AAPM Summer School 2004

# The Nature of the Digital Image


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# Outline

- What is digital imaging
- Basic descriptors of digital imaging

| | |
|---|---|
| Field of view | Uniformity |
| Artifacts | Latitude |
| Resolution | Noise |
| Efficiency | Scatter sensitivity |
| Speed | Lag |

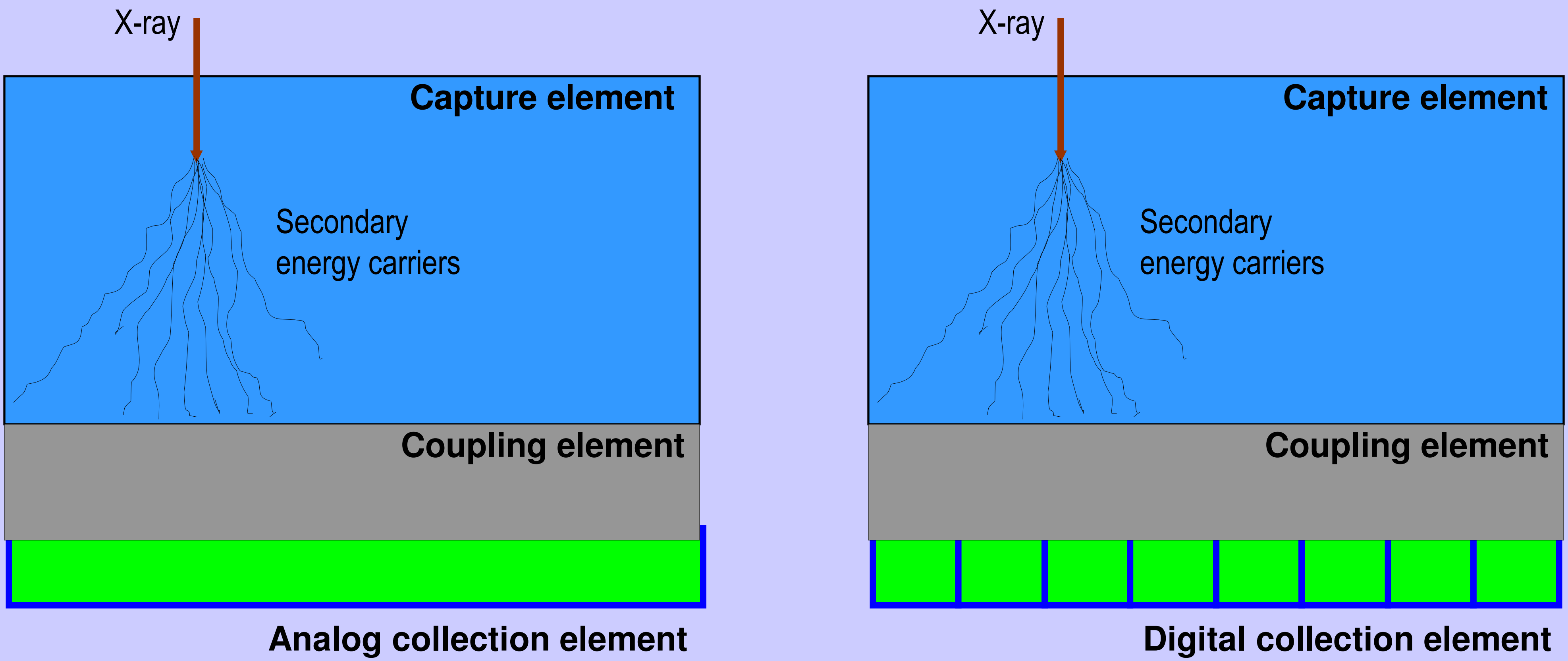
# Why digital imaging?

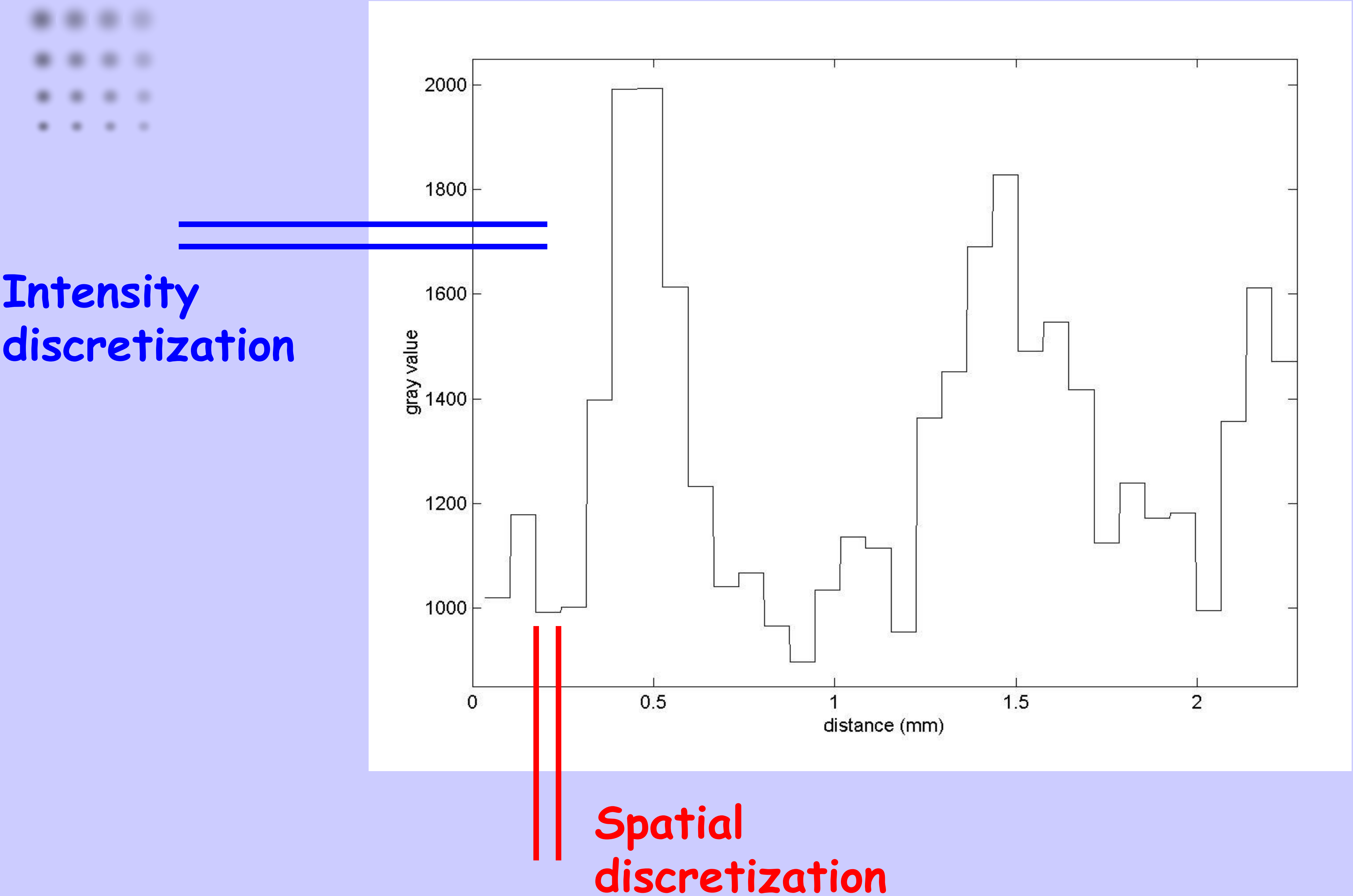
- Separation of the capture, processing, display, and storage functions
  - Improved dynamic range
  - Possibility of image post-processing
  - Improved image storage via PACS
  - Improved image transmission and distribution via PACS
  - New imaging applications (tomosynthesis, dual-energy)

# What is digital imaging?

- Imaging in which the image data are sampled into discrete elements in spatial and intensity dimension
  - Initial image capture in analog mode
  - Digitization of analog to digital data
  - Processing and transfer of the digital data by computers

# Analog => Digital

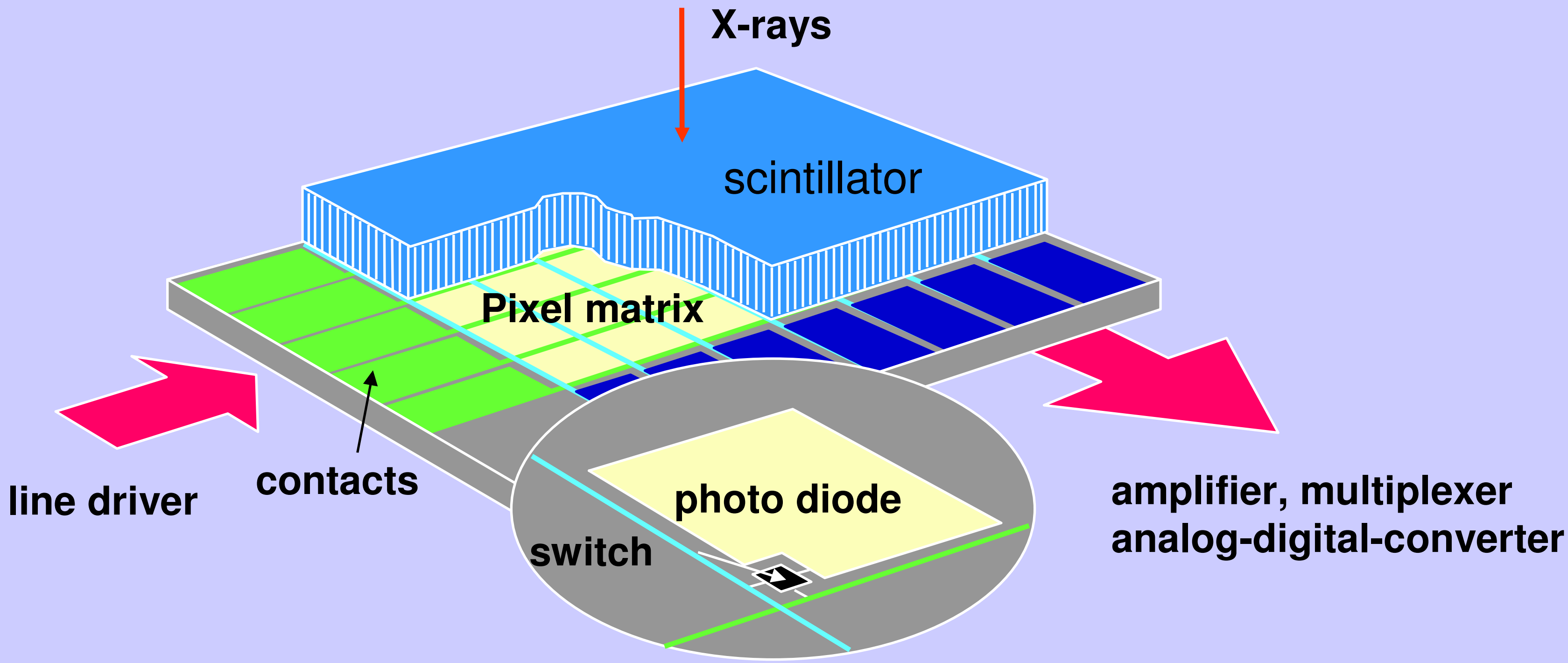



2000
1800
1600
1400
1200
1000
gray value
0
0.5
1
1.5
2
distance (mm)
Intensity discretization
Spatial discretization

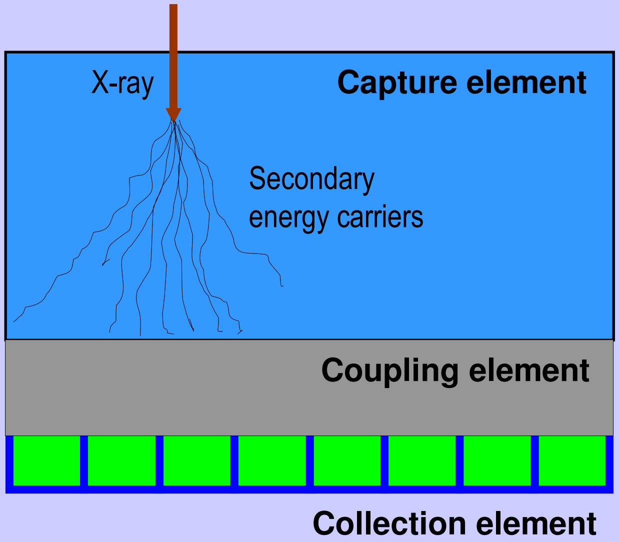
# Digital technologies

1. Computer Radiography (CR)
2. Flat-panel radiographic and fluoro systems
   - Direct detectors
   - Indirect detectors
3. CCD/CMOS-based radiographic and fluoro systems
   - Full-field detectors
   - Scanning-slot detectors
4. Electrostatic radiographic system
   - Selenium drum detector

# Digital technologies



# Digital technologies




| Detector Technology | Typical capture element | Typical coupling element | Collection element |
|---|---|---|---|
| **CR** | PSL phosphor (e.g., BaFBr) | PSL light-guide | Photo-multiplier tube; signal digitization |
| **CCD/CMOS-based** | CsI or $G_2O_2S$ phosphor | Lens or fiber-optic taper | CCD or CMOS |
| **Indirect flat panel** | CsI or $G_2O_2S$ phosphor | Contact layer | Photodiode /TFT array |
| **Direct flat panel** | a-Se | None | TFT array |
| **Electrostatic** | a-Se | Induction space | Electrometer probes; signal digitization |

# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. Spatial artifacts
4. Latitude
5. Spatial resolution
6. Noise
7. Efficiency
8. Scatter sensitivity
9. Speed
10. Lag

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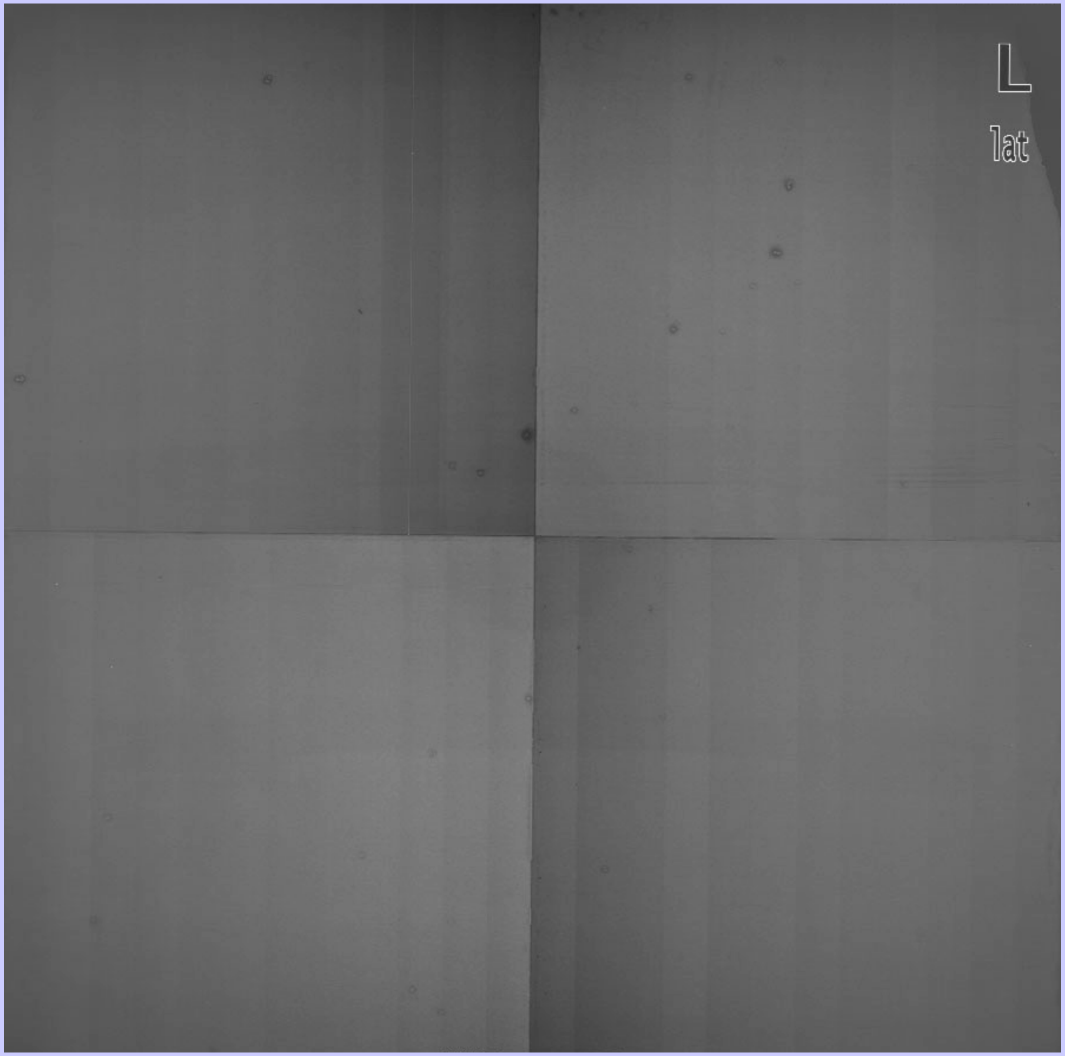
# Field of view

- Detector size should match the anatomy being imaged
  - 20 x 25 cm extremity
  - 18 x 23 and 25 x 29 cm mammography
  - 43 x 43 cm chest and general rad
  - 30 x 30 cm + fluoro
- Particular challenge for most DR technologies

