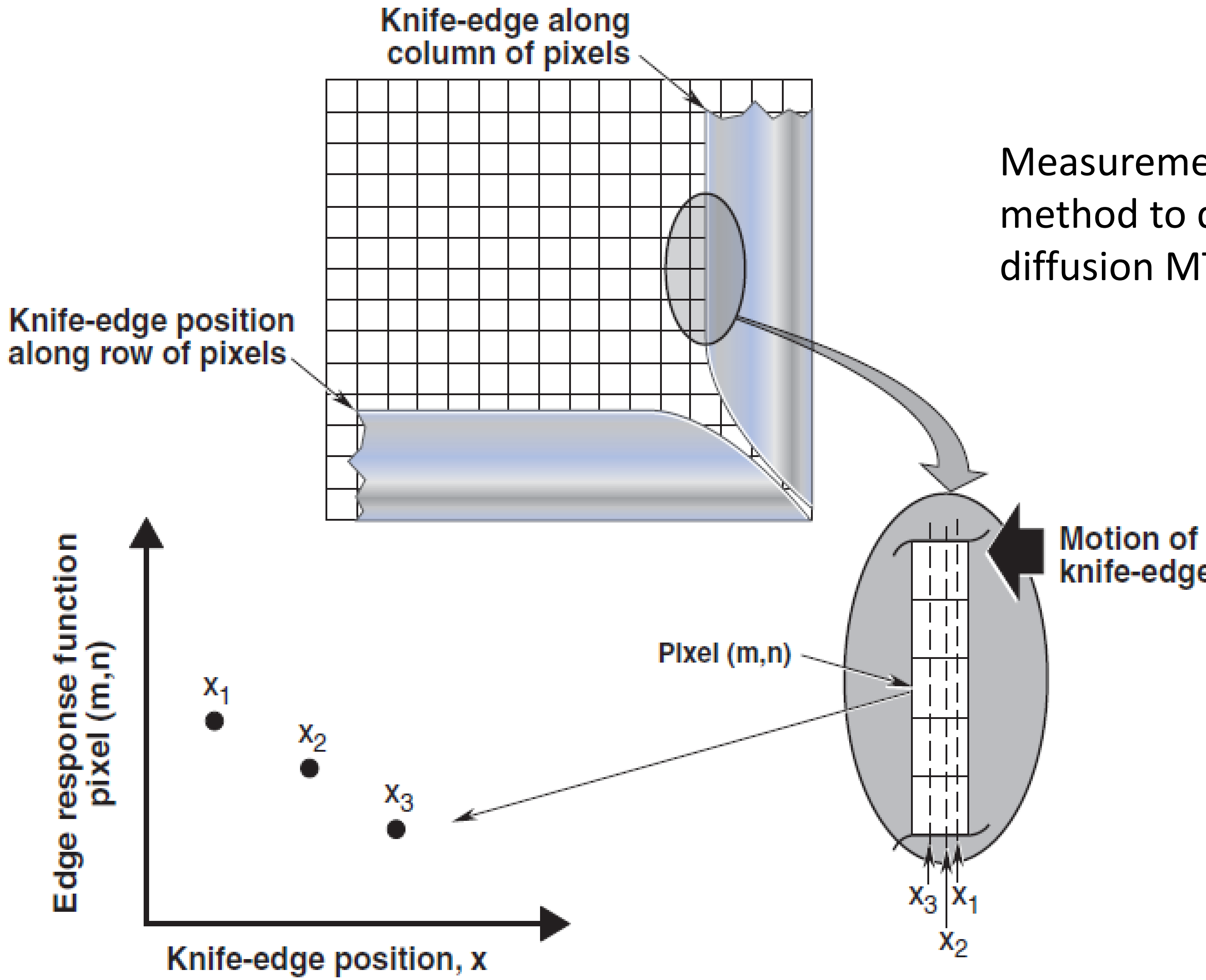
NIR and Stars: notch?

