MTF as an indicator of image quality, data efficiency, user friendliness, and product competitiveness

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Outline

- PSF, LSF (Point/Line Spread Function)
  - FWHM (Full Width at Half Maximum)
  - MTF (modulation transfer function)
- MTF := retaining rate of detail @Nyquist Frequency
- Appearance of small objects
- Effects of over-sampling with a factor > 2 (FWHM_LSF > 2.0 pixels)

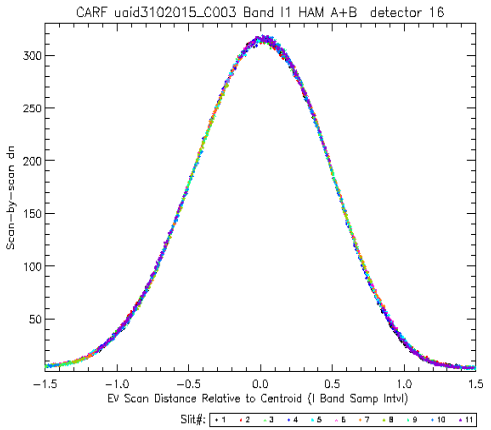
A theorem on Nyquist frequency

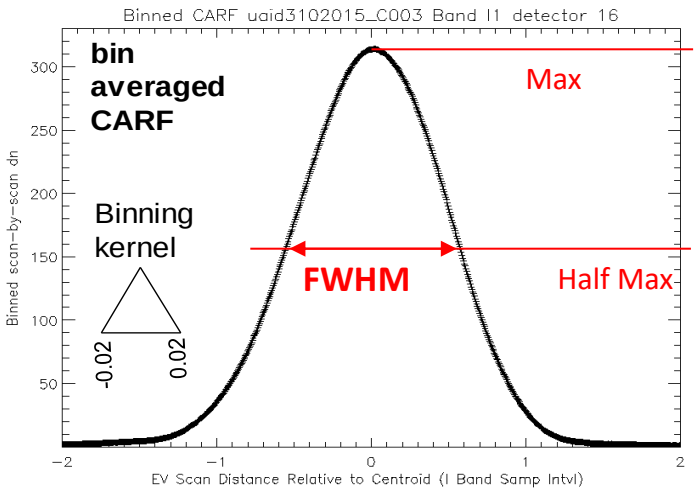
The "Shannon theorem," also referred to as the **Nyquist-Shannon sampling theorem**, states that to accurately reconstruct an analog signal from its digital samples, the sampling rate must be at least twice the highest frequency present in the signal, and the "**Nyquist frequency**" is the **maximum frequency** that can be accurately captured based on the sampling rate, that is exactly **half of the sampling rate** itself.

Nyquist–Shannon sampling theorem - Wikipedia

- Digital sampling is designed to potentially preserve the detail at the Nyquist frequency
- Sensor system PSF/LSF may filter out that potential

LSF → FWHM, MTF





Modulation transfer function (MTF)

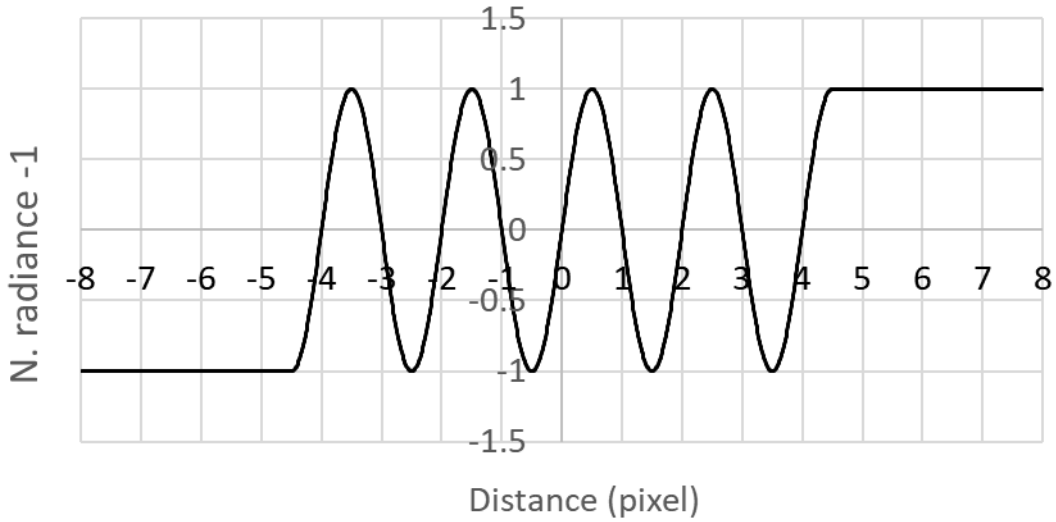
$$\mathrm{MTF}(\omega) = \frac{|FourierTransform(LSF)|}{|FourierTransform(LSF)|_{\omega=0}}$$

ω is expressed in fraction of Nyquist frequency (NF)

$$\mathrm{NF} = \frac{1\ cycle}{2\ sampling\ intervals}$$

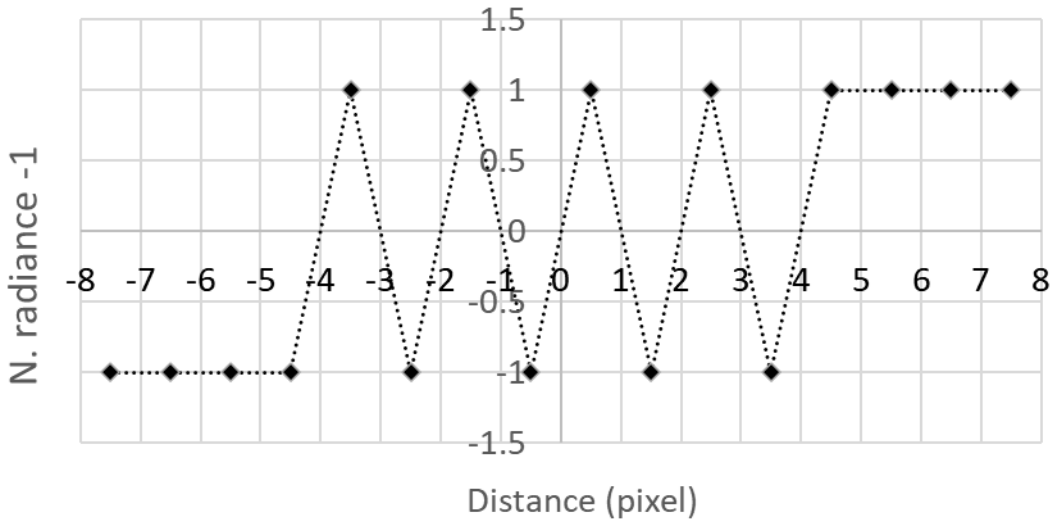
FWHM = Full Width at Half Maximum, a metric for an image's true spatial resolution

Hypothetical scene with detail at Nyquist frequency



Hypothetical scene with detail at Nyquist frequency

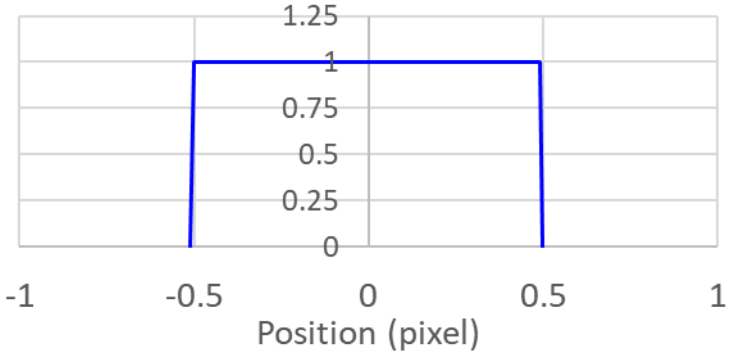
Point sampling



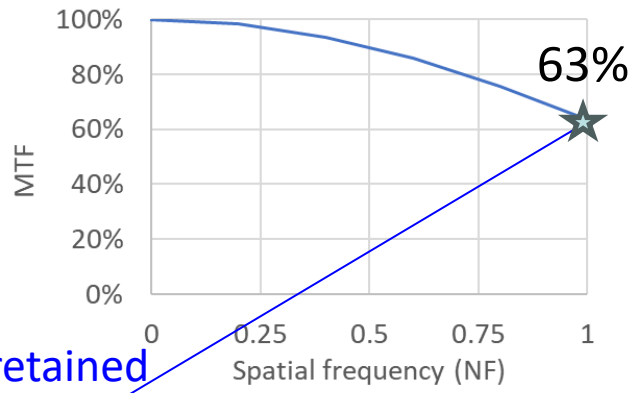
Hypothetical scene with detail at Nyquist frequency