# Sub-detector tiling

- Potential for large-area non-uniformities and discontinuities



# Basic descriptors of the digital image

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# Uniformity

- Applies to uniformity of response within the field of view of the imaging system
- Affected by non-linear response of pixel elements
- Can be minimized if capture and collection elements are coupled
  - Offset and gain calibration

# Uniformity

- Offset and gain calibration

$$P_c(i,j) = \left(P_{uc}(i,j) - O_m(i,j)\right)\frac{M}{G_n^{XV}(i,j) - O_m(i,j)}$$

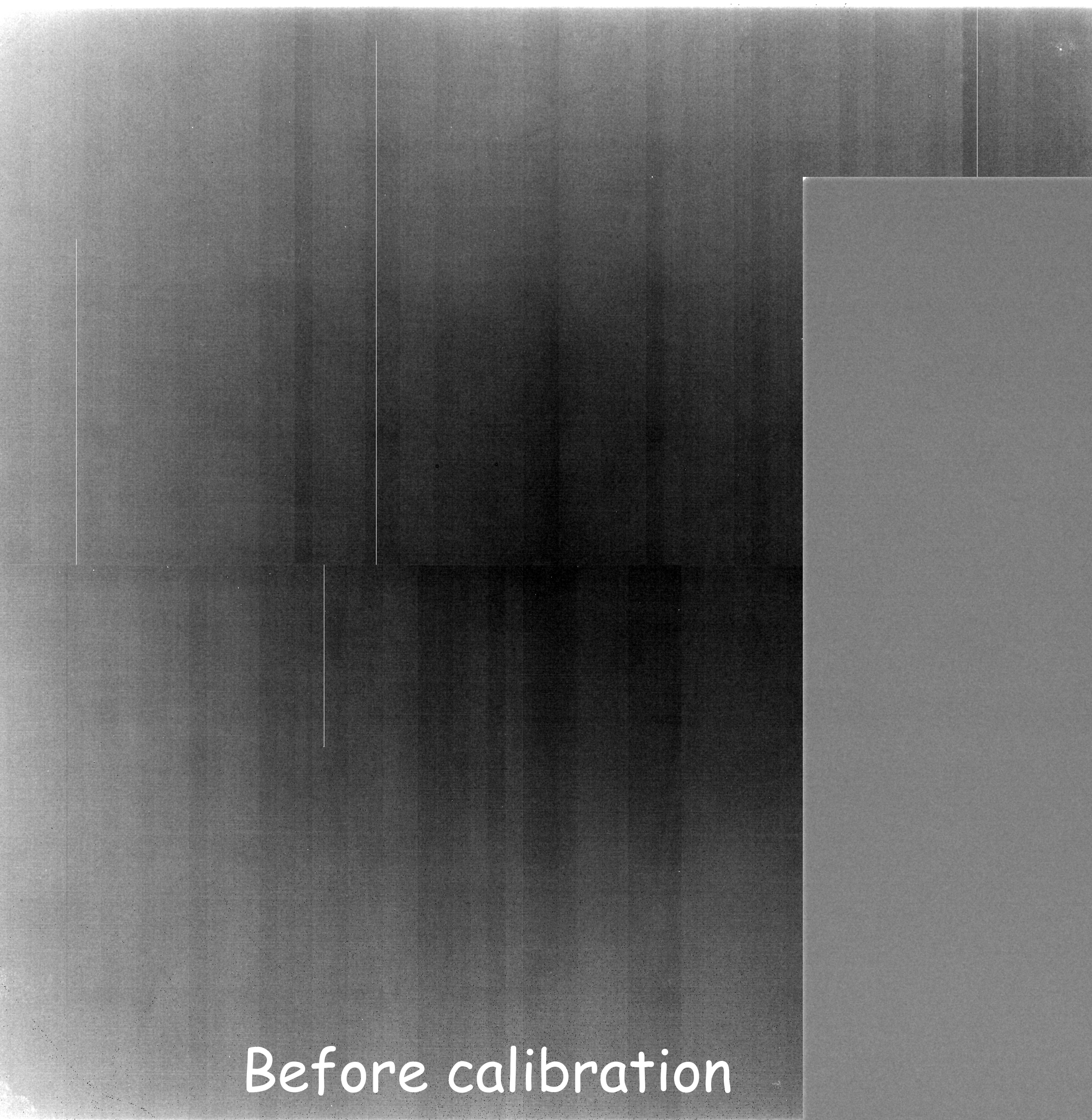
$P_c(i,j)$ = corrected pixel value at coordinate (i,j)

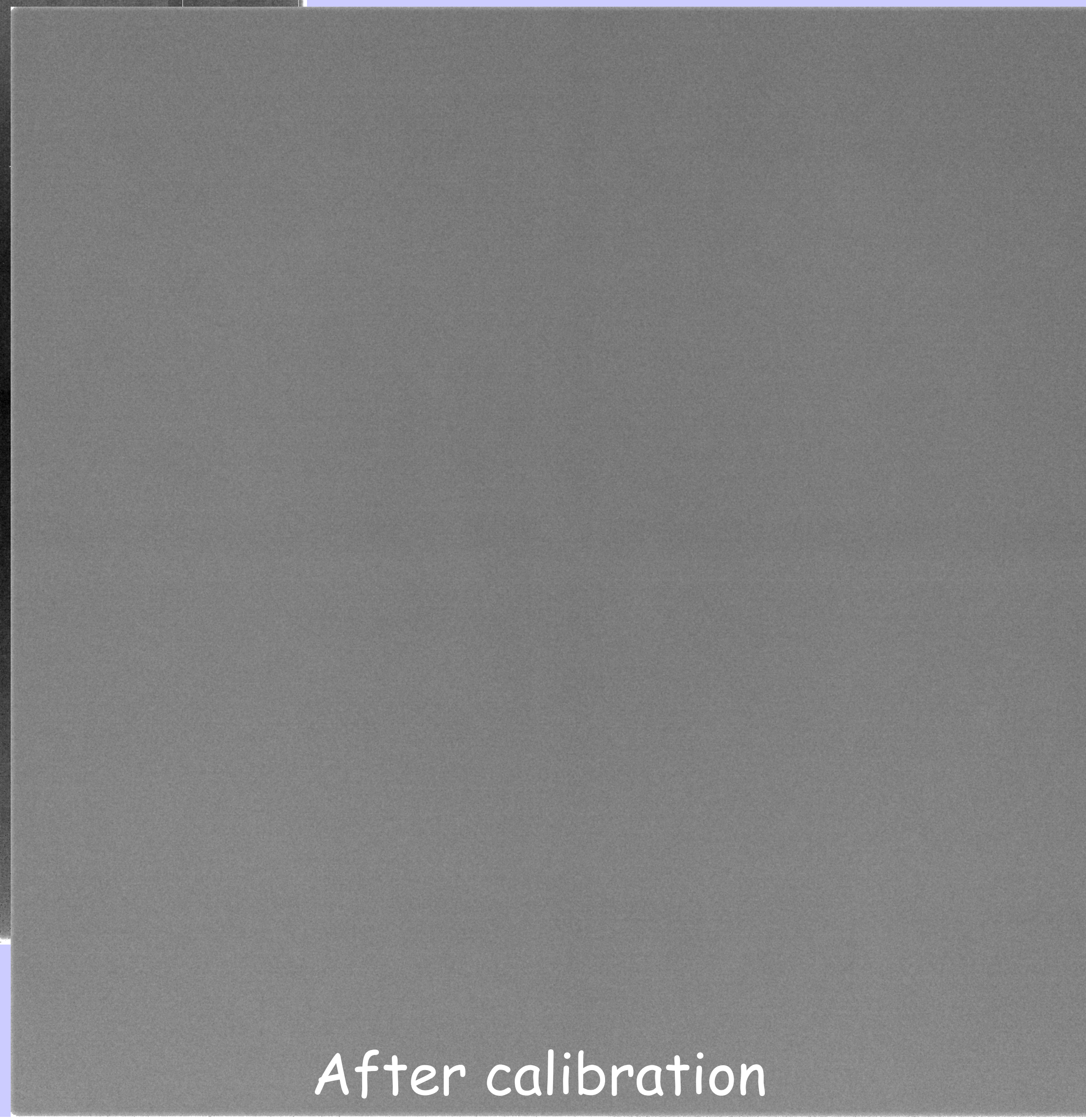
$P_{uc}(i,j)$ = uncorrected pixel value at (i,j)

$G_n^{XV}(i,j)$ = gain image, average of n sequential flat-field images at X exposure and V kVp

$O_m(i,j)$ = offset image, average of m sequential flat-field images with no exposure

$M = \langle G_n^{XV} - O_m \rangle$


Before calibration


After calibration

# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. **Spatial artifacts**
4. Latitude
5. Spatial resolution
6. Noise
7. Efficiency
8. Scatter sensitivity
9. Speed
10. Lag

# Spatial artifacts

- Pixel dropouts
  - Corrected by dead pixel corrections but can lead to image data loss
- Sub-detector seams
  - Partially corrected by gain calibration
- Grid lines
  - Partially corrected by gain calibration
- CR artifacts
  - Dust and scanning optics non-uniformity

# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. Spatial artifacts
4. Latitude
5. Spatial resolution
6. Noise
7. Efficiency
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10. Lag

# Latitude

a) The dynamic range over which the detector is able to provide clinically useful images
b) The detector response within its dynamic range
c) Signal quanitization within the dynamic range

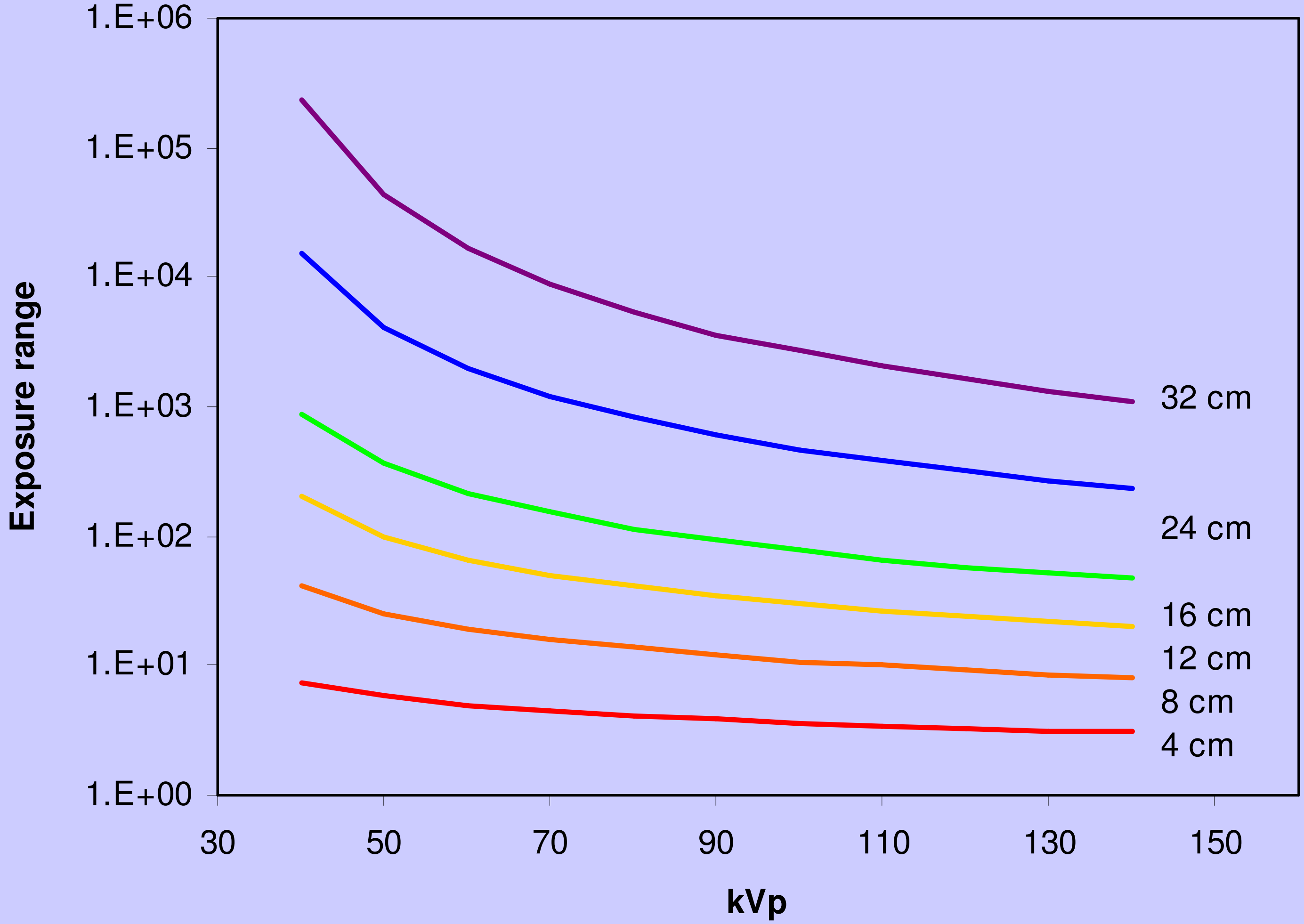
# a) Dynamic range

$$DR = \frac{E_{Max}}{k\, E_{Min}}$$

- $E_{max}$: Saturation exposure
  - e.g. exposure for PV=4095 in a 12-bit detector
- $E_{min}$: Base exposure
  - Exposure raising PV just above dark noise
- K: threshold SNR
  - 3-5 based on Rose model