- As shown NIR can cause smearing of objects
- Stars are bright and contain broadband including NIR
- If your filters don't notch NIR, you may get bloat from the NIR in the stars caused by diffusion MTF issues
- Try a NIR blocking filter to see if it changes the bloat

Measuring Sensor MTF

Knife-edges Aligned Along the Row and Column Directions of a Two-dimensional Focal Plane Array

Response of Pixel (m,n) to Knife-edge Positions x_1, x_2, and x_3 is Shown



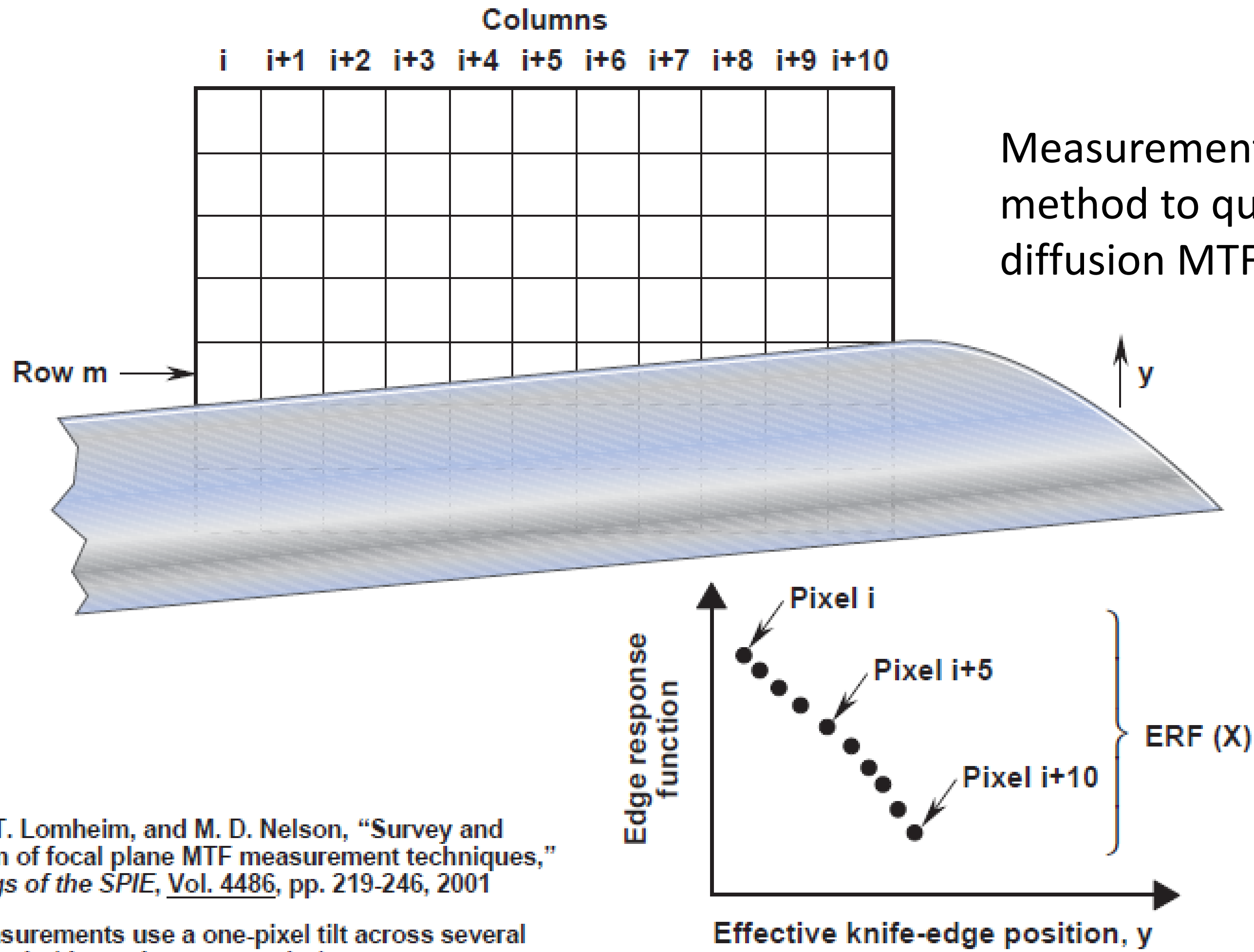
Measurement method to quantify diffusion MTF