Nyquist sampling

Rectangular LSF FWHM = 1

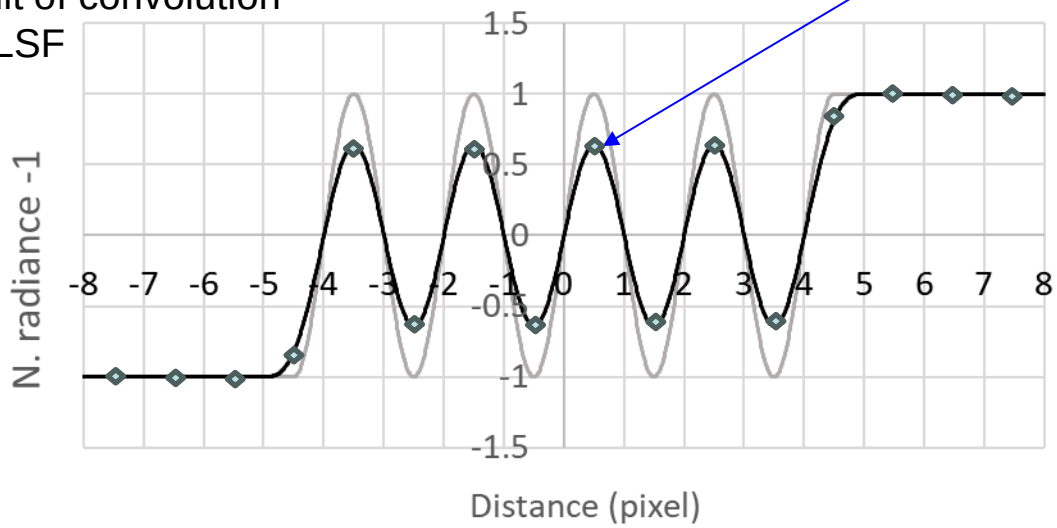


MTF



63% amplitude retained

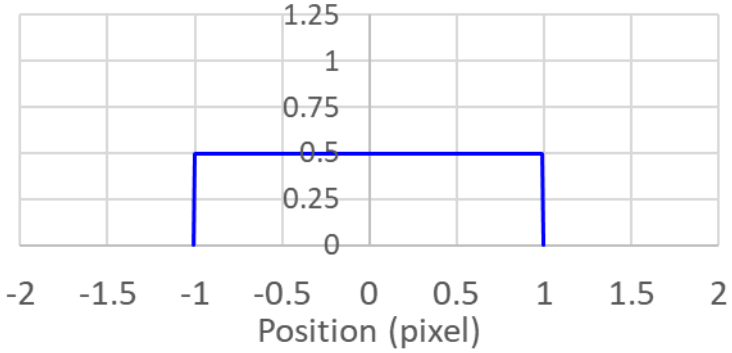
Black curve is the result of convolution of gray curve with the LSF



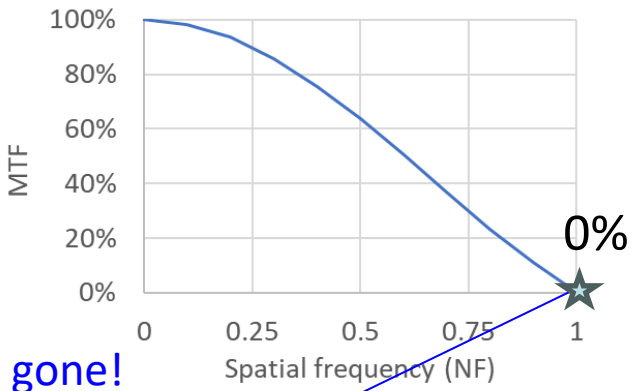
Hypothetical scene with detail at Nyquist frequency

Over-sampling, factor = 2

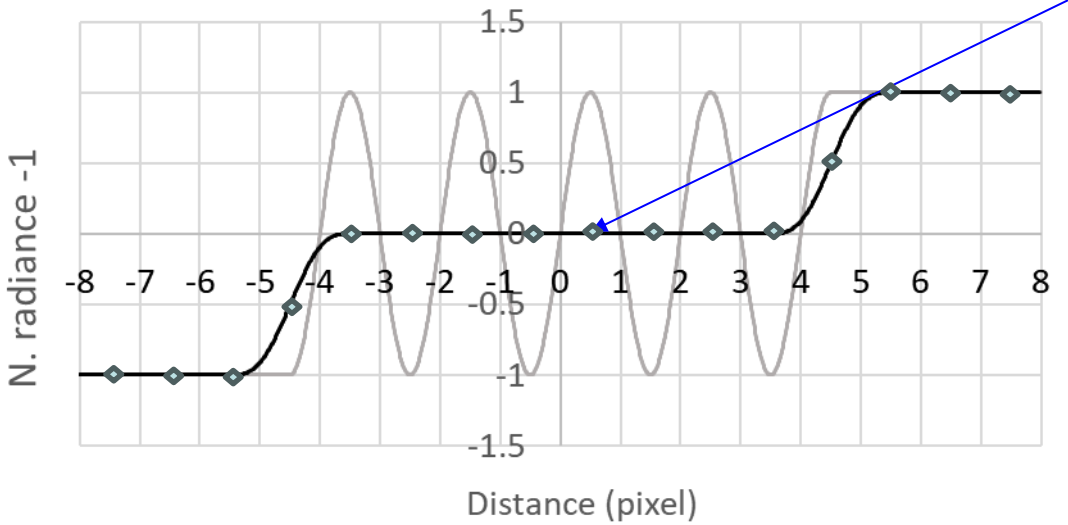
Rectangular LSF FWHM = 2



MTF



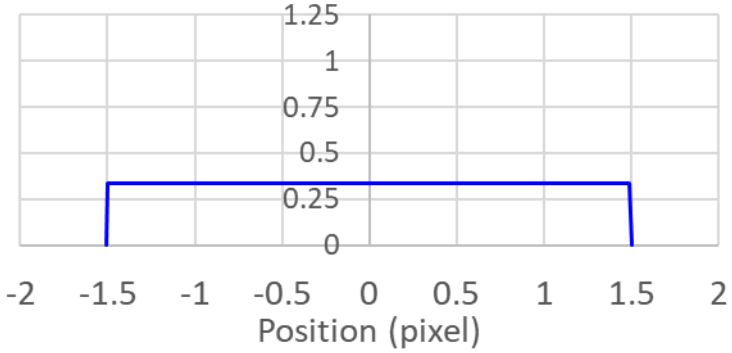
Amplitude gone!