# a) Dynamic range

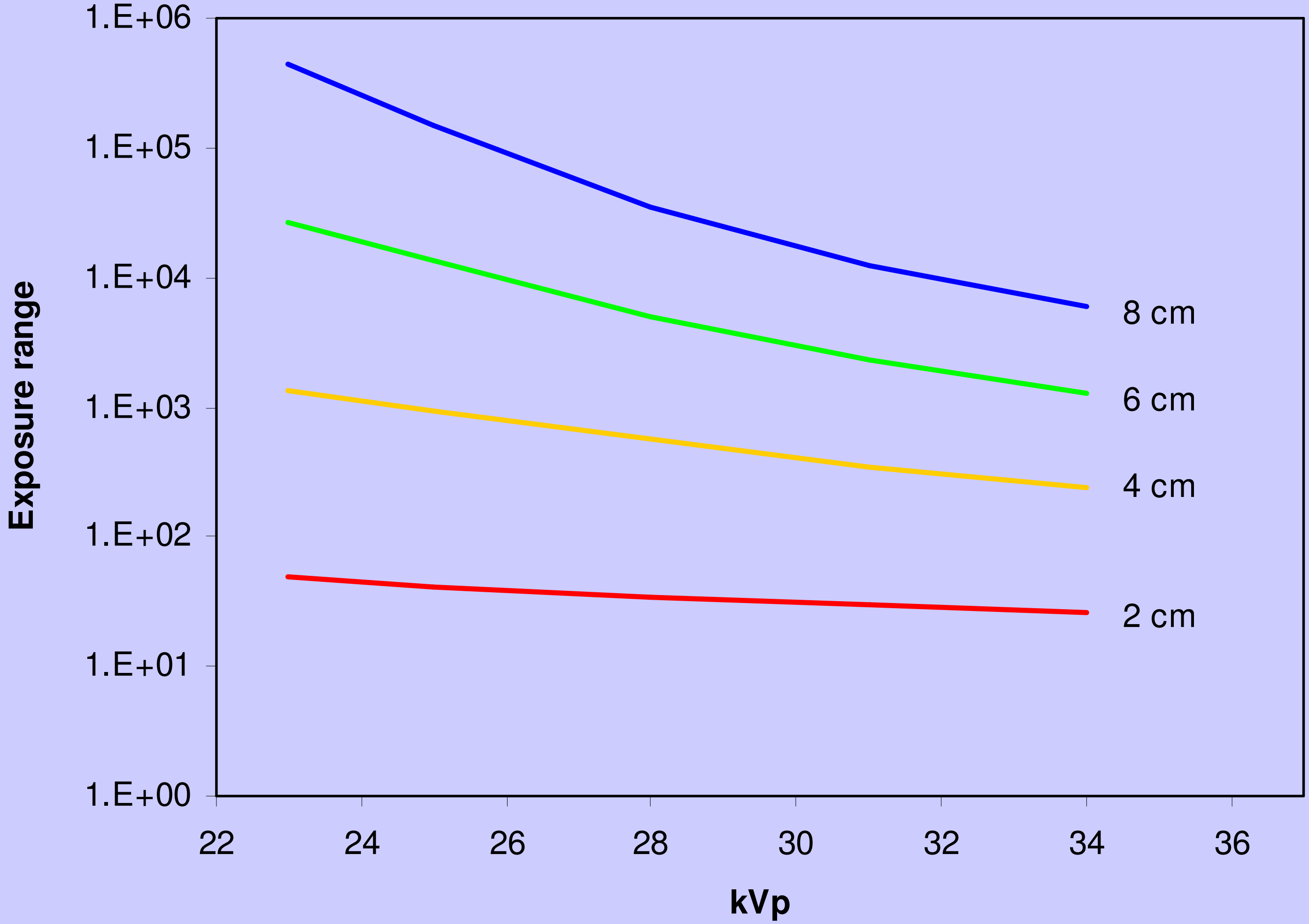
## Radiography & fluoroscopy




*xSpect, muscle-equivalent material, 2 mm intrinsic Al*

# a) Dynamic range

## Mammography

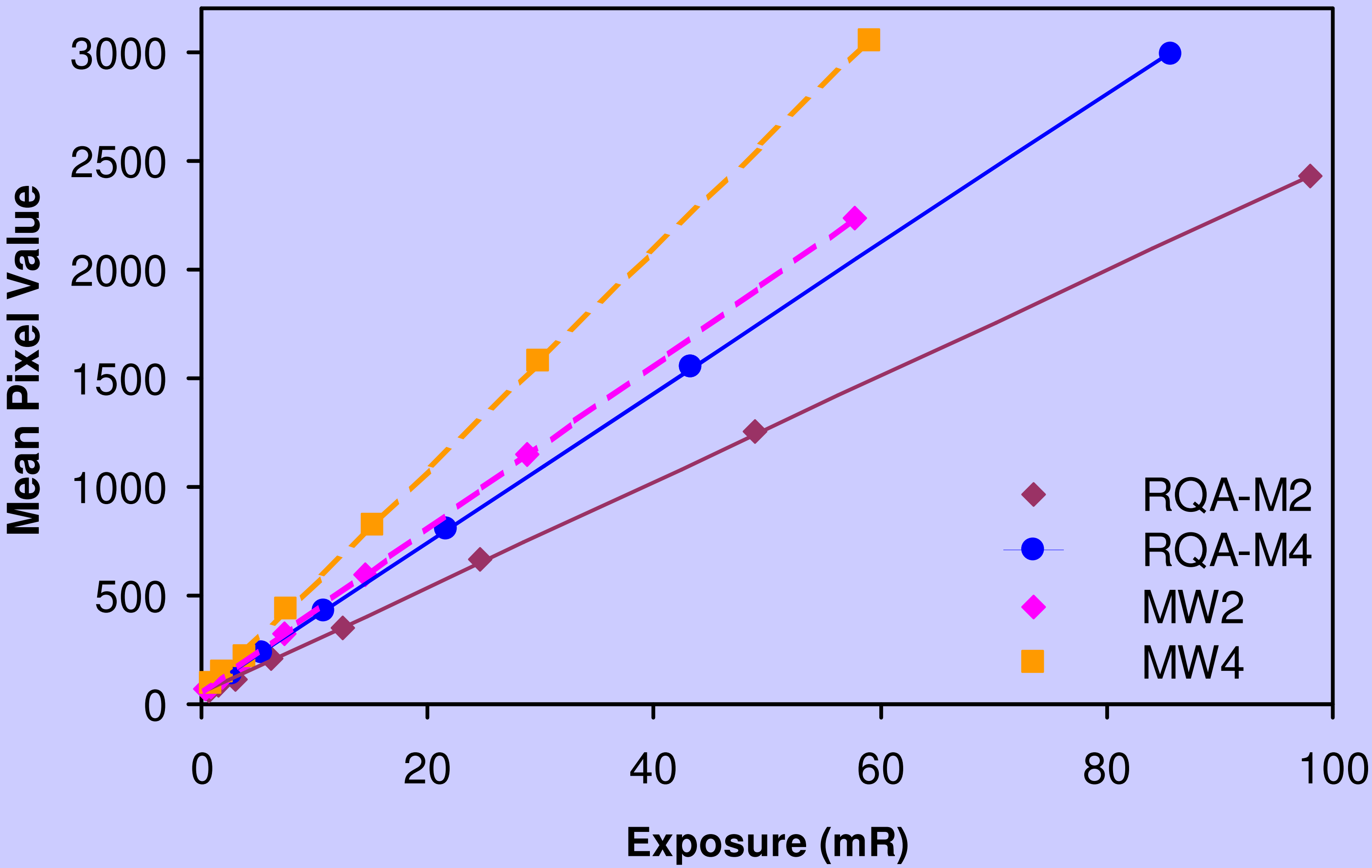



*xSpect, 50/50% glandular/adipose, 30 um intrinsic Mo*

# b) Response

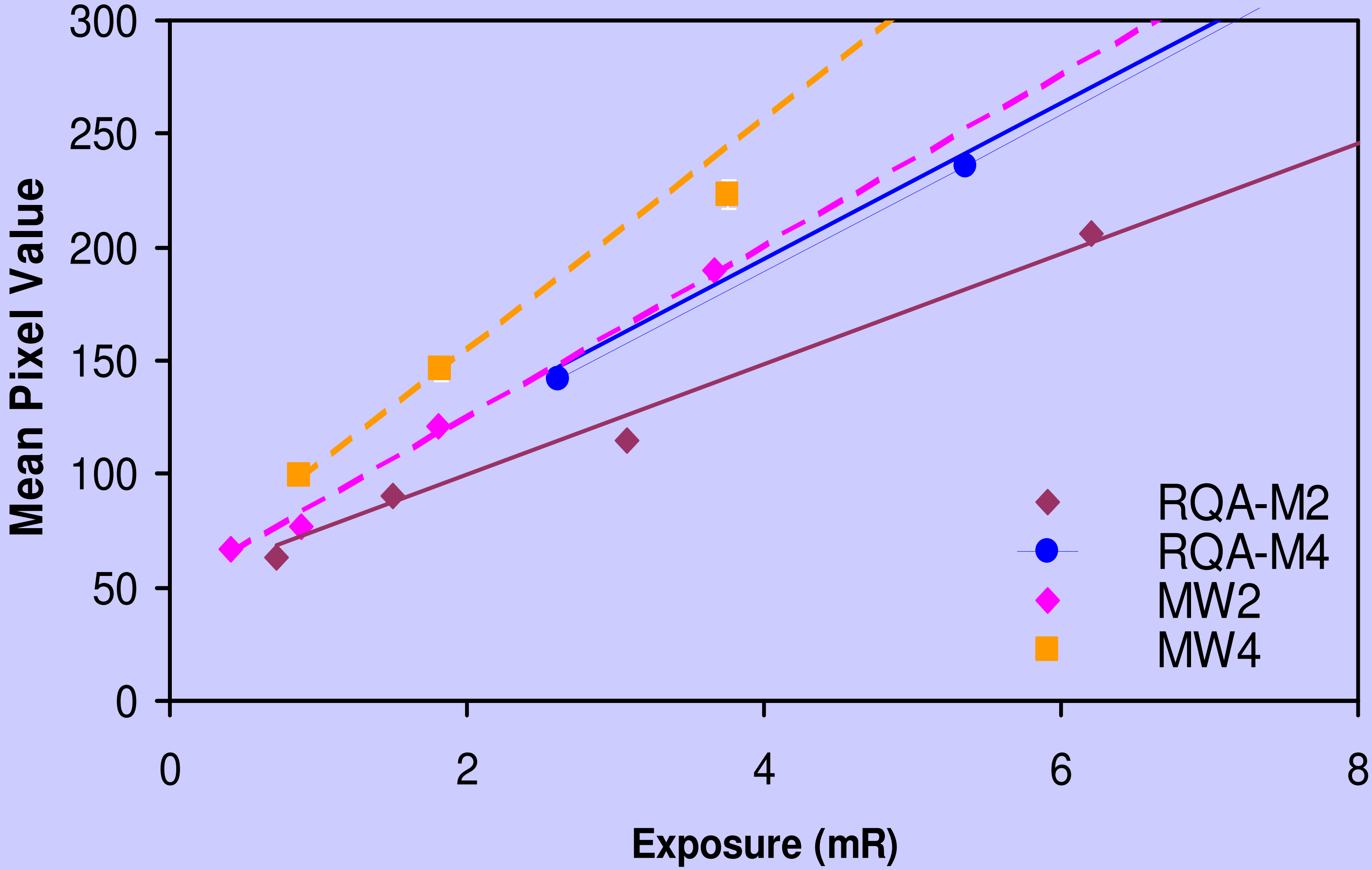
- Within the dynamic range, the detector response should be well-behaved
  - Linear
  - Logarithmic
  - Square-root
- Particular problems at low and high exposures limiting effective latitude

# b) Response




*Siemens prototype FFDM unit*

# b) Response




*Siemens prototype FFDM unit*

# c) Quantization

- Within the dynamic range, the detector should provide sufficiently fine contrast discritization
- With logarithmic response $C_{PV} = 1/g$
- With linear response $C_{PV} = 1/PV$

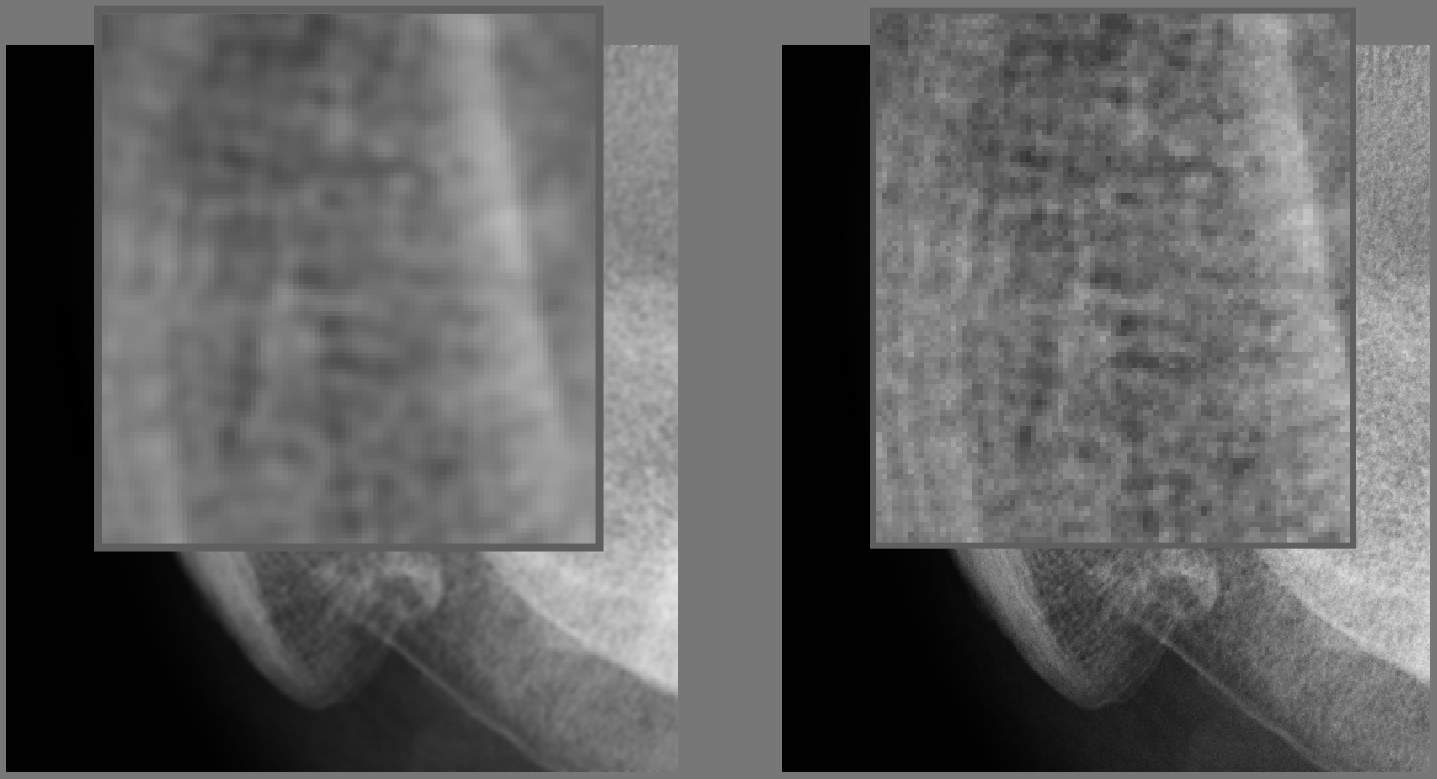
  - e.g., 200:1 dynamic range, g=1
  - 12 bit log response $C_{PV} = 200/4095 = 0.5\%$
  - 10 bit log response $C_{PV} = 200/1023 = 2\%$
  - 12 bit linear response $C_{PV} = 100\% - 0.025\%$

# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. Spatial artifacts
4. Latitude
5. **Spatial resolution**
6. Noise
7. Efficiency
8. Scatter sensitivity
9. Speed
10. Lag

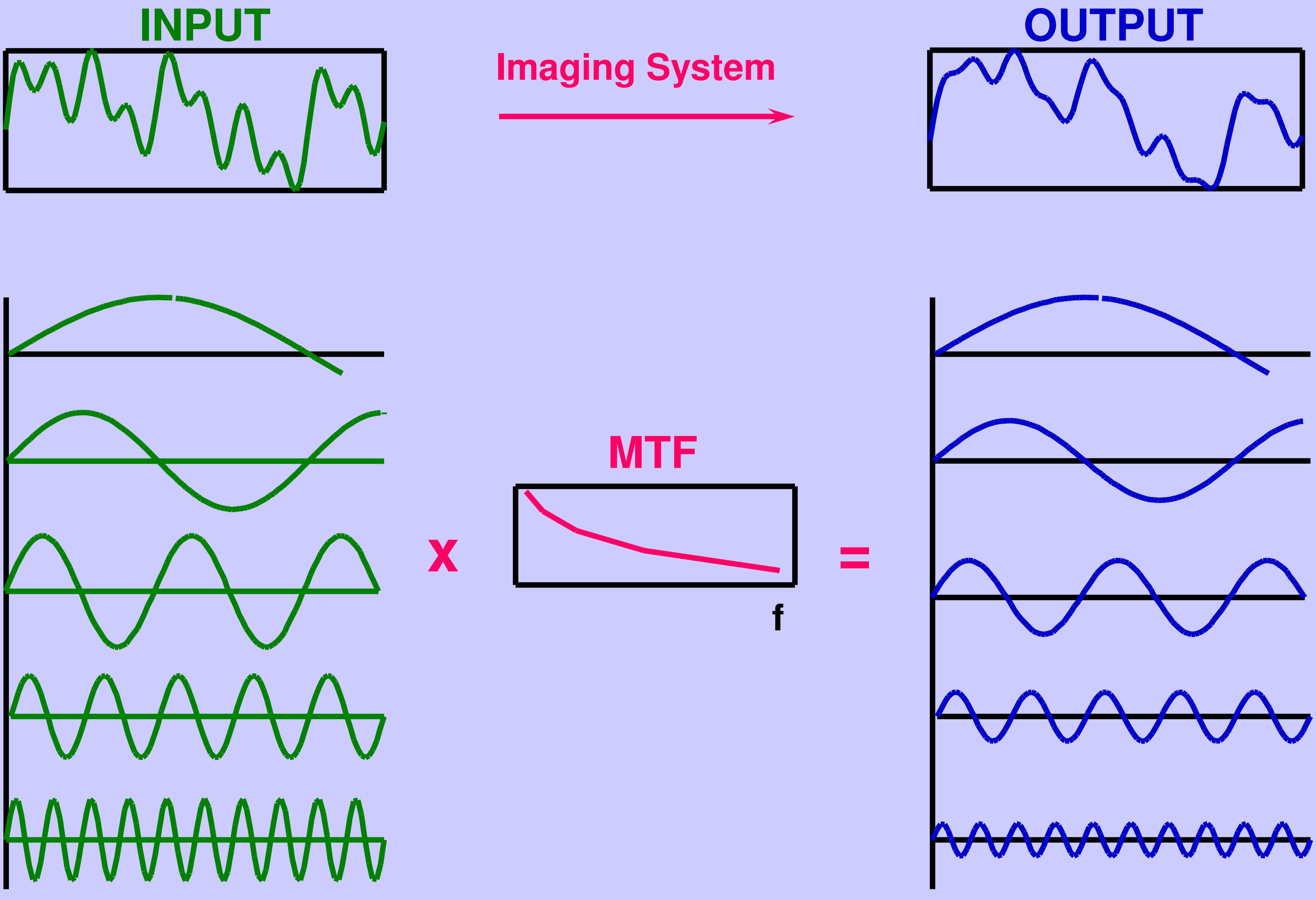
# Resolution

- Ability to image/resolve distinct features of the imaged object from each other