Source: Lomheim

Static Tilted Knife-edge[1] Across the 10-pixels in Row

Edge Response Function (ERF) is Synthesized from Responses of the 10 Pixels as Shown*

Measurement method to quantify diffusion MTF



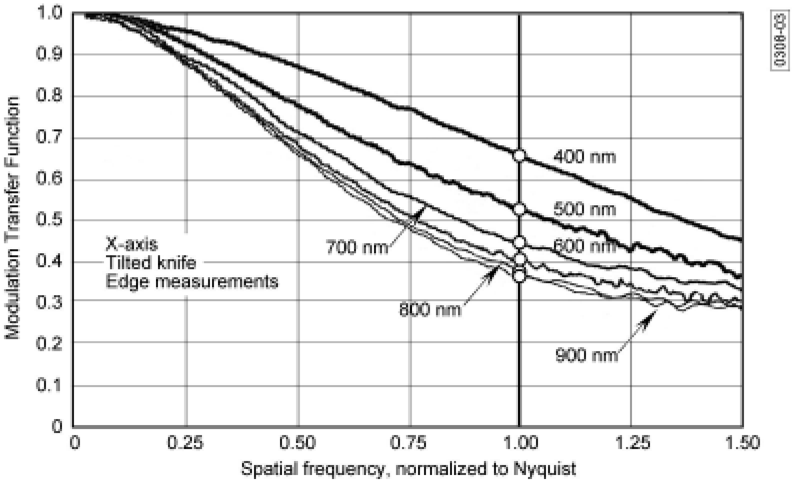
[1] T. Dutton, T. Lomheim, and M. D. Nelson, "Survey and comparison of focal plane MTF measurement techniques," *Proceedings of the SPIE*, Vol. 4486, pp. 219-246, 2001

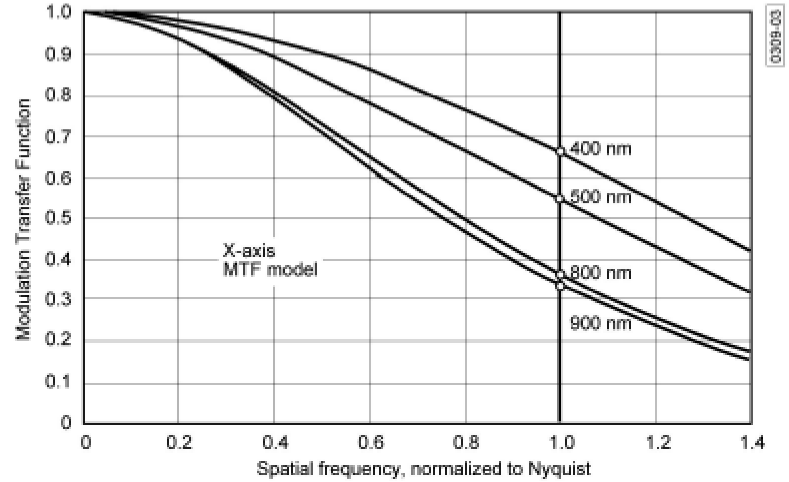
*Actual measurements use a one-pixel tilt across several hundred pixels (depends on array size)

Source: Lomheim

Spectral MTF Measurement and Modeling Results

JPL VIDI APS – x-direction





VIDI APS

- 12 μm pixel pitch (Nyquist = 41.7 p/mm)
- n+ photodiode (shallow depletion depth)
- Thin epitaxial layer
- Photodoide area (x-direction = 11 μm; y-direction = 6 μm)

Model Assumptions

- Photodiode width = 11 μm
- Depletion layer = 0.3 μm
- Epitaxial layer = 7 μm

- MTF model: $MTF_{APS} = \underbrace{MTF_{pixel}}_{\text{“sinc”}} \times \underbrace{MTF_{diffusion}}_{\text{Blouke/Robinson Model}}$
- General features fit well by model below ~1.2 $f_{Nyquist}$
  - Anomalous MTF response above 1.2 $f_{Nyquist}$ suggests more complex pixel aperture
- Pixel sinc behavior is evident at 400 nm
- Rapid onset of diffusion is due to shallow depletion layer
- Curves coalesce for $\lambda > 800$ nm due to 7 μm epi thickness

Source: Lomheim