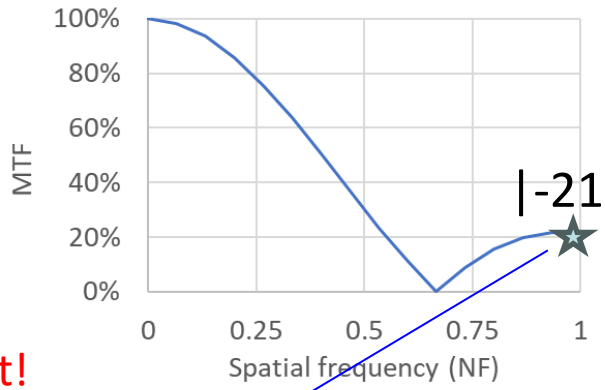
Hypothetical scene with detail at Nyquist frequency

Over-sampling, factor = 3

Rectangular LSF FWHM = 3

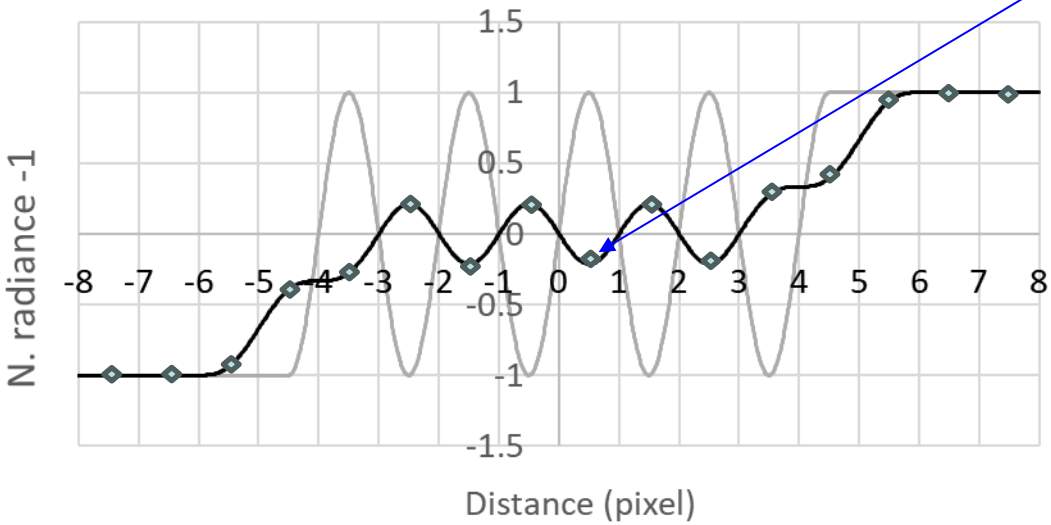


MTF



|-21%|

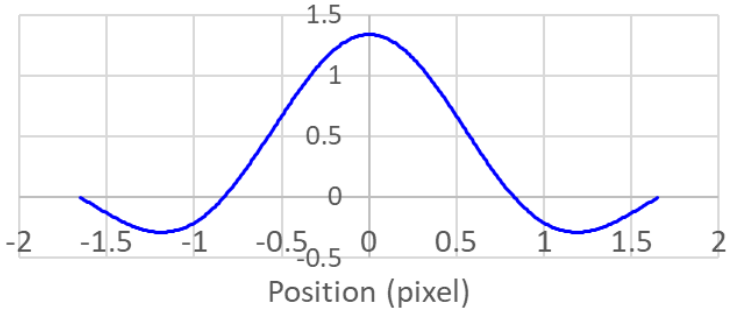
Phase shift!



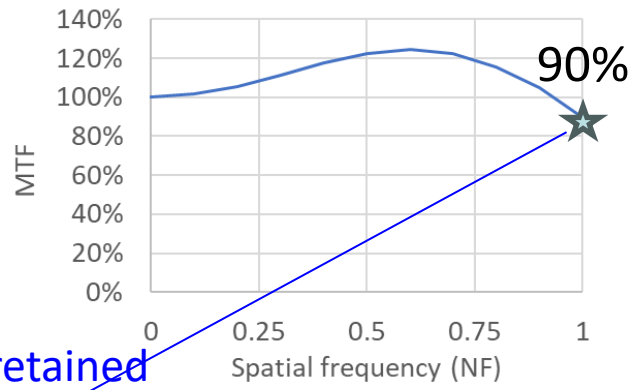
Hypothetical scene with detail at Nyquist frequency

Nyquist sampling

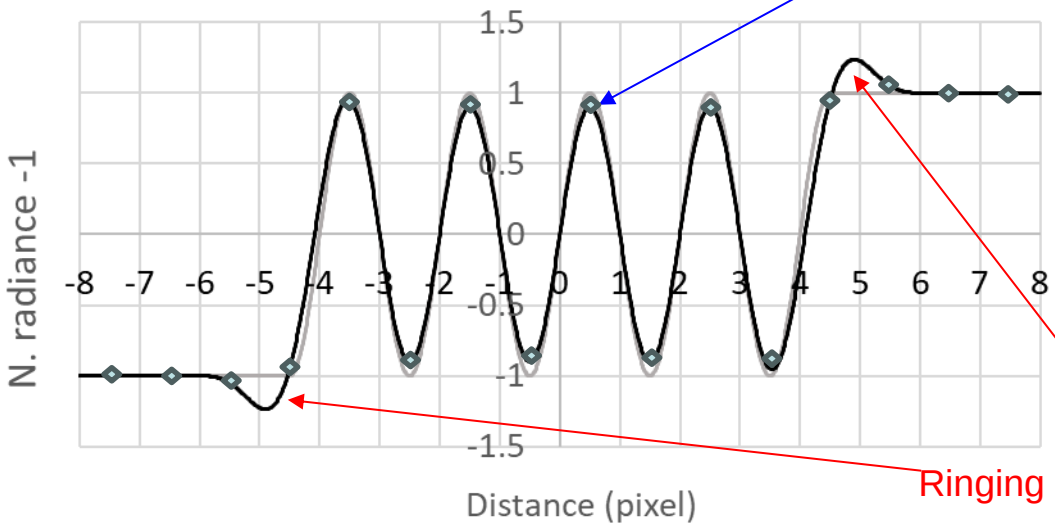
Sinc function LSF FWHM = 1



MTF



90% amplitude retained

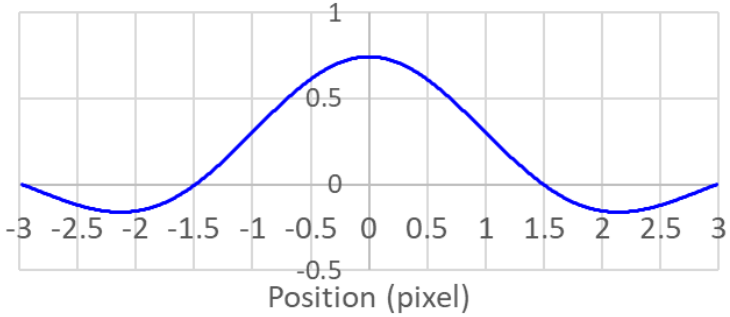


Ringing artifacts

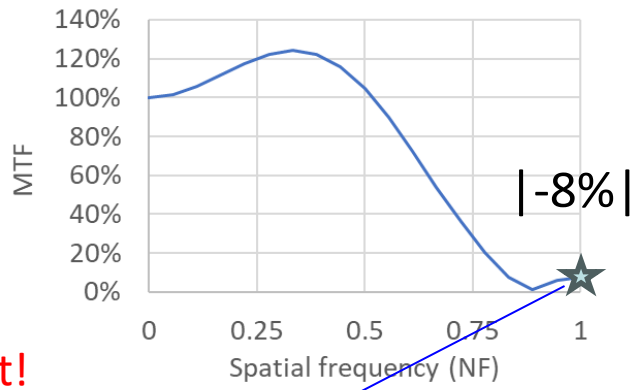
Hypothetical scene with detail at Nyquist frequency