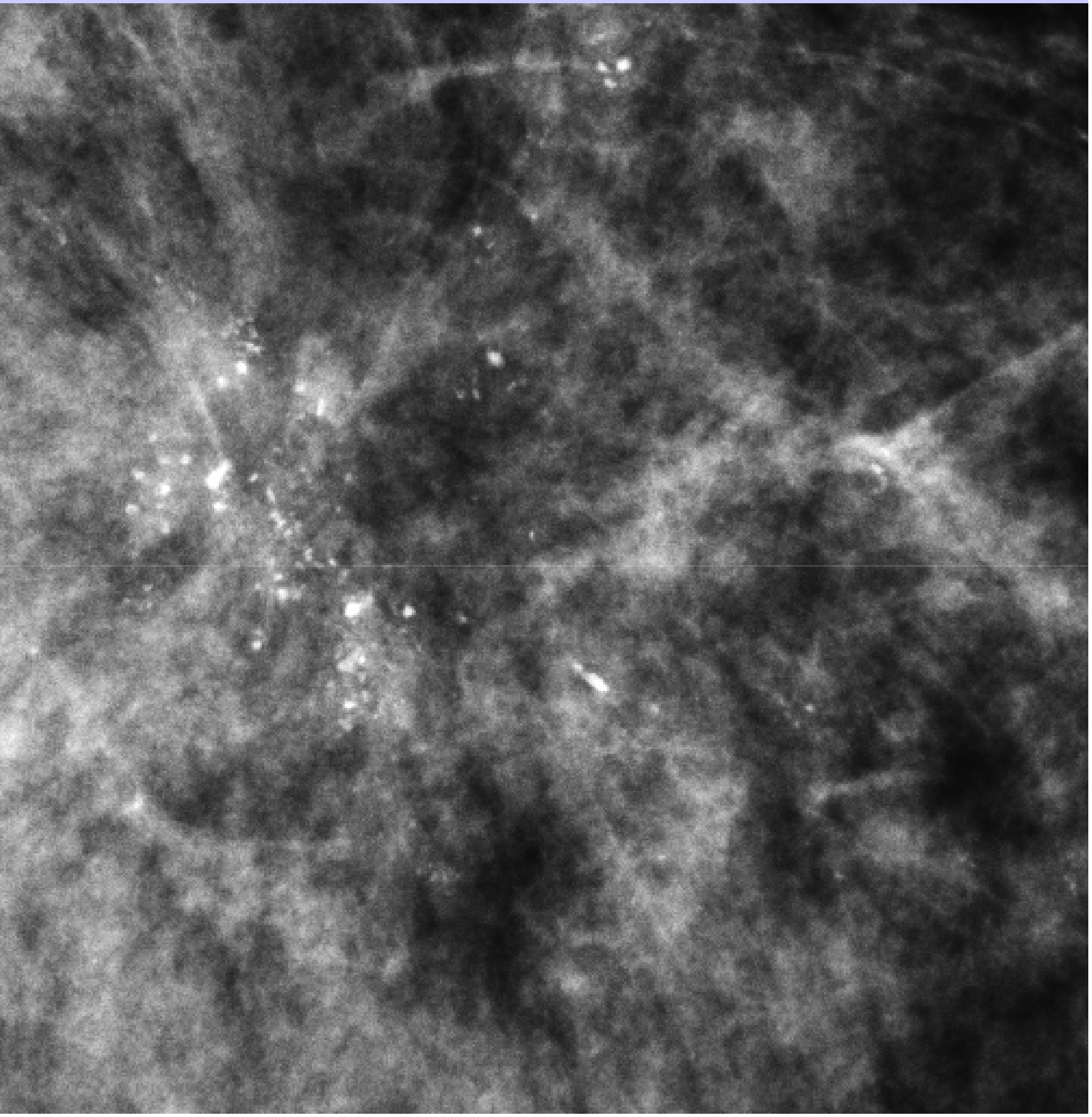


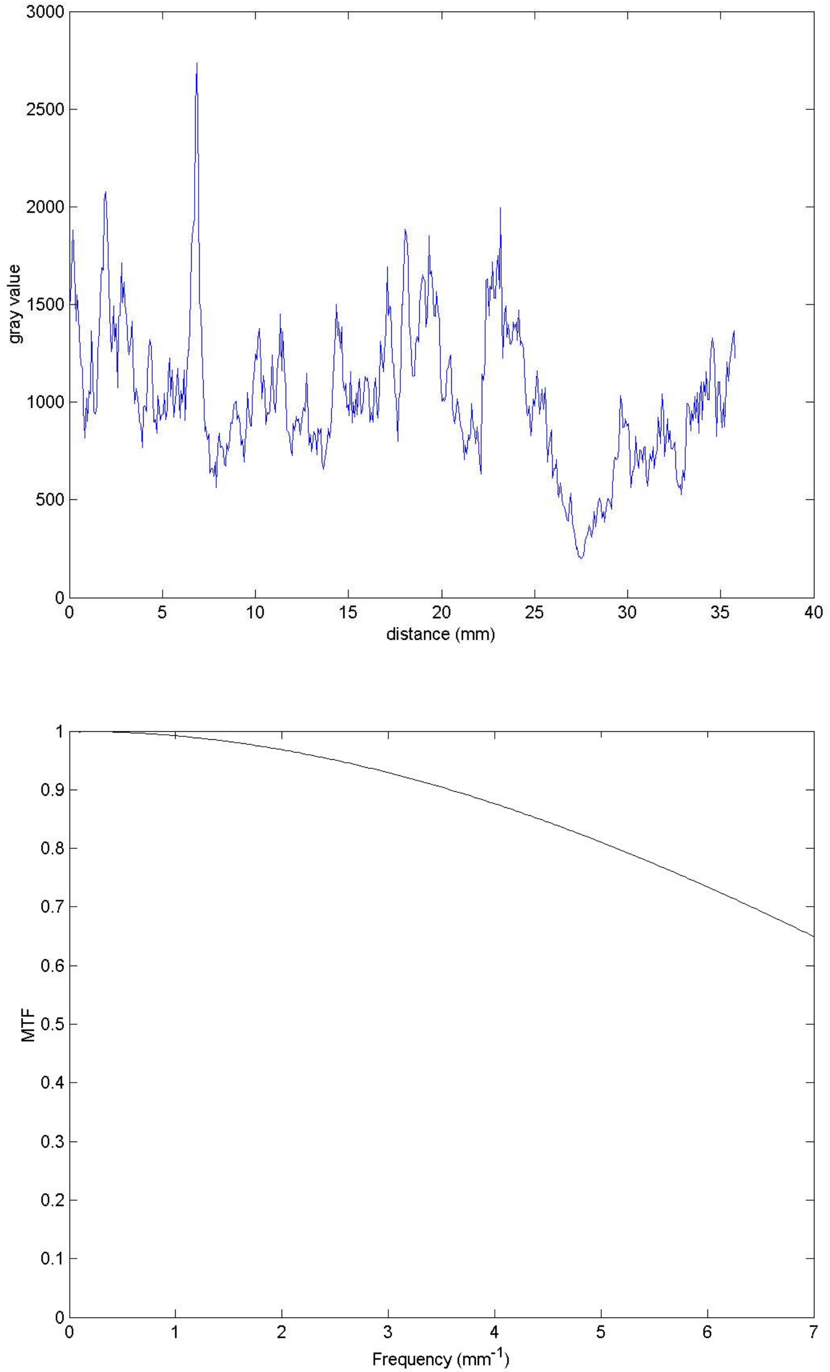
# Resolution

- Best characterized by the modulation transfer function (MTF):
  - **The efficiency of the imaging system in producing contrast at various spatial frequencies**
- Higher the MTF, better the resolution

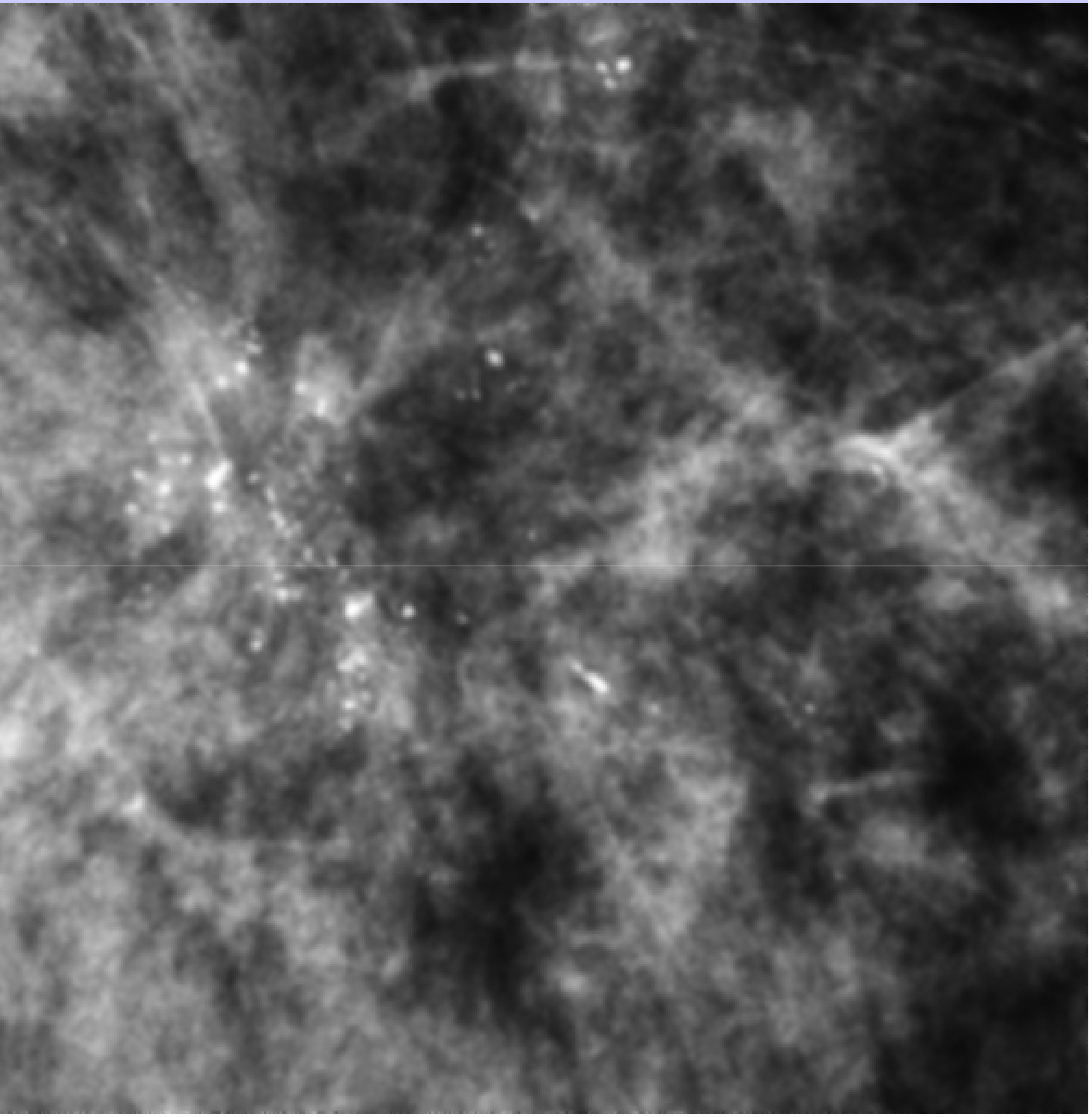

INPUT
Imaging System
OUTPUT
MTF
x
=
f

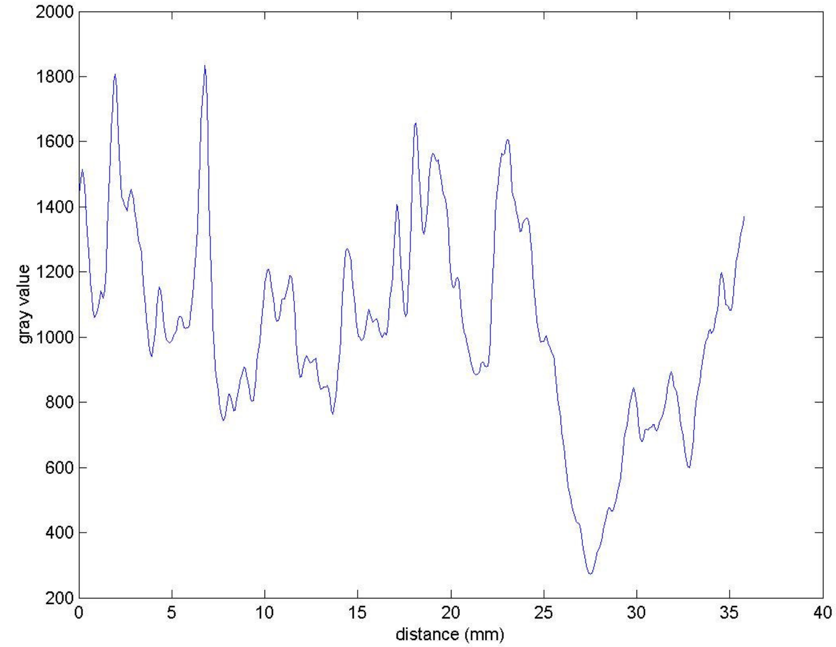
# High MTF



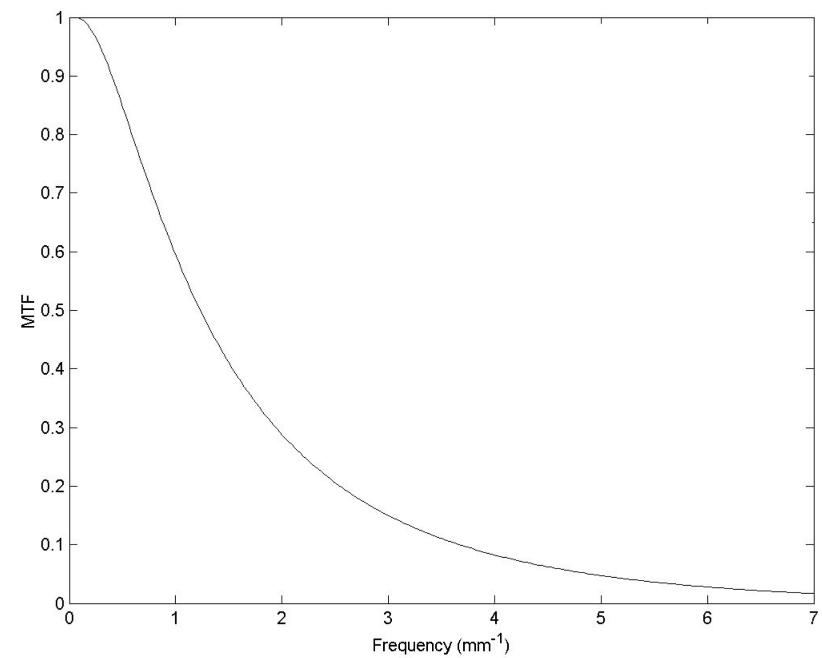

3000
2500
2000
1500
1000
500
0
gray value
0
5
10
15
20
25
30
35
40
distance (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
MTF
0
1
2
3
4
5
6
7
Frequency (mm-1)

# Low MTF





gray value
distance (mm)
0
5
10
15
20
25
30
35
40
200
400
600
800
1000
1200
1400
1600
1800
2000

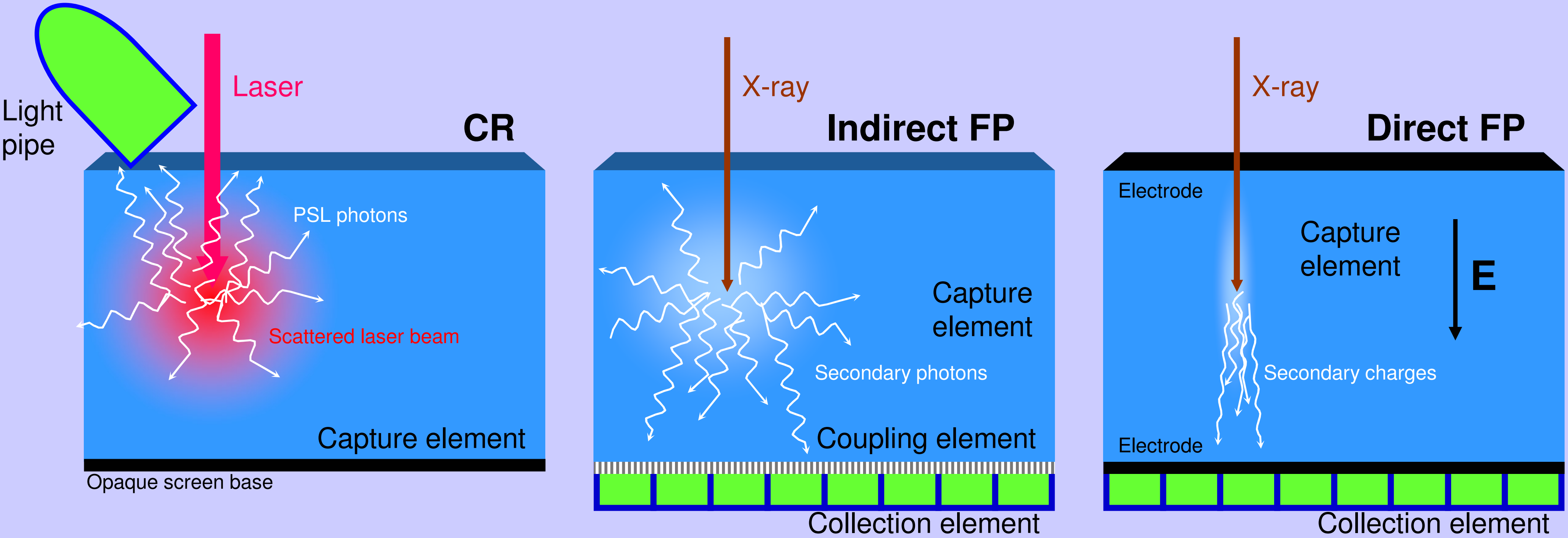
MTF
Frequency (mm$^{-1}$)
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

# Resolution factors

1. Capture element blur
2. Coupling element blur
3. Collection element blur
4. Geometrical blur (focal spot penumbra)
5. Motion blur