Over-sampling, factor = 1.8

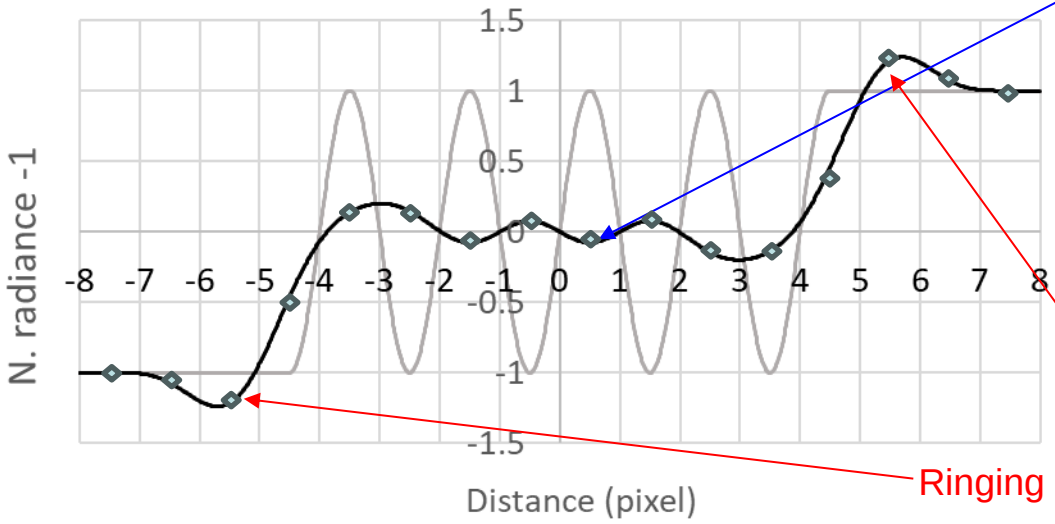
Sinc function LSF FWHM = 1.8



MTF



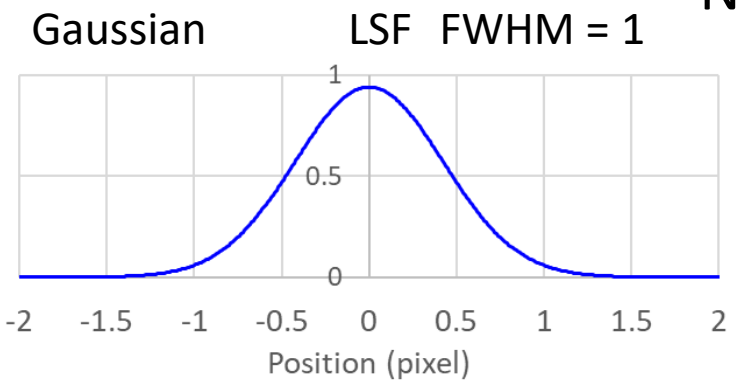
Phase shift!

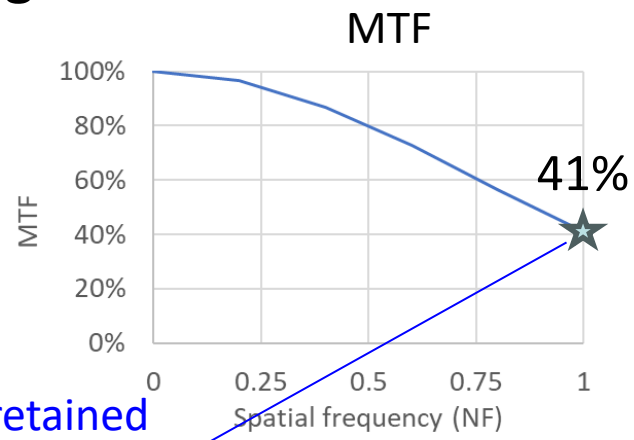


Ringing artifacts

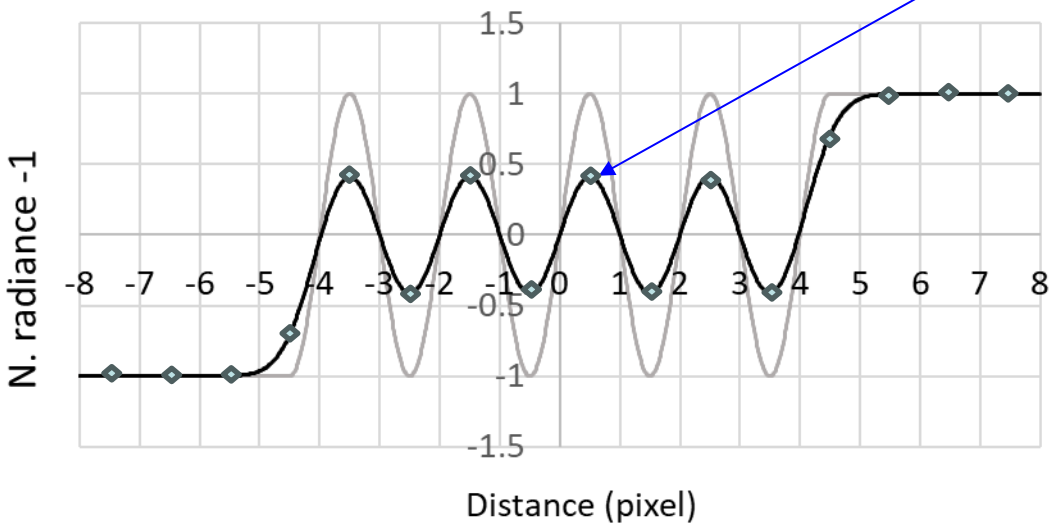
Hypothetical scene with detail at Nyquist frequency

Nyquist sampling





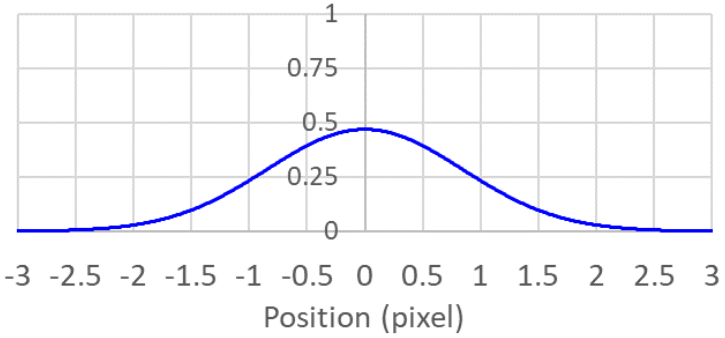
41% amplitude retained



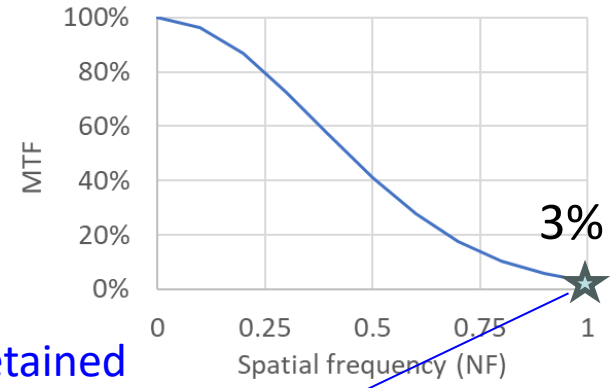
Hypothetical scene with detail at Nyquist frequency

Over-sampling, factor = 2

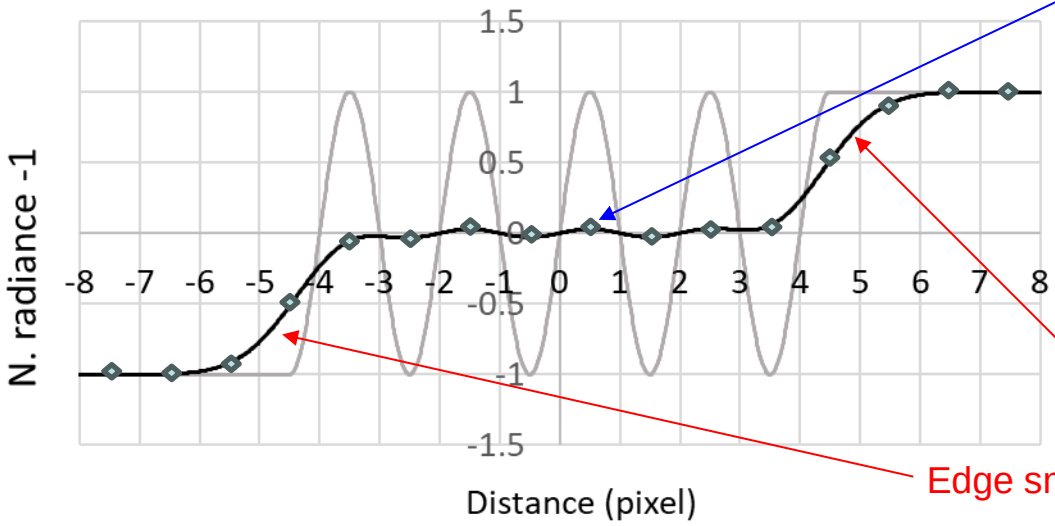
Gaussian LSF FWHM = 2



MTF



3% amplitude retained

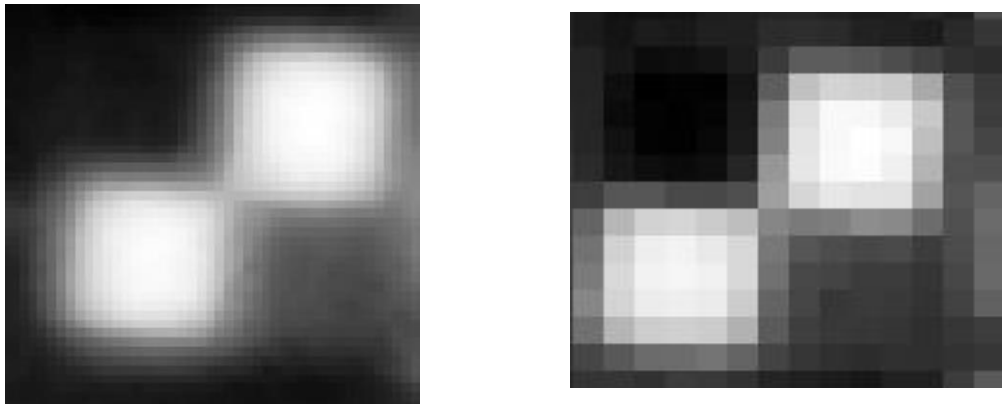


Edge smearing

Room for improvement

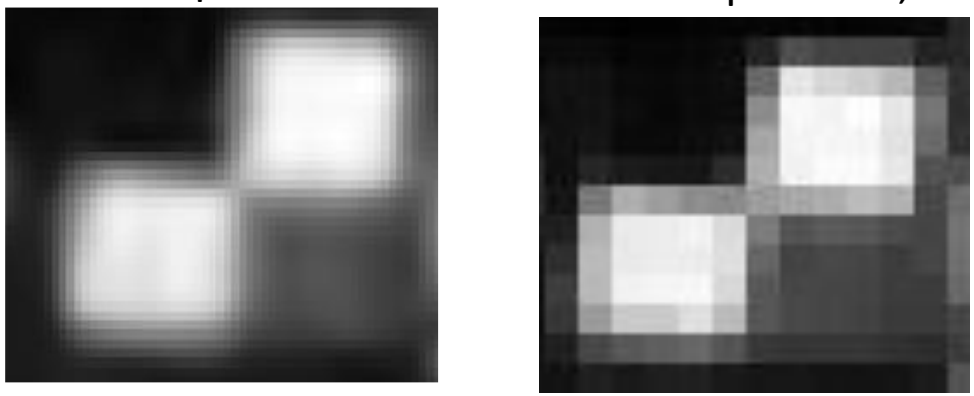
A Commercial image

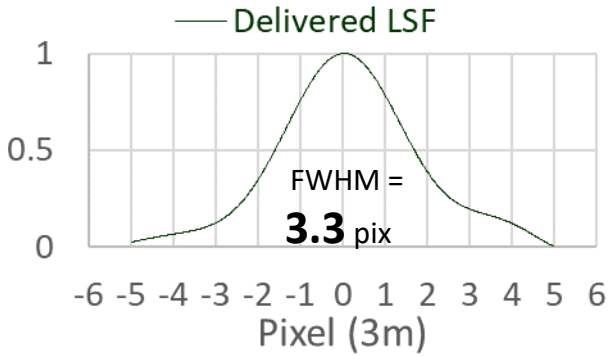
Delivered pixel size, 3 m → Aggregated, 9 m