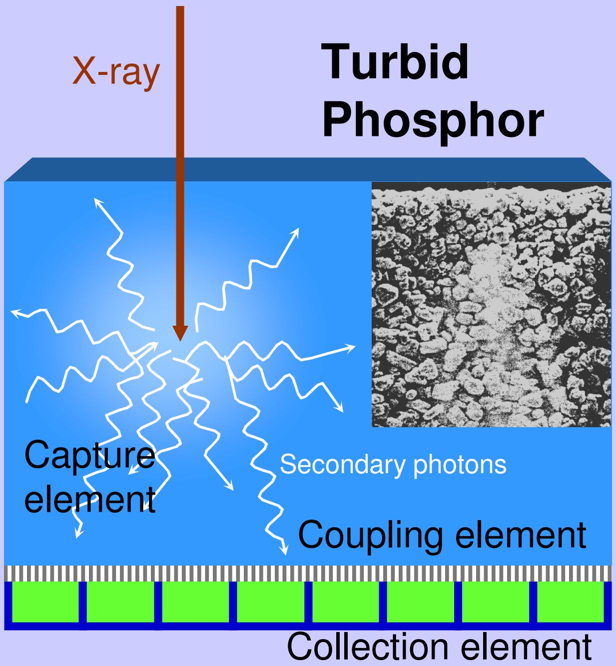
# Capture element blur

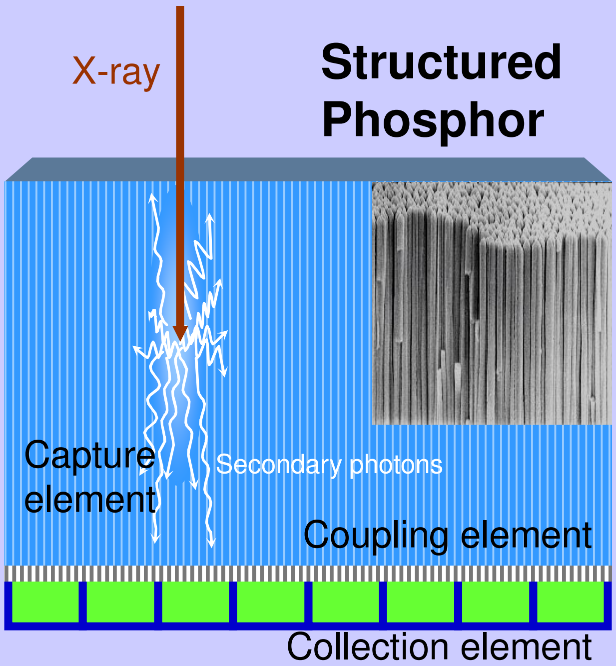
- Due to spreading of secondary energy-carriers
- Dominant in CR and indirect FPs



# Capture element blur

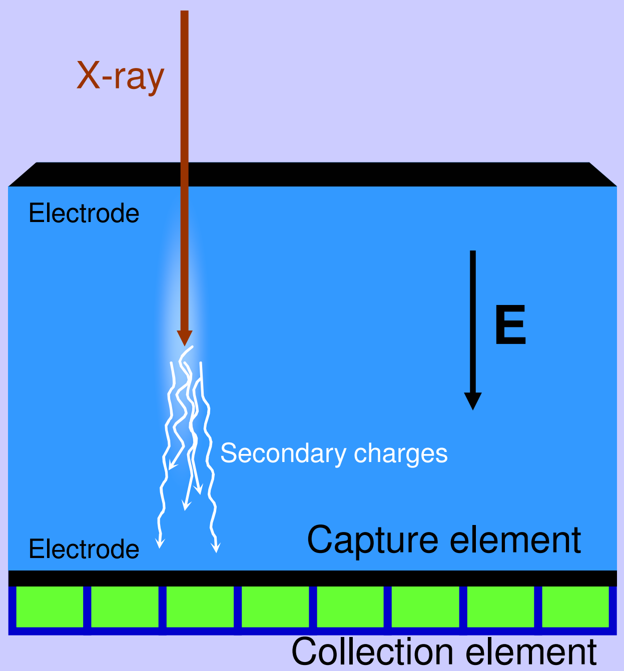
- Can be reduced using structured phosphors

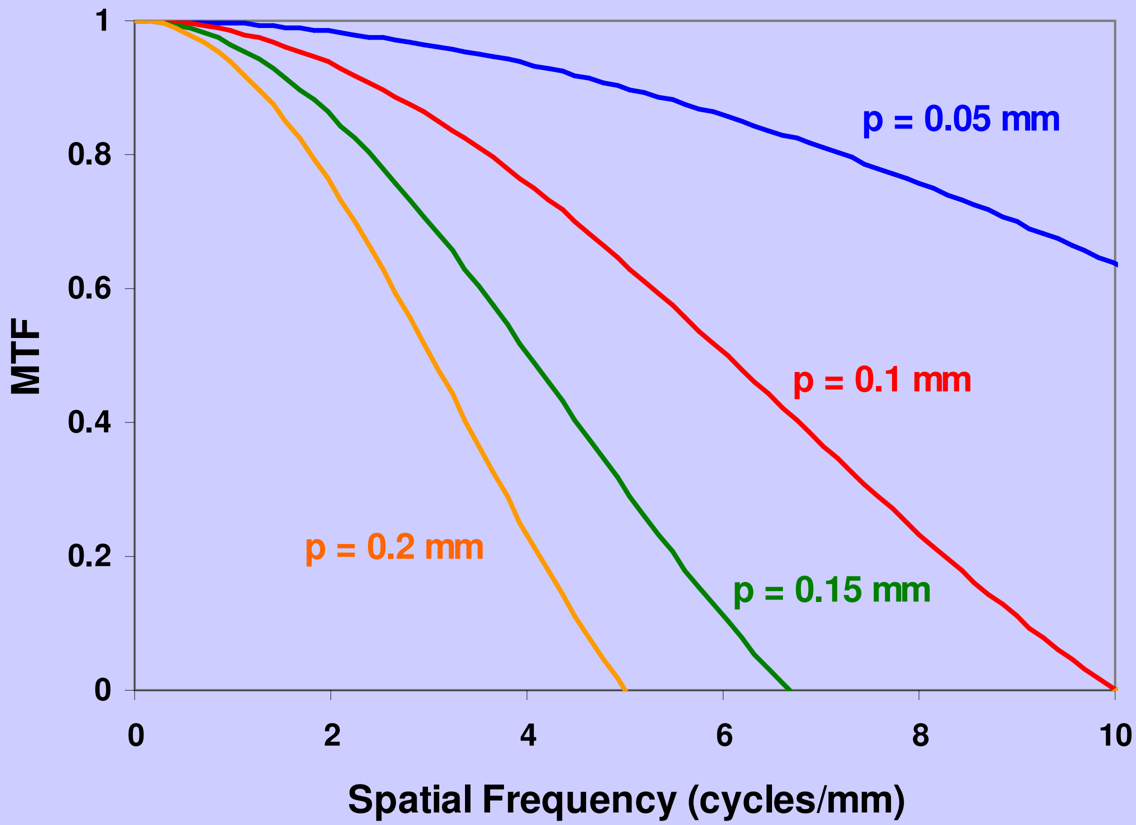


# Collection element blur

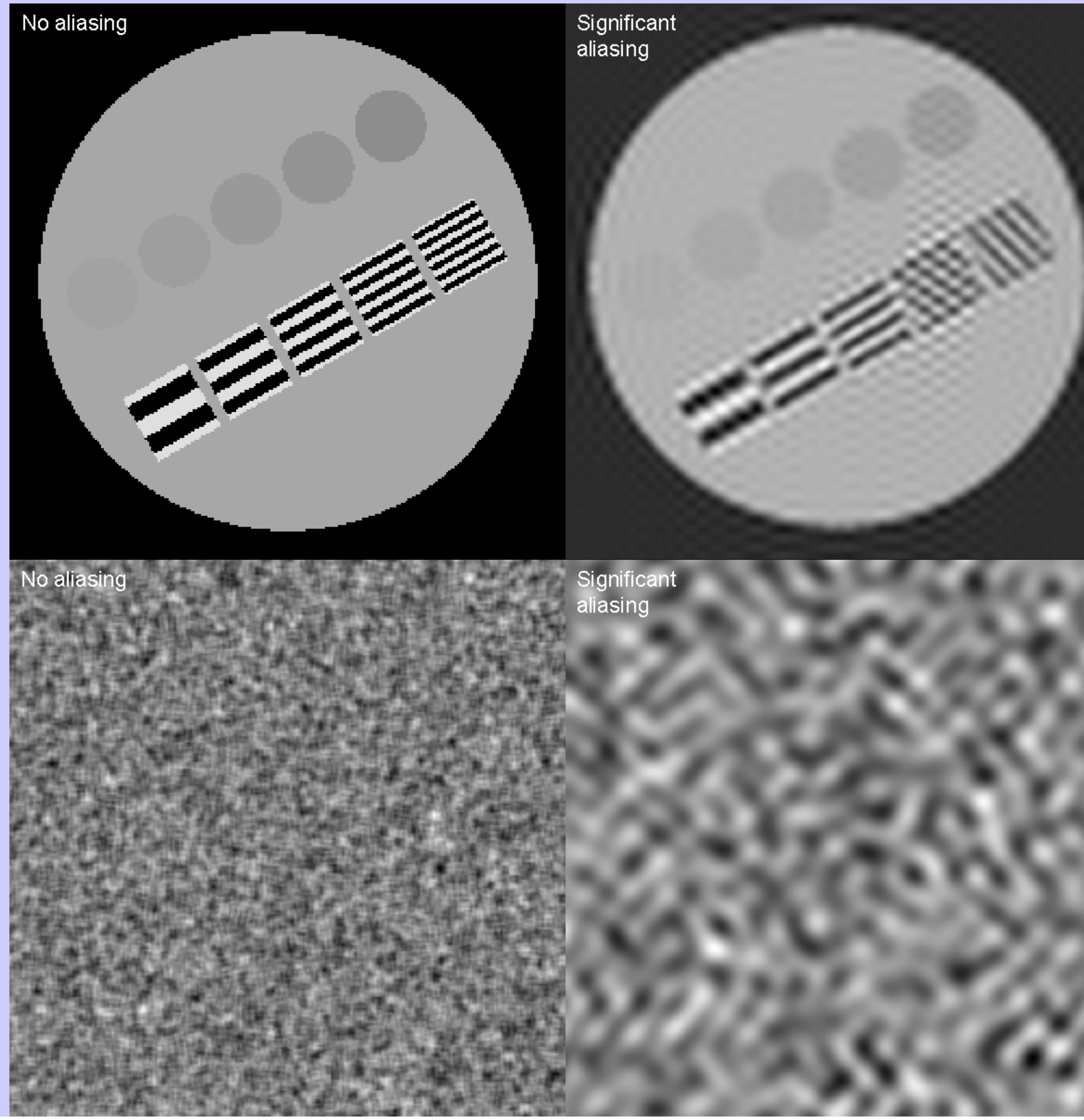
- Inherent resolution limit in CR and DR due to finite aperture size ~ 1/2p
- Dominant in direct FPs and electro-static DRs



# Collection element blur

- Very high MTF =>
- Aliasing
  - Distortion of the low-frequency components of the image due to under-sampled high-f details



# Techniques

- Three common methods:
  - Square Wave Response Method
  - Slit method
  - Edge method
- Newer methods:
  - Disk method (3D)
  - Multiple-hole method (3D)

# Techniques

- Comparable to desirable application, 50-120 kVp, or 25-35 kVp for mammo
- Filtration necessary to
  - Make spectrum similar to post-patient's
  - Remove lower energy x-rays responsible for most tube-to-tube variations

# Assessment methods

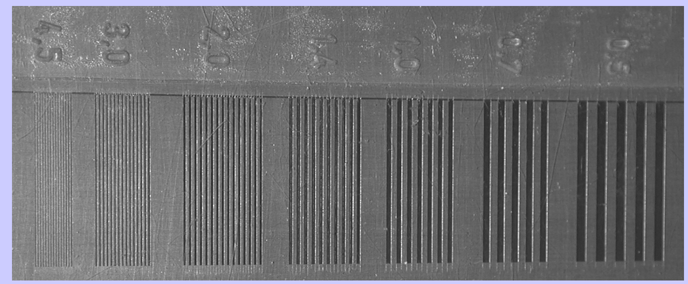
- RQA techniques per IEC 61267

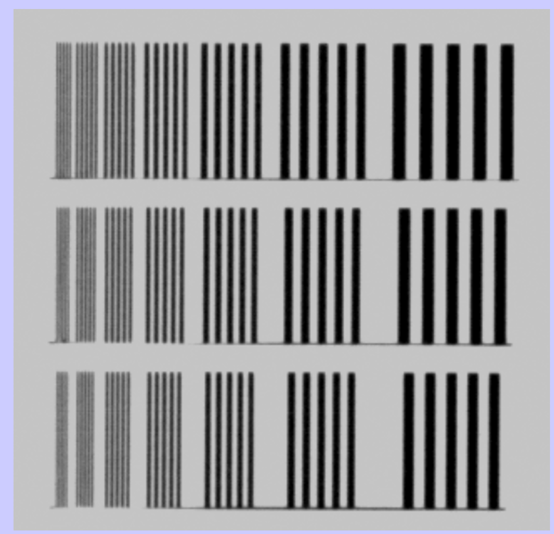
| Technique | kVp | Filtration (mm Al) | HVL (mm Al) | $SNR^2/mm^2mR$ (counting) |
|---|---|---|---|---|
| RQA5 | 70 | 21.0 | 7.1 | 255,232 |
| RQA9 | 120 | 40.0 | 11.5 | 273,548 |
| RQA-M2 | 28 | 2.0 | 0.56 | 47,231 |
| RQA-M4 | 35 | 2.0 | 0.68 | 55,587 |

# MTF methodology

Square Wave Response Method

- Bar pattern test device
- SWR deduced from image data
- MTF estimated from SWR
- Advantages:
  - Simple and quick
- Disadvantages:
  - Low precision
  - Susceptible to noise
  - Coarse sampling of the MTF

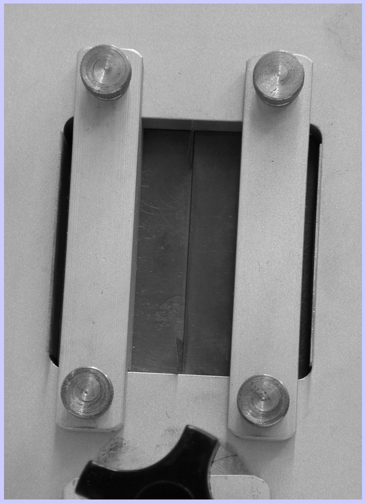


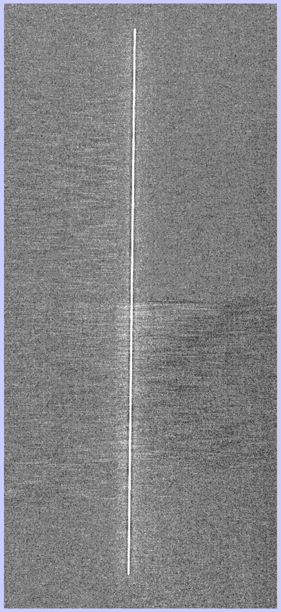


# MTF methodology

Slit Method

- Slit test device
- LSF deduced from image data
- MTF from LSF via Fourier transformation
- Advantages:
  - High precision, particularly at high frequencies
  - Established method
- Disadvantages:
  - Precise alignment necessary
  - Multiple acquisitions
  - Extrapolation of LSF tails and low low-f precision

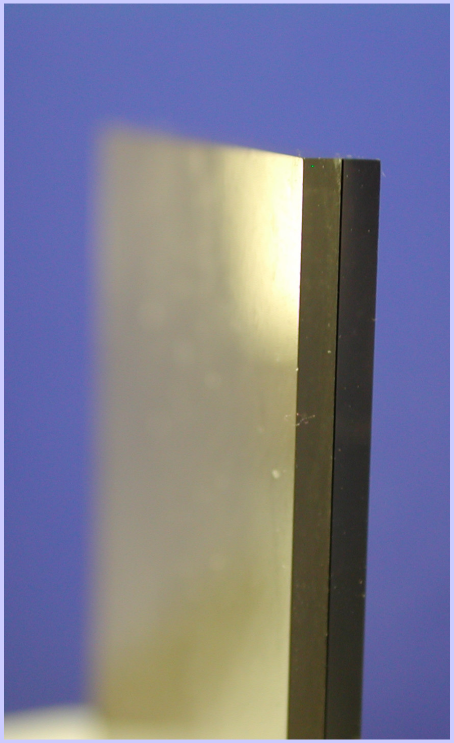


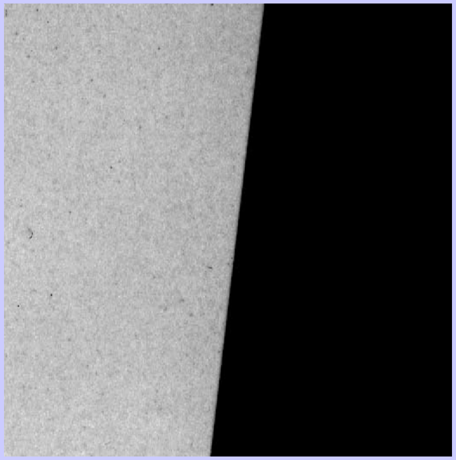


# MTF methodology

Edge Method

- Edge test device
- ESF deduced from image data
- MTF from ESF via differentiation and Fourier transformation
- Advantages:
  - High precision, particularly at low frequencies
  - Simple and quick alignment
  - Established method (endorsed by the IEC)
- Disadvantages:
  - Susceptible to noise due to differentiation
  - Less precise at high frequencies