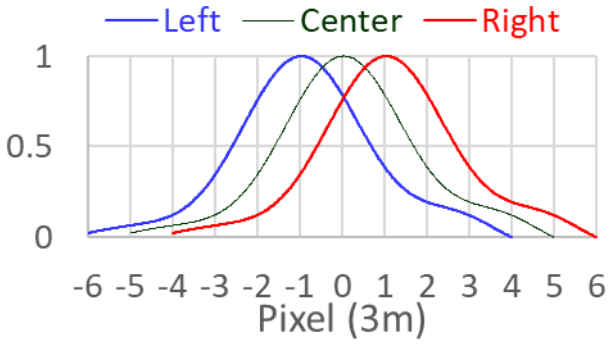


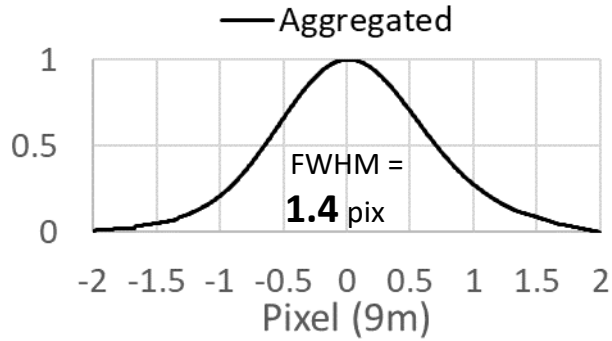
Sentinel-2

Resampled, 3 m ← Delivered pixel size, 10 m

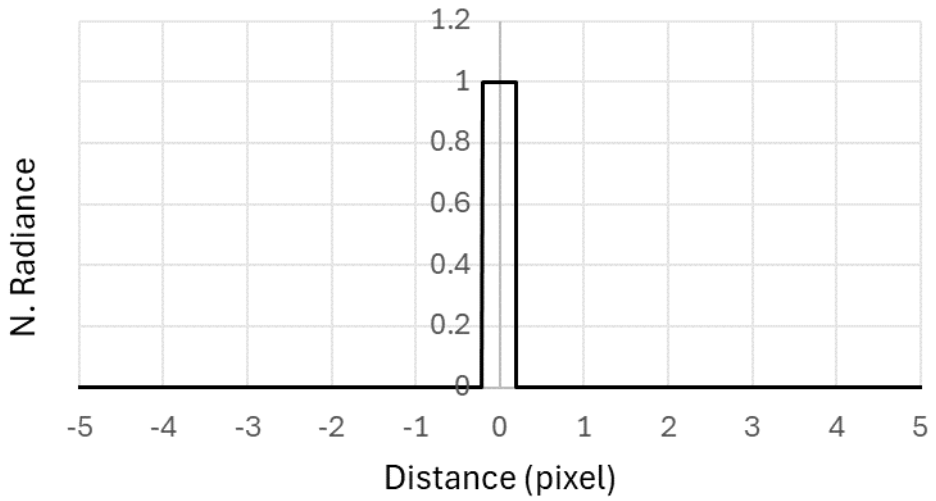






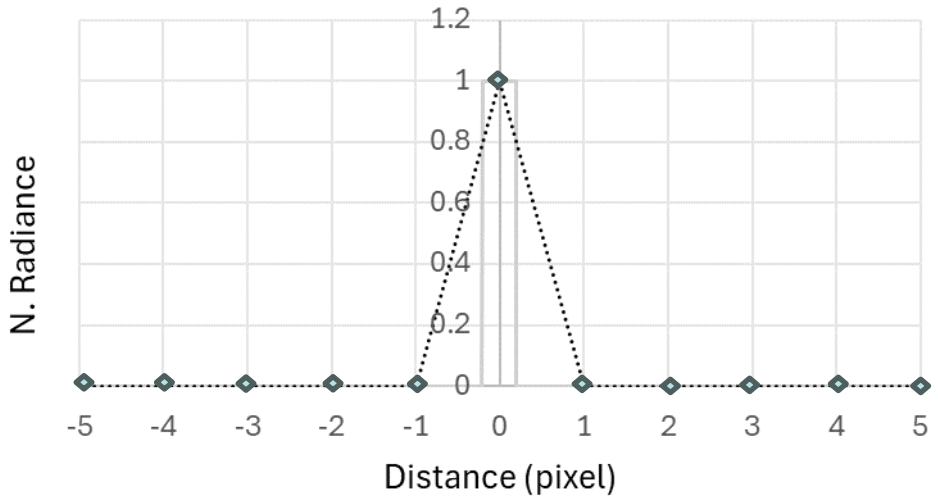


An isolated small object



An isolated small object

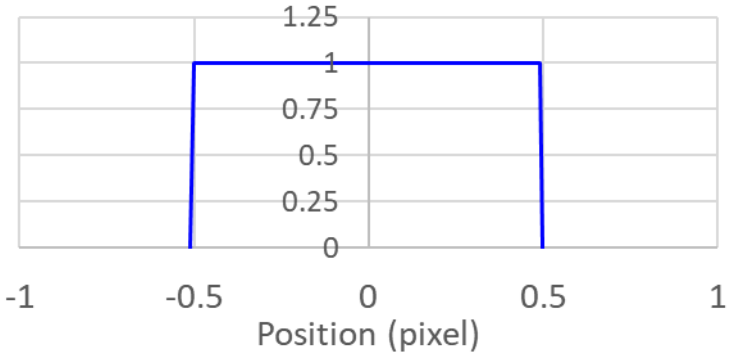
Point sampling



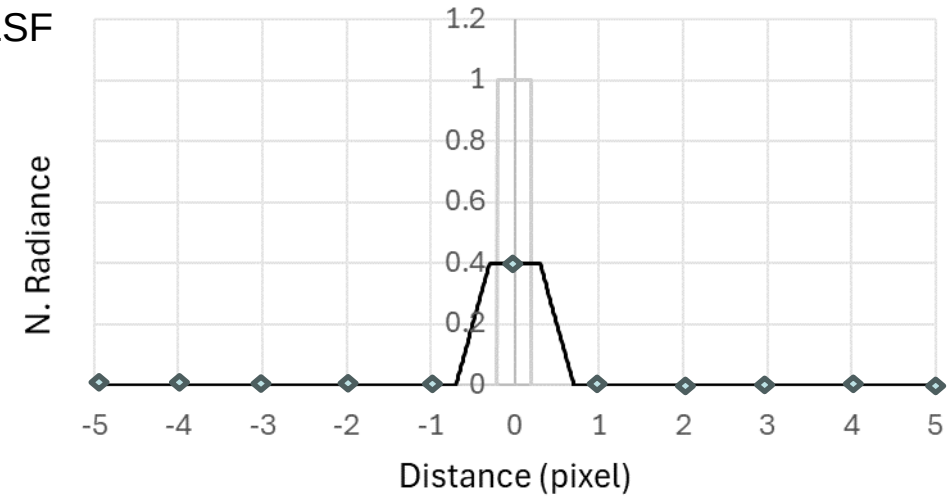
An isolated small object

Nyquist sampling

Rectangular LSF FWHM = 1



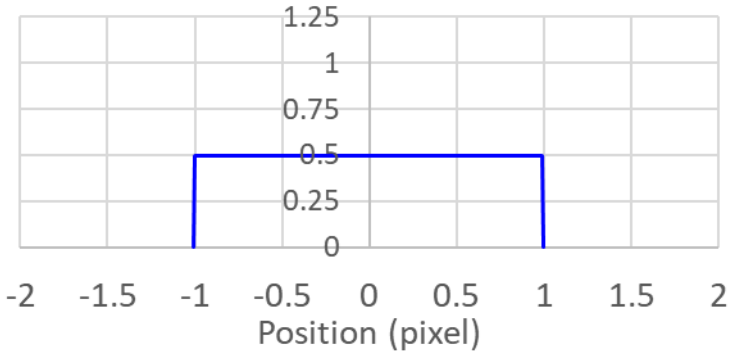
Black curve is the result of convolution of gray curve with the LSF