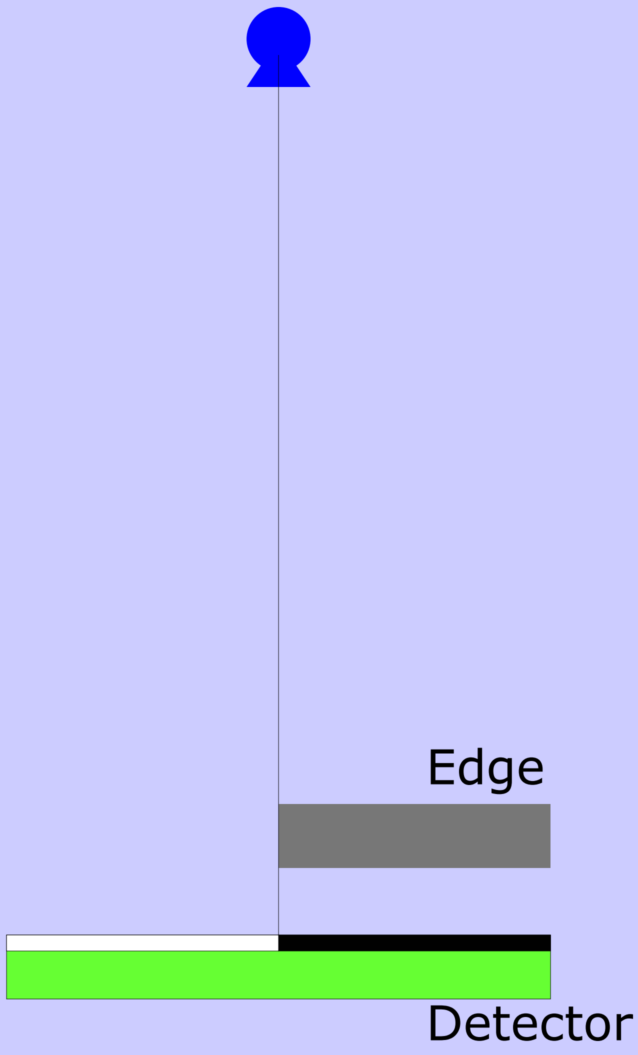




# MTF methodology

Edge Method

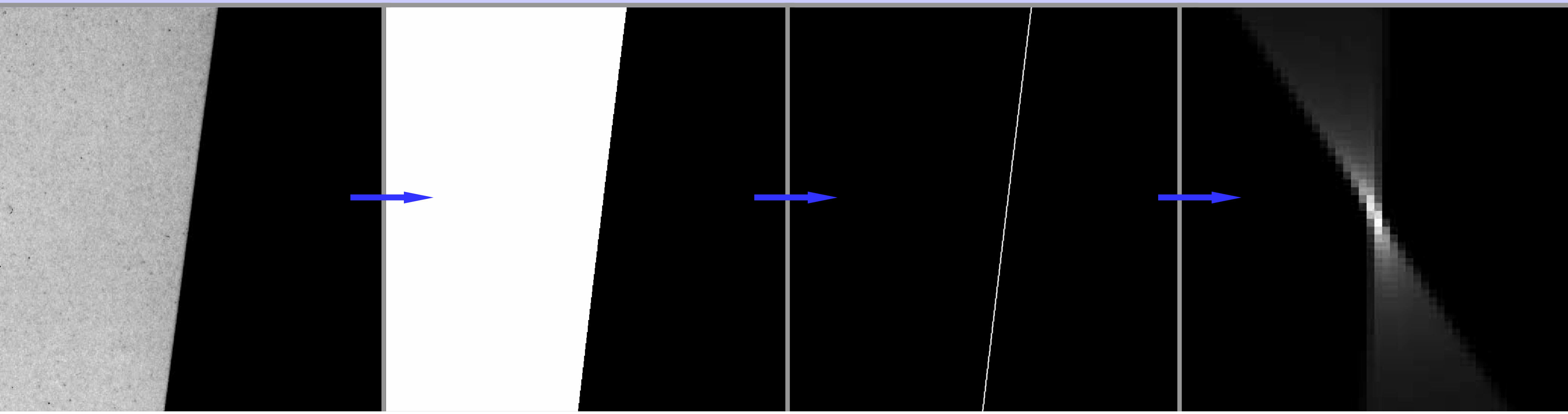
- Edge image acquisition
  - Largest possible SID
  - Smallest possible focal spot
  - Desired technique
  - @ 2/3 of max exposure



# MTF methodology

Edge Method

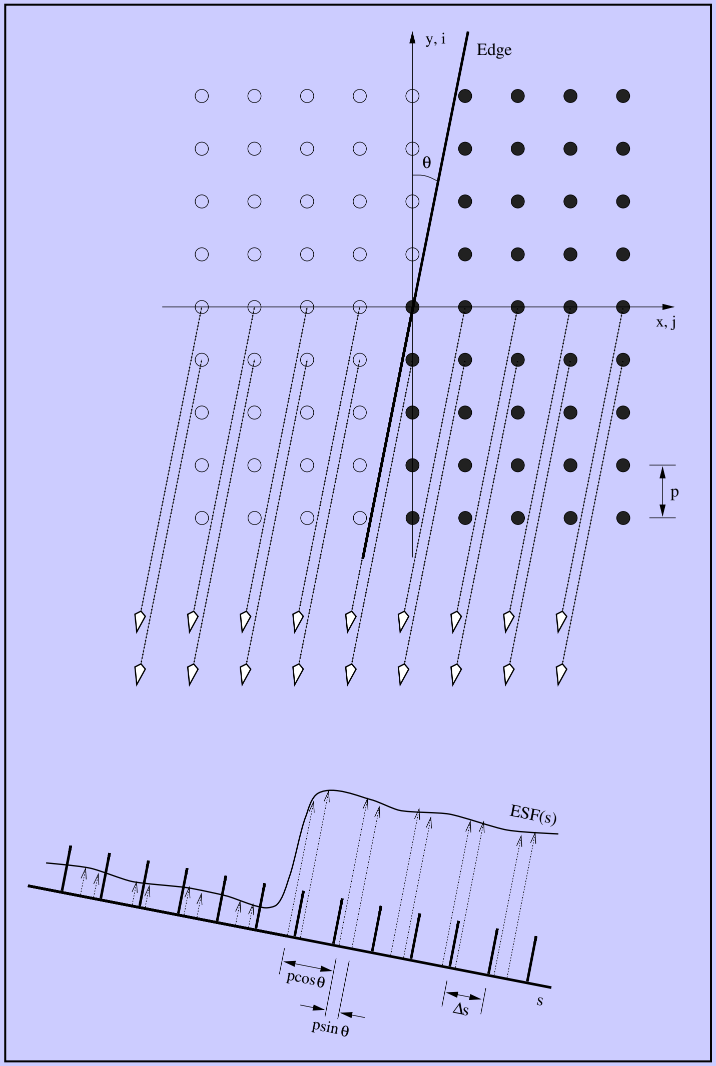
- Edge image processing
  - Linearize the image data wrt exposure (per linear system theory requirement)
  - Finding the edge angle (Least square fits or differentiation and Hough transformation)



# MTF methodology

Edge Method

- Edge image processing
  - 2D projection of the image data to obtain the ESF
  - Differentiation and smoothing of the ESF to obtain the line spread function (LSF)
  - Fourier transformation of the LSF to get the presampled MTF
  - Normalization of the MTF at 0 spatial frequency



# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. Spatial artifacts
4. Latitude
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6. Noise
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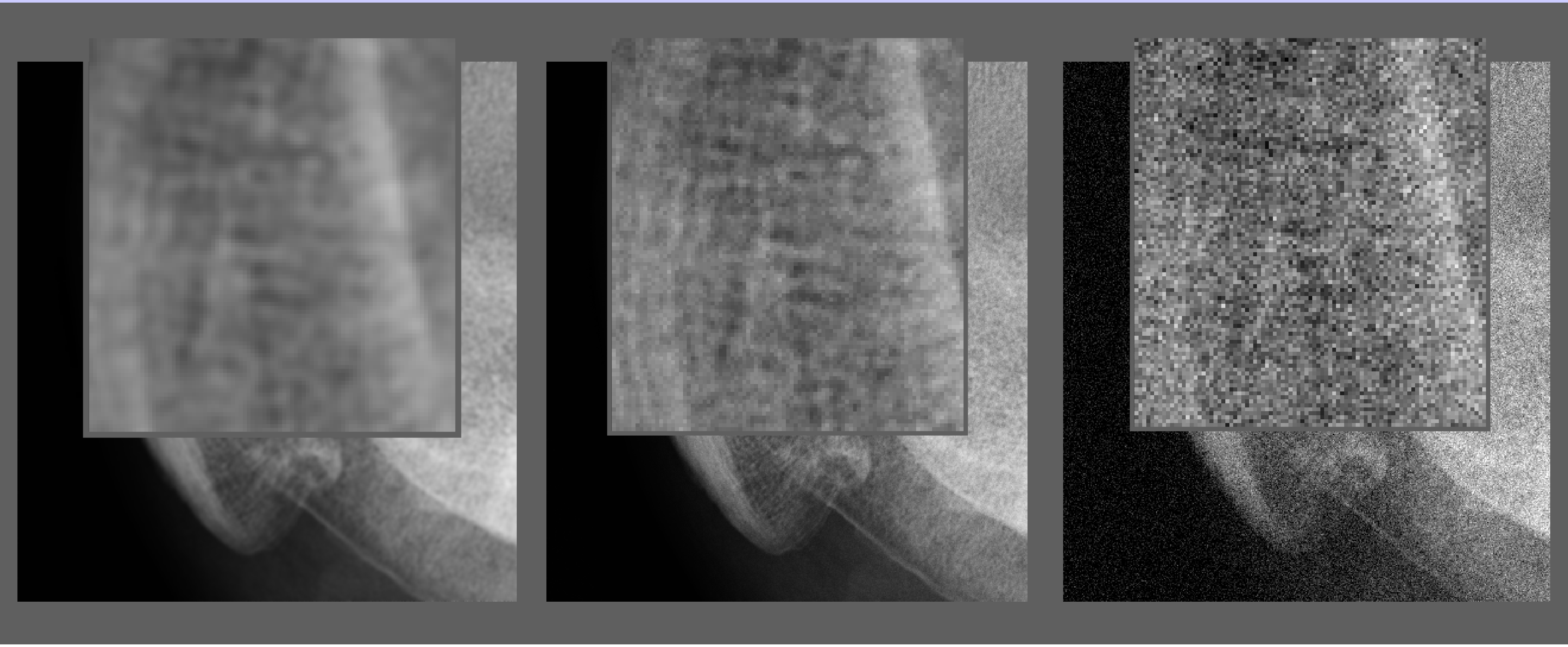
# Noise

- Unwanted signals that interfere with interpretation



# Noise

- Best characterized by the noise power spectrum (NPS):
  - **The variance of noise in an image in terms of spatial frequency components**
- Lower the NPS, better the noise

$$NPS(f) = \Im\{ACF(x)\}$$

$$ACF(x) = \frac{1}{L}\int_{L} \Delta i(x + x')\Delta i(x')dx'$$

# NPS

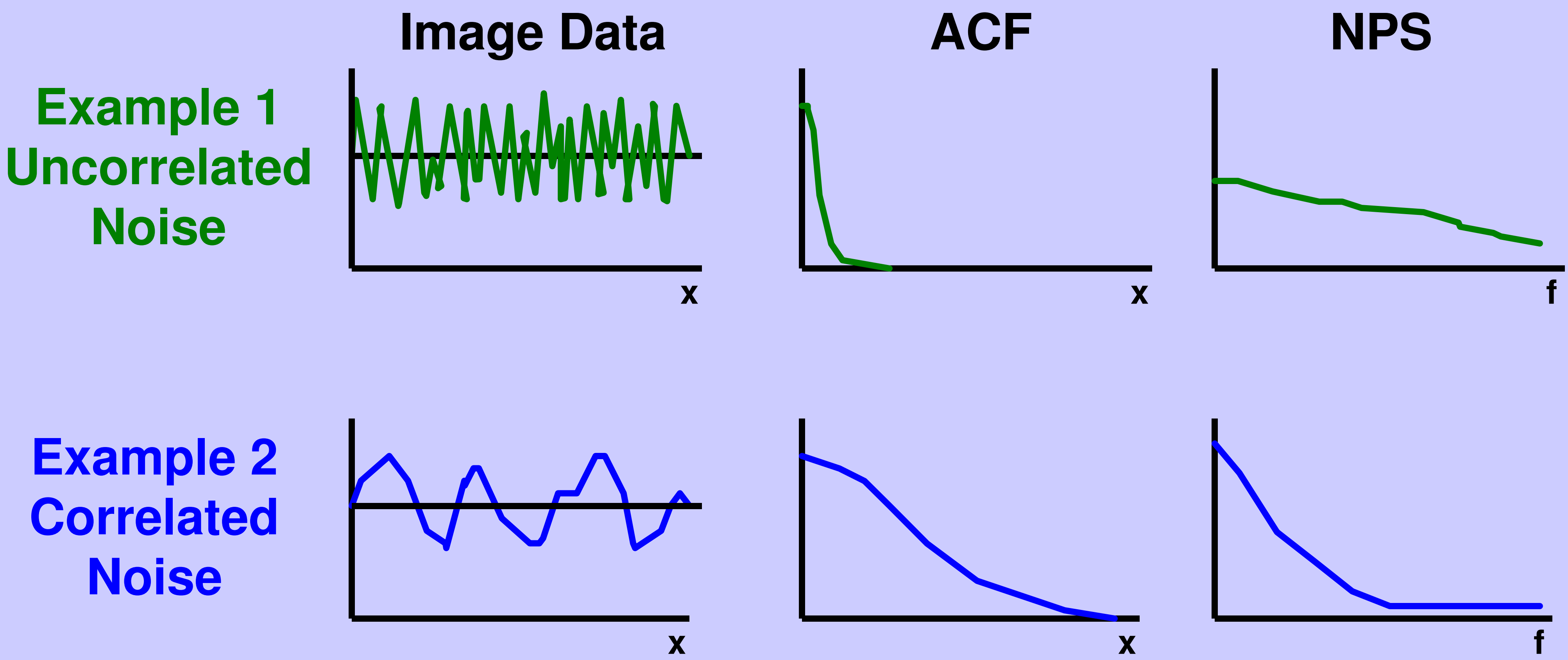
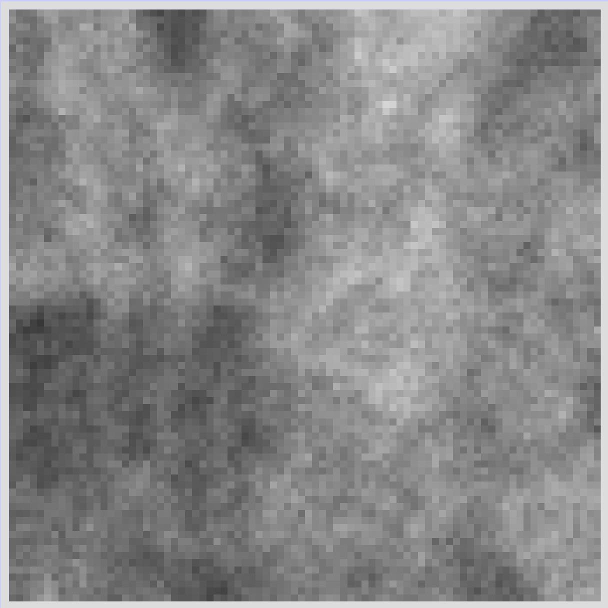
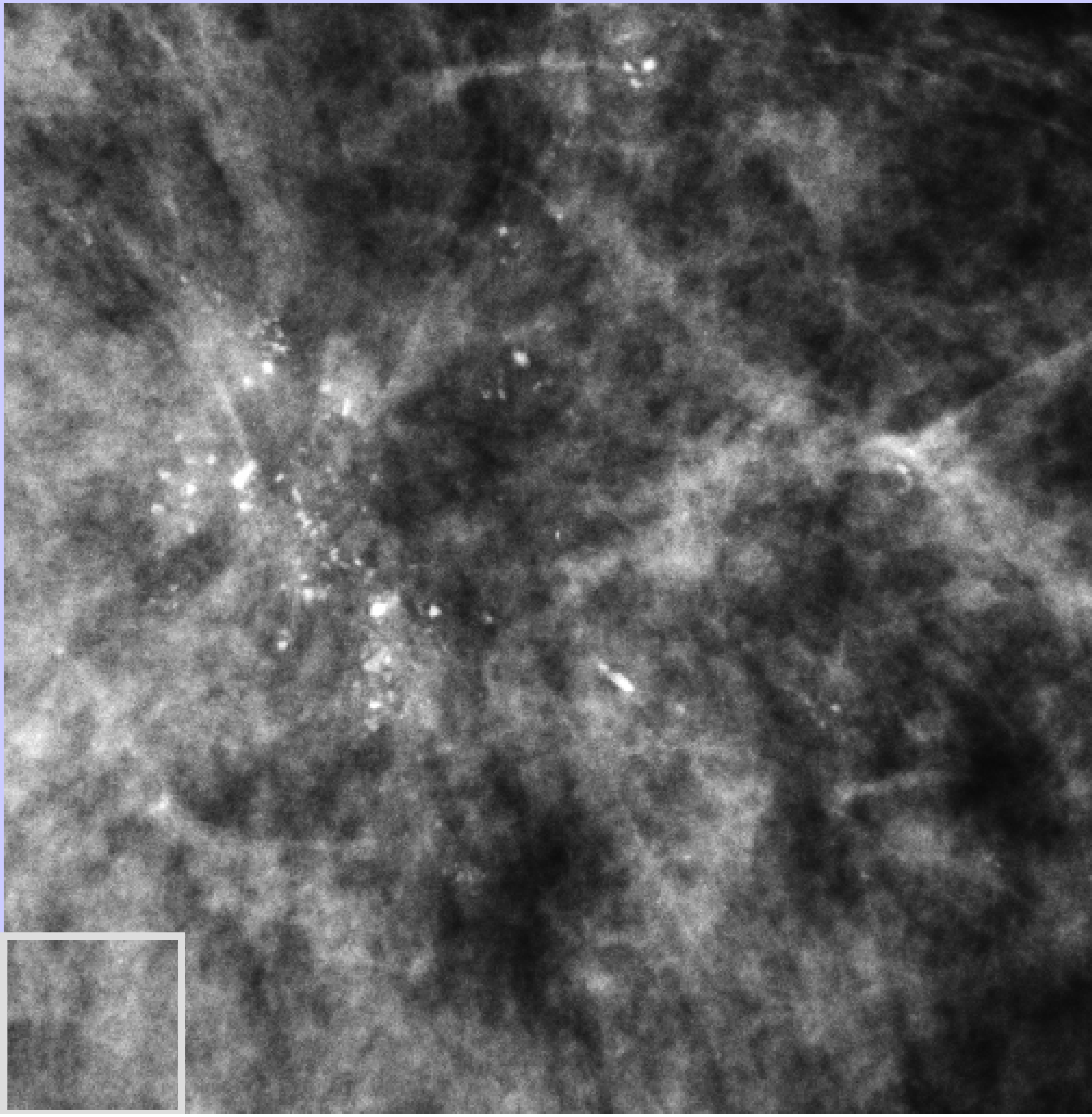
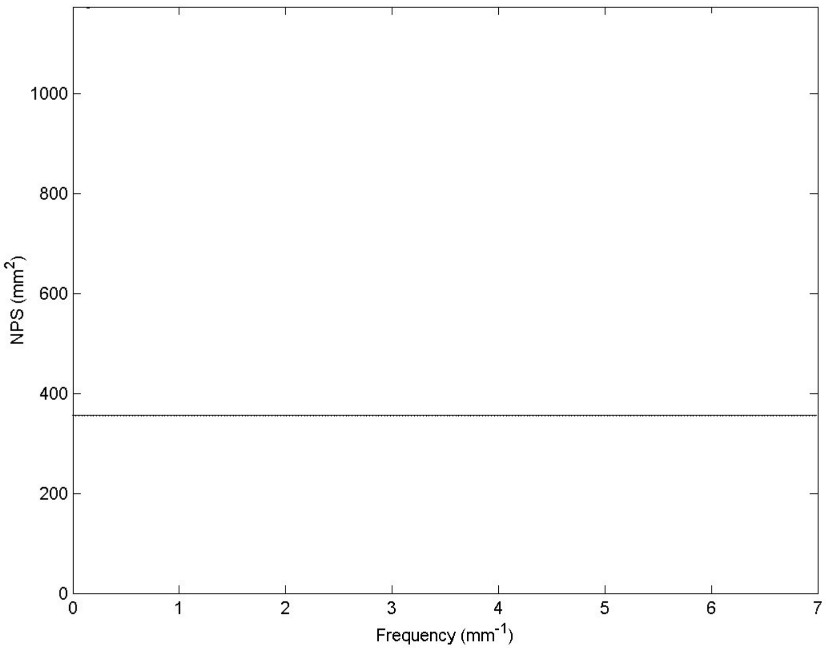


Image Data
ACF
NPS
Example 1
Uncorrelated
Noise
Example 2
Correlated
Noise
x
x
f
x
x
f

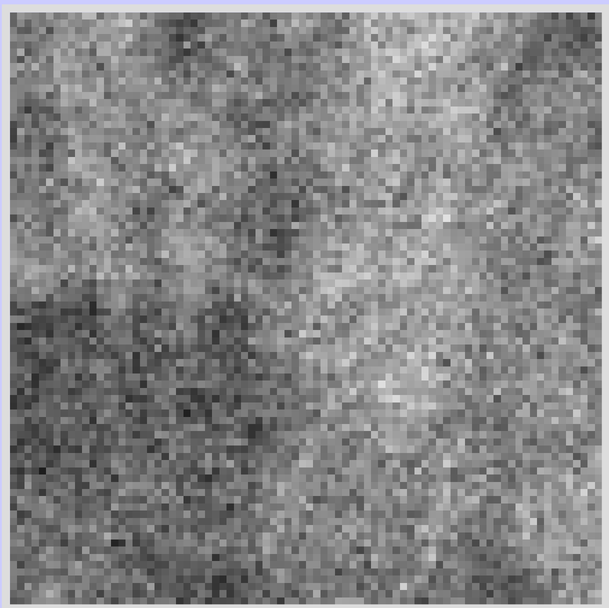
# Image without noise

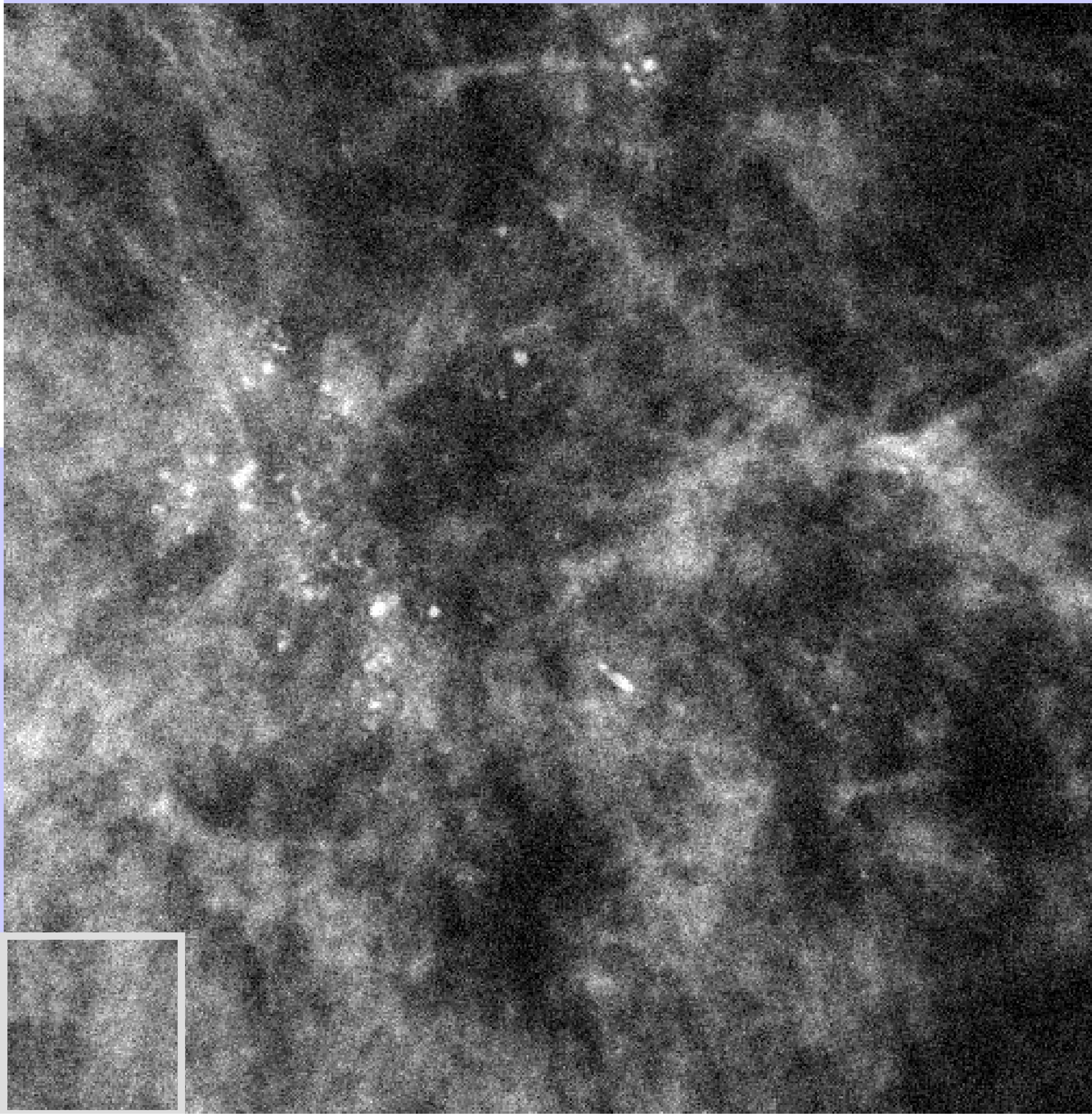




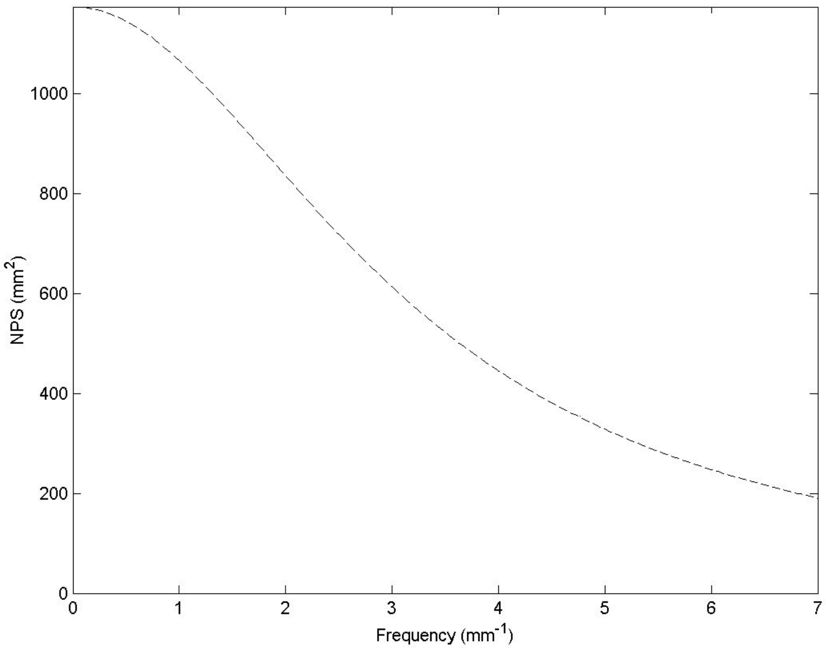


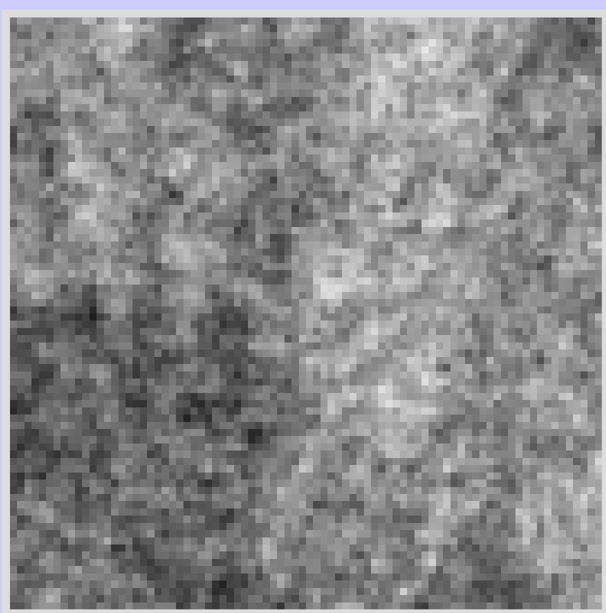

# Uncorrelated noise

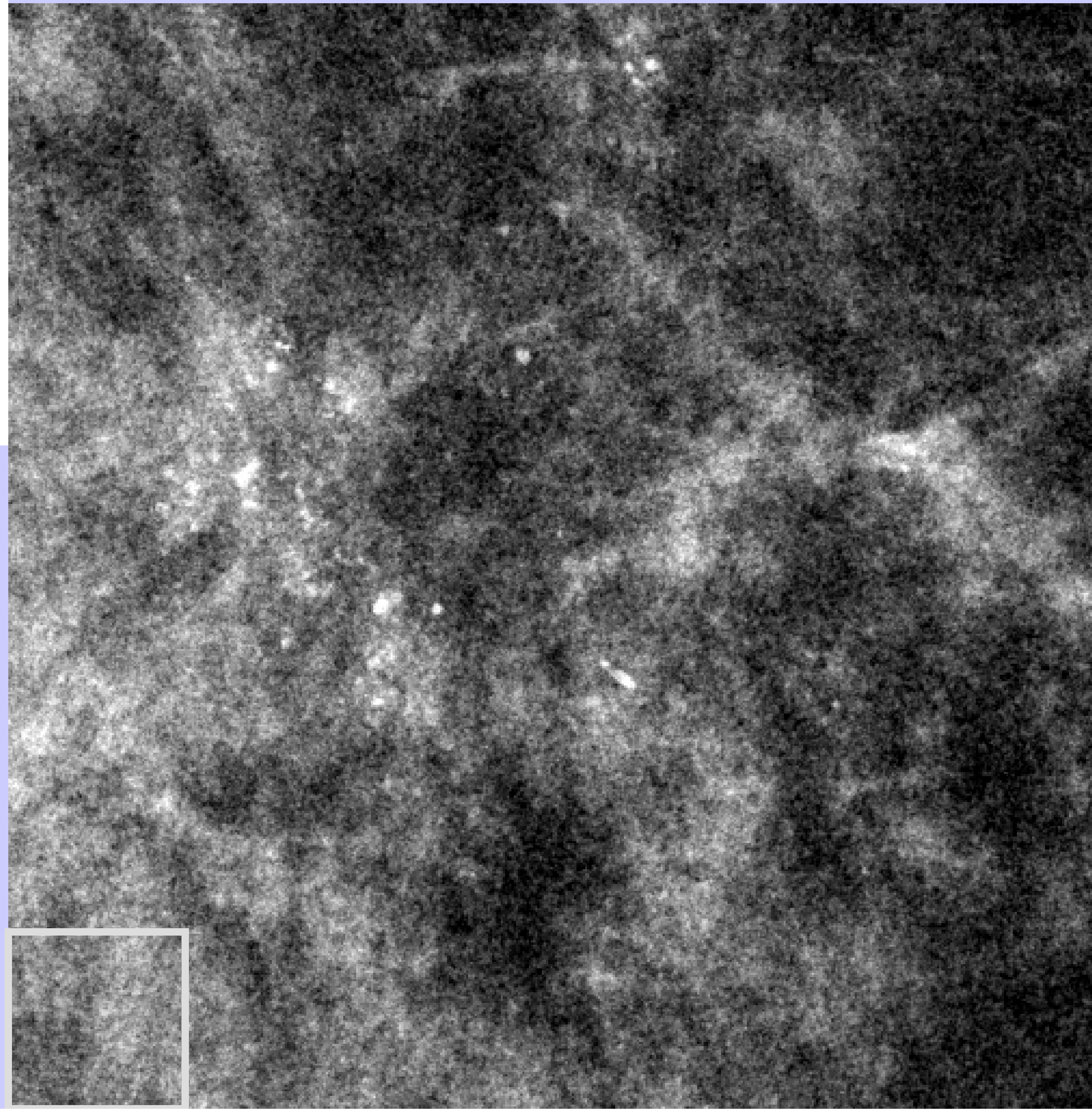




# Correlated noise

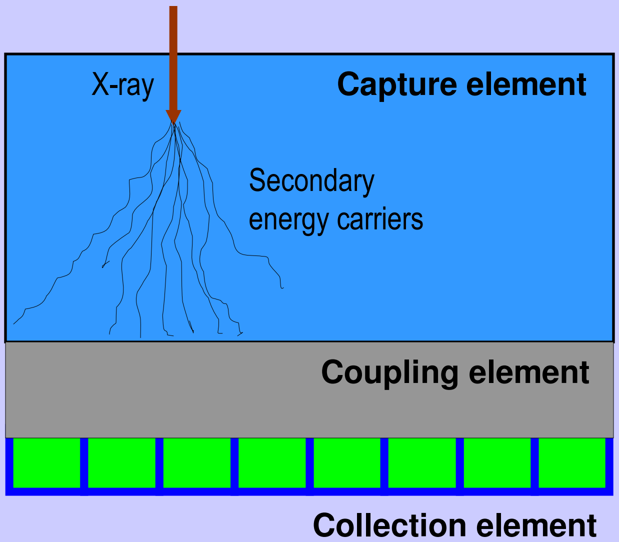




# Noise factors

1. Capture element noise
2. Coupling element noise
3. Collection element noise



# Capture element noise

## 1. Quantum noise

$$S = \varphi_0 \eta g \qquad N = \sigma_q^2 = \varphi_0 \eta (g^2 + \sigma_g^2)$$

$$SNR^2 = \varphi_0 \eta \frac{1}{1 + \sigma_g^2 / g^2}$$

Can be reduced by

- Increasing patient dose (not detector dependent)
- Increasing the thickness of the sensitive layer
  => Resolution trade-off
- Increasing the atomic number of the sensitive layer

# Capture element noise

## 2. Conversion noise

$$S = \varphi_0 \eta g \qquad N = \sigma_q^2 = \varphi_0 \eta (g^2 + \sigma_g^2)$$