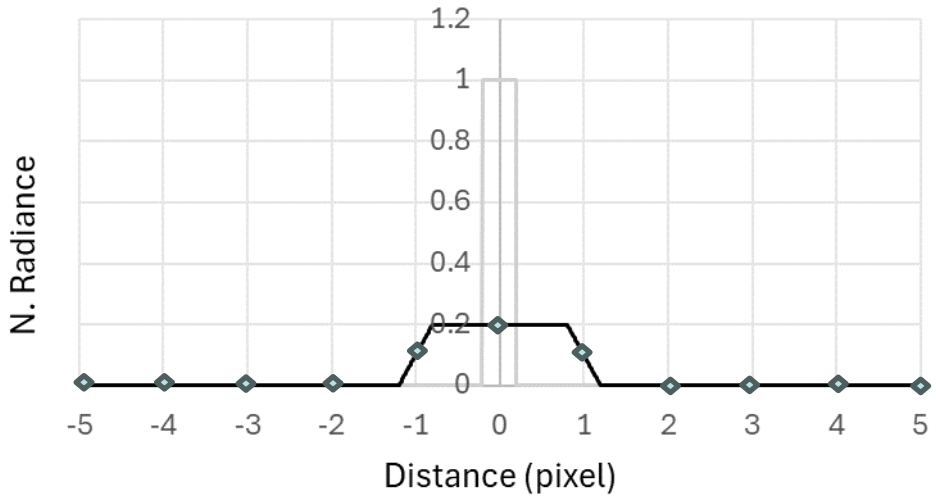


An isolated small object

Over-sampling, factor = 2

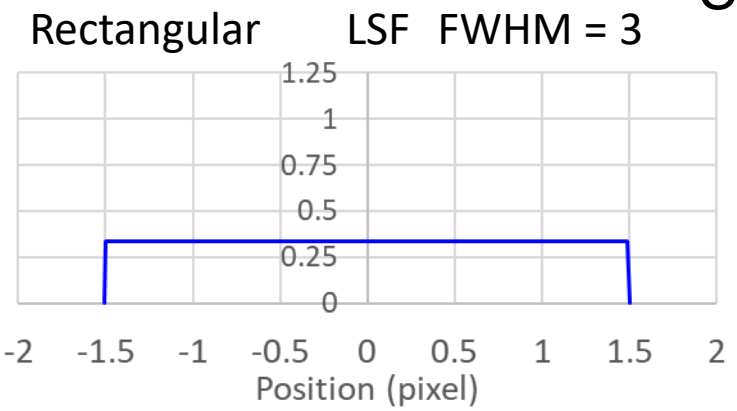
Rectangular LSF FWHM = 2

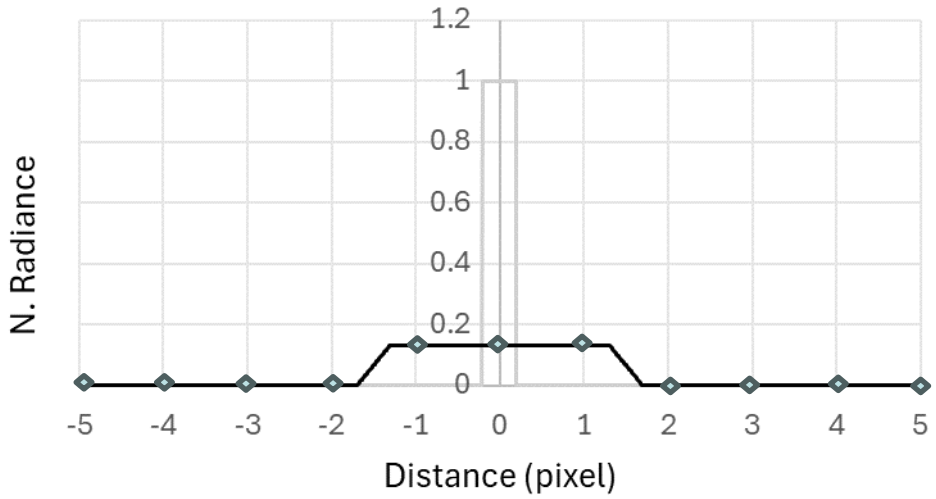




An isolated small object

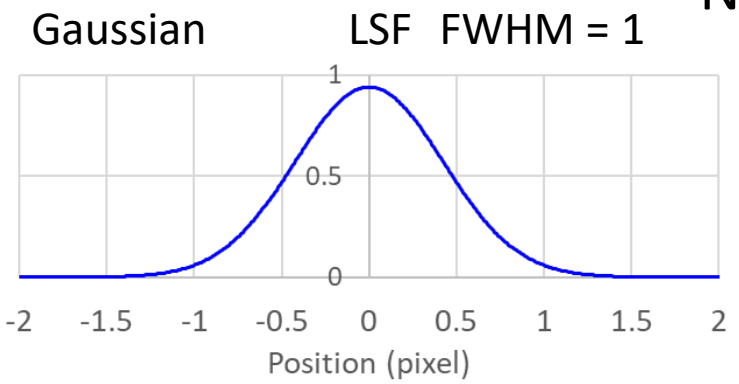
Over-sampling, factor = 3

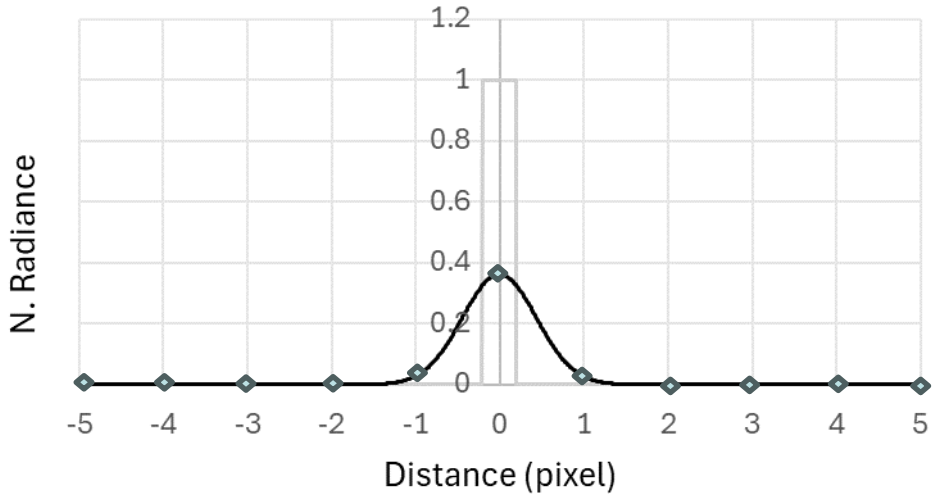




An isolated small object

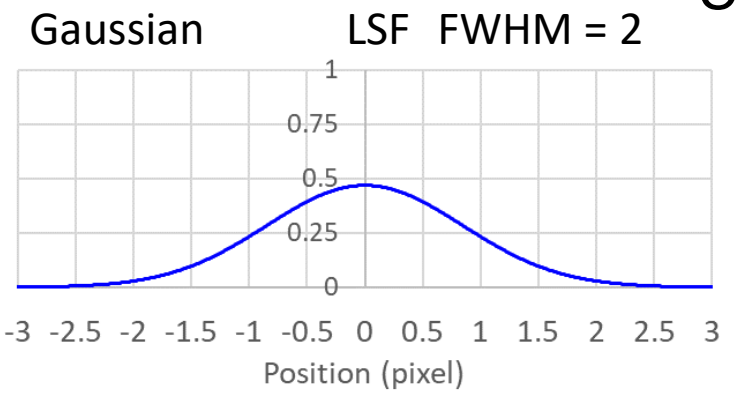
Nyquist sampling

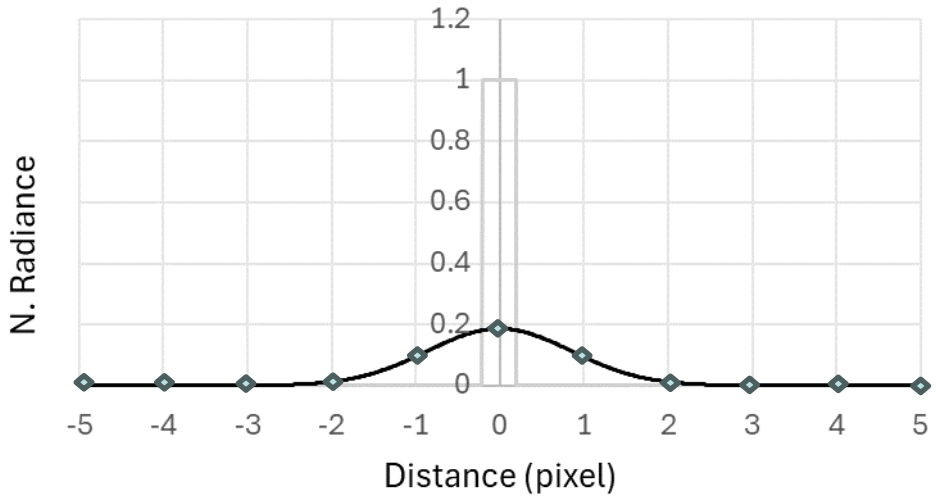




An isolated small object

Over-sampling, factor = 2

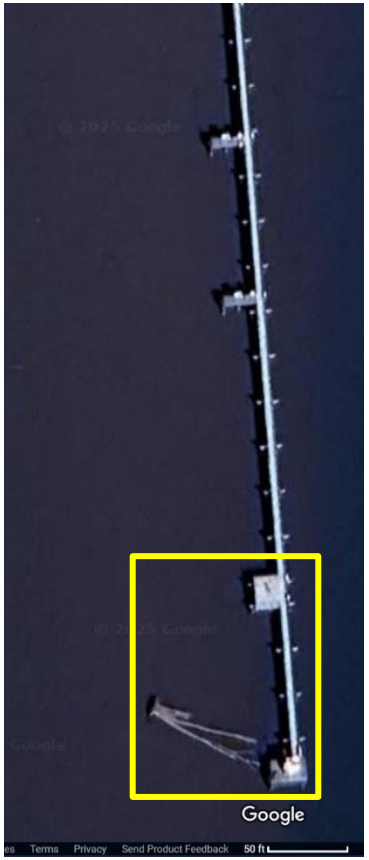




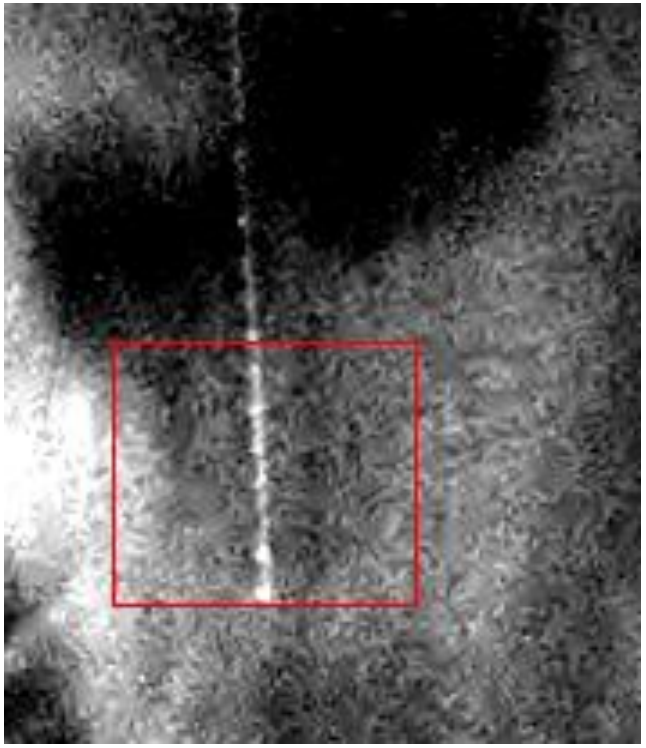
Google Earth images

Ronald Reagan Airport (Washington, DC)

Zoomed in on the guide

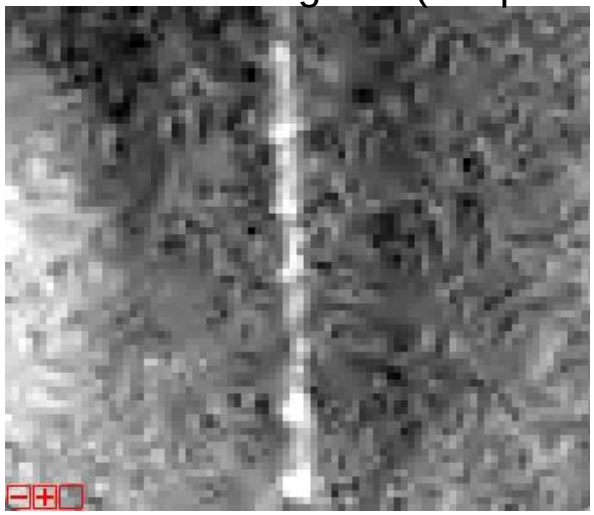


A commercial image of Reagan Airport Guide



*Color scaled to bring out the guide

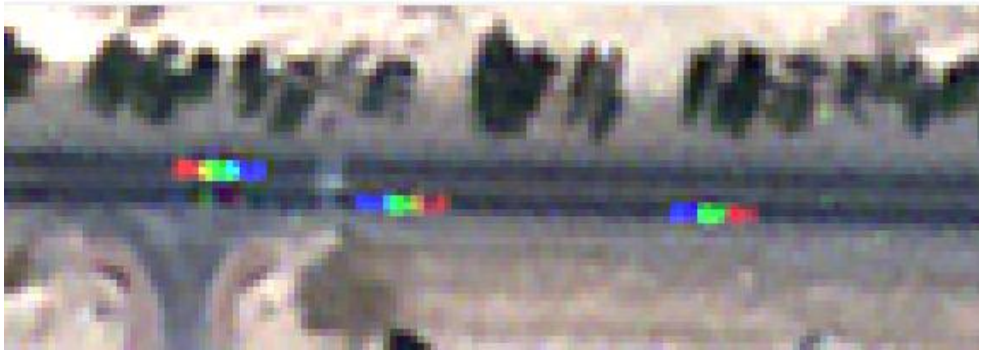
Zoomed in on guide (3m pixels)



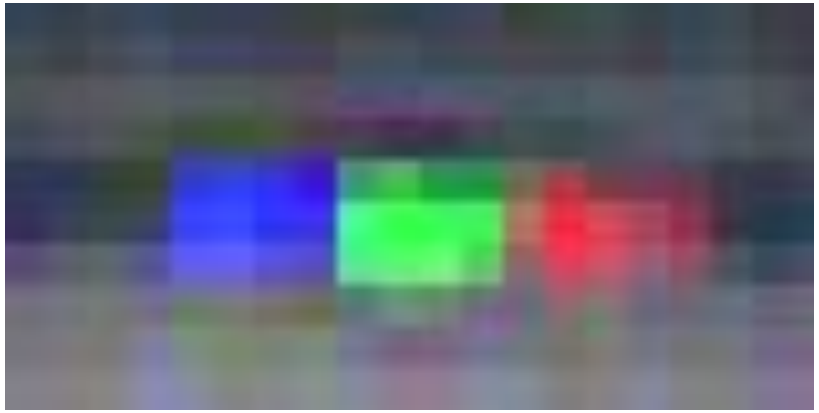
The 1.5 m guide appears 3-4 pixels wide, 10 m in the image. That results in a Sensor spatial resolution 3.3 pixels wide, 10 m

Brightness change is where the guide is wider, but the underlying width is the same. The wider guide in the image is due to much larger sensor spatial resolution than the pixel size.

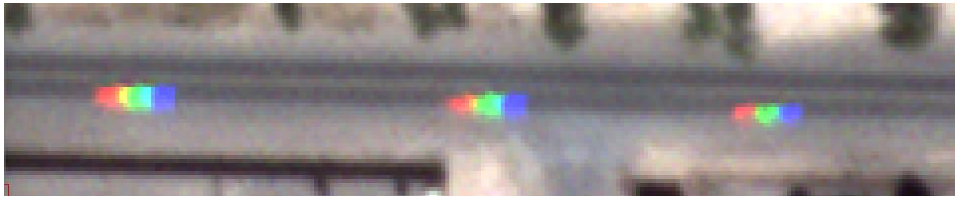
Another set of Commercial satellite images



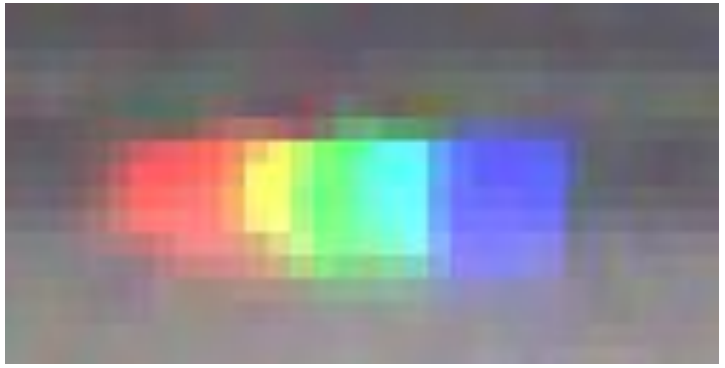
Generation-1



1m pixels, FWHM ~1.4 pixels = 1.4m



Generation-2



0.7m pixels, FWHM ~ 2.8 pix =2.0m
(vehicle width ~ 3.5m?)

WorldView-2 image

~1.8 m pixels
FWHM = 1.5 pixels = 2.7 m.

Slanted edges show up in saw tooth shapes
➔ excellent sharp image!

Updated grading on FWHM & MTF

- FWHM to pixel-size ratio

	Ideal	Excellent	Good	Basic	**Poor**
FWHM/pixel ratio	(0.75, 1.25]	(1.25, 1.5]	(1.5, 1.75]	(1.75, 2.0]	**> 2.0**

- MTF based on Gaussian LSF

	Ideal	Excellent	Good	Basic	**Poor**
MTF@NF	[0.25, 0.6)	[0.13, 0.25)	[0.07, 0.13)	[0.03, 0.07)	**< 0.03**

Acronyms:
FWHM: full-width at half-maximum of an LSF
LSF: sensor system line spread function
MTF: modulation transfer function
NF: Nyquist frequency

Concluding remarks

Effects of over-sampling with a factor >2 (FWHM_LSF > 2.0 pixels)

1. Filters out MTF@Nyquist Frequency
2. Lowers data efficiency, < 25%
3. Poses unfriendliness to users
    1) Wastes data storage, > 75%
    2) Increases data transfer time and data processing time
    3) Mis-identifies small objects
4. Loses product competitiveness