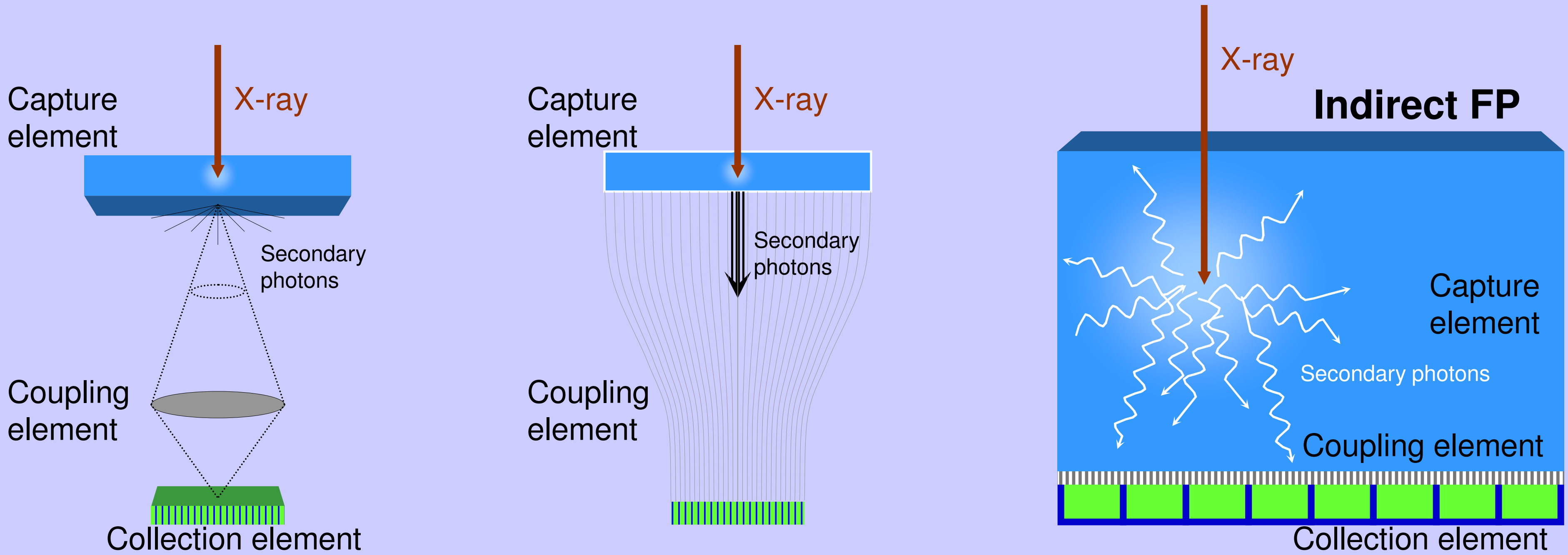
$$SNR^2 = \varphi_0 \eta \frac{1}{1 + \sigma_g^2 / g^2}$$

Can be reduced by

- –Higher-gain/lower-noise conversions
- –Generating and collecting more energy carriers
- –Having smaller number of conversion stages
- –Having larger fill factors in FP detectors

# Coupling element noise

- A conversion noise source
  - Dominant problem in lens-coupled DR systems
  - Can be improved by direct coupling or fiber-optic taper



# Collection element noise

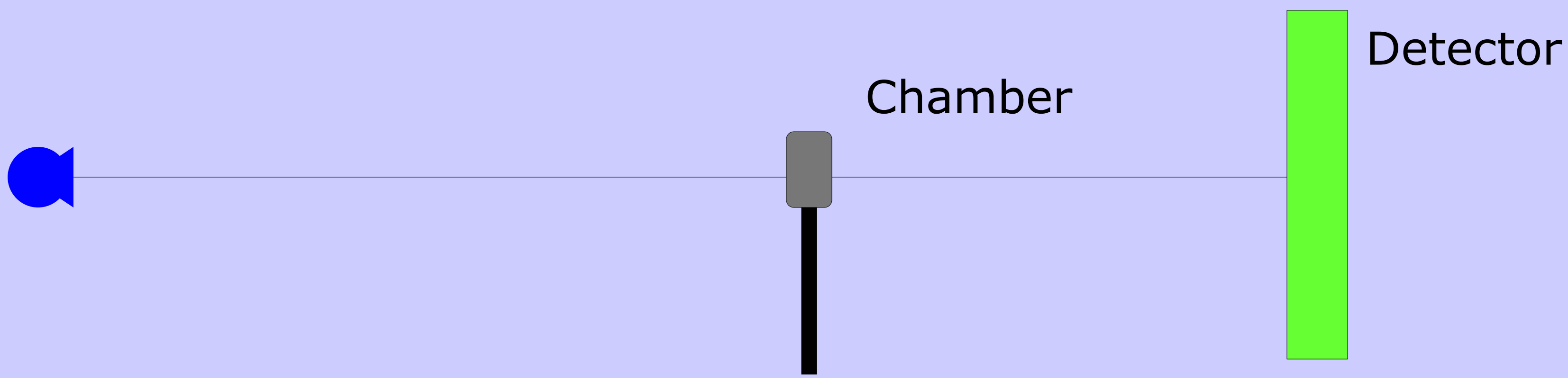
1. Conversion noise
   - ~ Efficiency by which secondary energy-carriers are captured
   - Can be improved by light spectral matching and larger fill factors
2. Additive electronic noise
   - Due to background electronic noise
   - Dominant problem for DR detectors at very low exposures, limiting fluoro applications
   - Leads to a drop in DQE at very low exposures
   - Can be improved by improved electronic or cooling the detector (in FP and CCD/CMOS systems)

# Collection element noise

3. Structured noise
   - Due to detector response non-uniformity
   - Dominant problem for DR and CR detectors at high exposures
   - Leads to drop in DQE at high exposures
   - Can be improved by improving uniformity of the sensitive layer
   - DR: Can by improved by reducing pixel-to-pixel variations and applying rigorous gain calibration

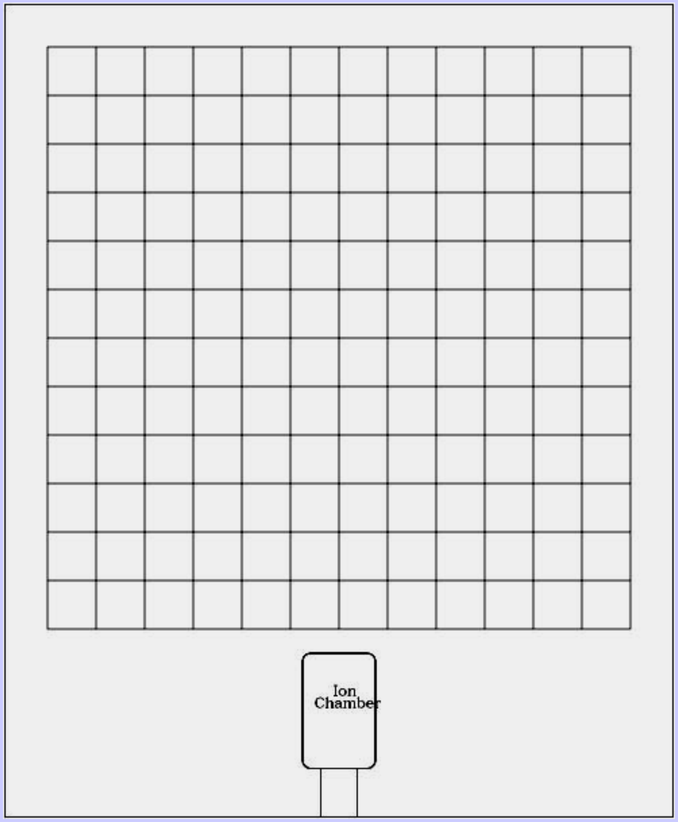
# NPS methodology

- Uniform image acquisition
  - Largest possible SID
  - Desired technique
  - Uniform images at various exposures corresponding to the desired application of the system
  - Exposure precisely measured free-in-air



# NPS processing steps

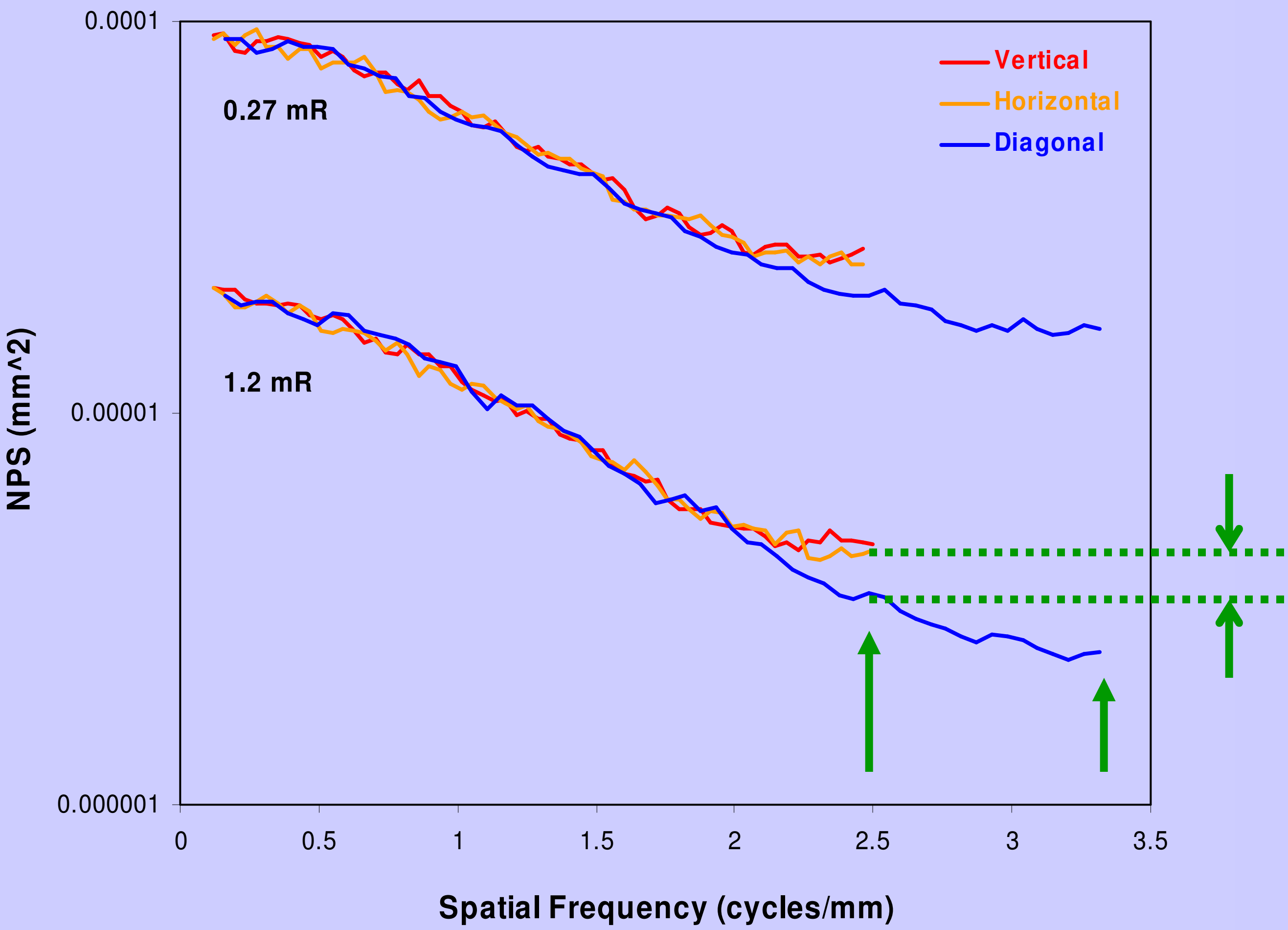
- Linearization wrt exposure
- Division of the image into small ROIs (sizes consistent with the desired precision of the resultant NPS)
- Detrending
- Fourier analysis
- Averaging ROI NPS
- Extracting directional 1D-NPS

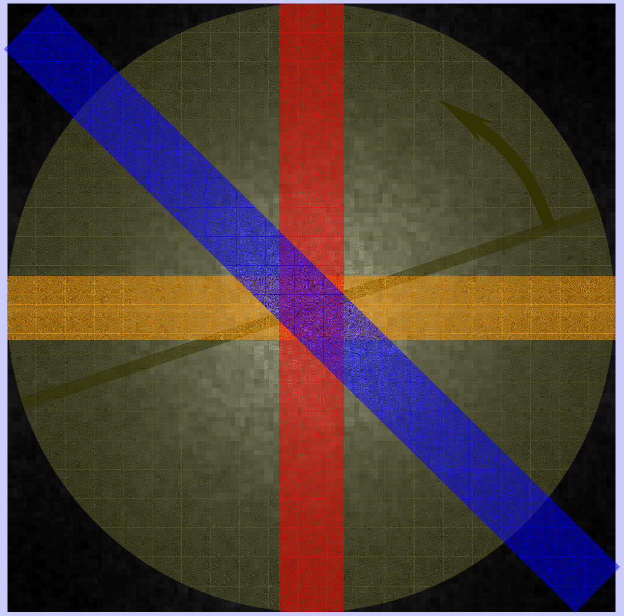


# NPS methodology

- Uniform image processing
  - Subtract a $2^{nd}$-order polynomial 2D fit from each ROI
  - Convert noise to relative noise by dividing the data by their DC value
  - Apply a Hamming filter and Fourier transformation (FFT) to obtain each ROI's NPS
  - Normalize each spectrum to that of a reference ROI
  - Assess the exposure at the reference ROI
  - Average ROI NPS to obtain the overall NPS

# NPS, Orthogonal vs Diagonal



GE, XQ/i, RQA5

# Basic descriptors of the digital image

1. Field of view
2. Uniformity
3. Spatial artifacts
4. Latitude
5. Spatial resolution
6. Noise
7. Efficiency
8. Scatter sensitivity
9. Speed
10. Lag

# Noise and resolution => SNR

- Threshold contrast and diameter ~ 1/SNR (Rose model)
- Higher the SNR =>

  Features w/ smaller C and D can be detected

$$SNR_{actual}^{2} = \frac{G \times MTF^{2}(f)}{NPS(f)}$$

# Efficiency

- Best characterized by the detective quantum efficiency (DQE):
  - Ability of a detector to utilize the maximum possible SNR provided by the finite number of x-ray photons forming the image

$$DQE(f) = \frac{SNR^2_{actual}}{SNR^2_{ideal}} = \frac{G \times MTF^2(f)}{SNR^2_{ideal} \times NPS(f)}$$

# DQE methodology

$$DQE(f) = \frac{G \cdot MTF^2(f)}{\left(SNR^2_{ideal}/X\right) \cdot X \cdot NPS(f)}$$

| | | |
|---|---|---|
| G | => | Gain factor = 1 |
| MTF | => | Measured |
| NPS | => | Measured |
| X | => | Measured |
| $SNR^2_{ideal}/X$ | => | Estimated |

# Basic descriptors of the digital image

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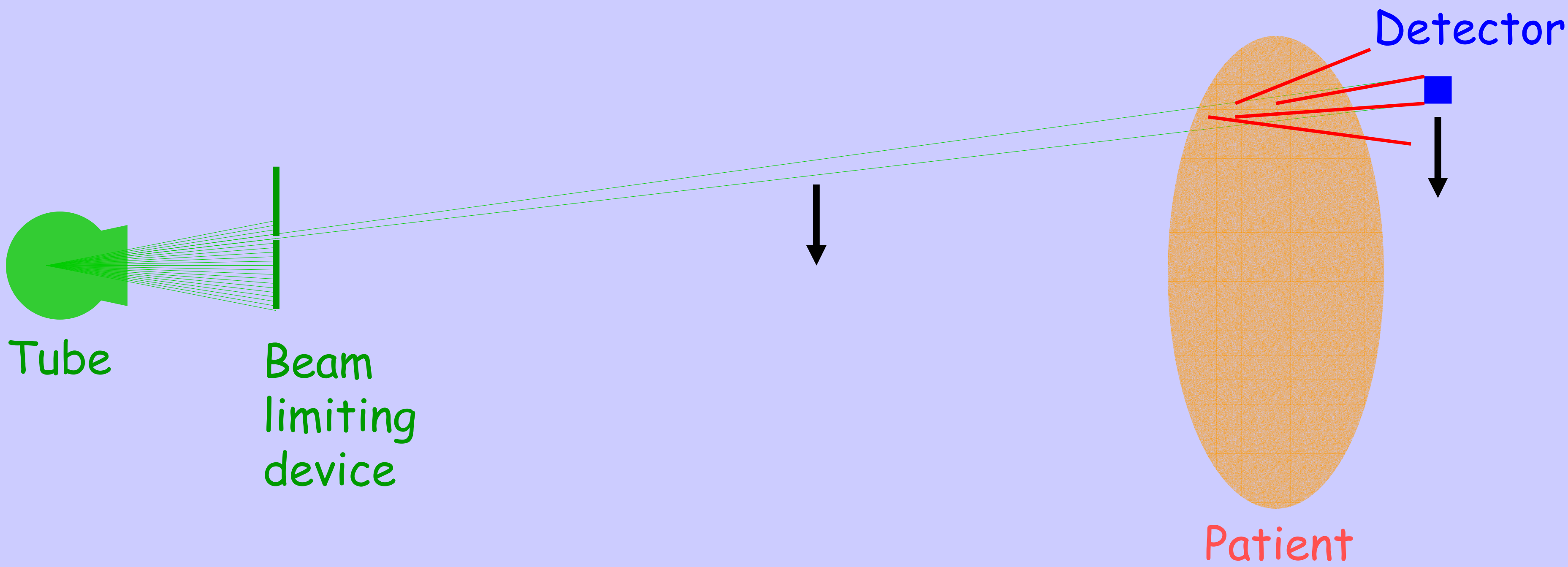
10. Lag

# Scatter (full-field)


SF = S / S+P

# Scatter (slot-scan)



# Scatter effect

- Contrast

$$C_{ws} = C_{wo}\,(1\text{-}SF)$$

- Differential signal

$$dS_{ws} = dS_{wo}$$

- Relative noise

$$N^2_{ws} = N^2_{wo}\,(1\text{-}SF)$$

- Differential SNR

$$SNR^2_{ws} = SNR^2_{wo}\,(1\text{-}SF)$$

# Scatter effect

- Differential SNR + grid attenuation

$$SNR^2_{ws} = t * SNR^2_{wo} (1-SF)$$

Effective DQE:

$$eDQE = t\ (1-SF)\ DQE$$

# DQE limitations, e.g.,

Wide-beam (WB) flat-panel detector

DQE(0) = 45%

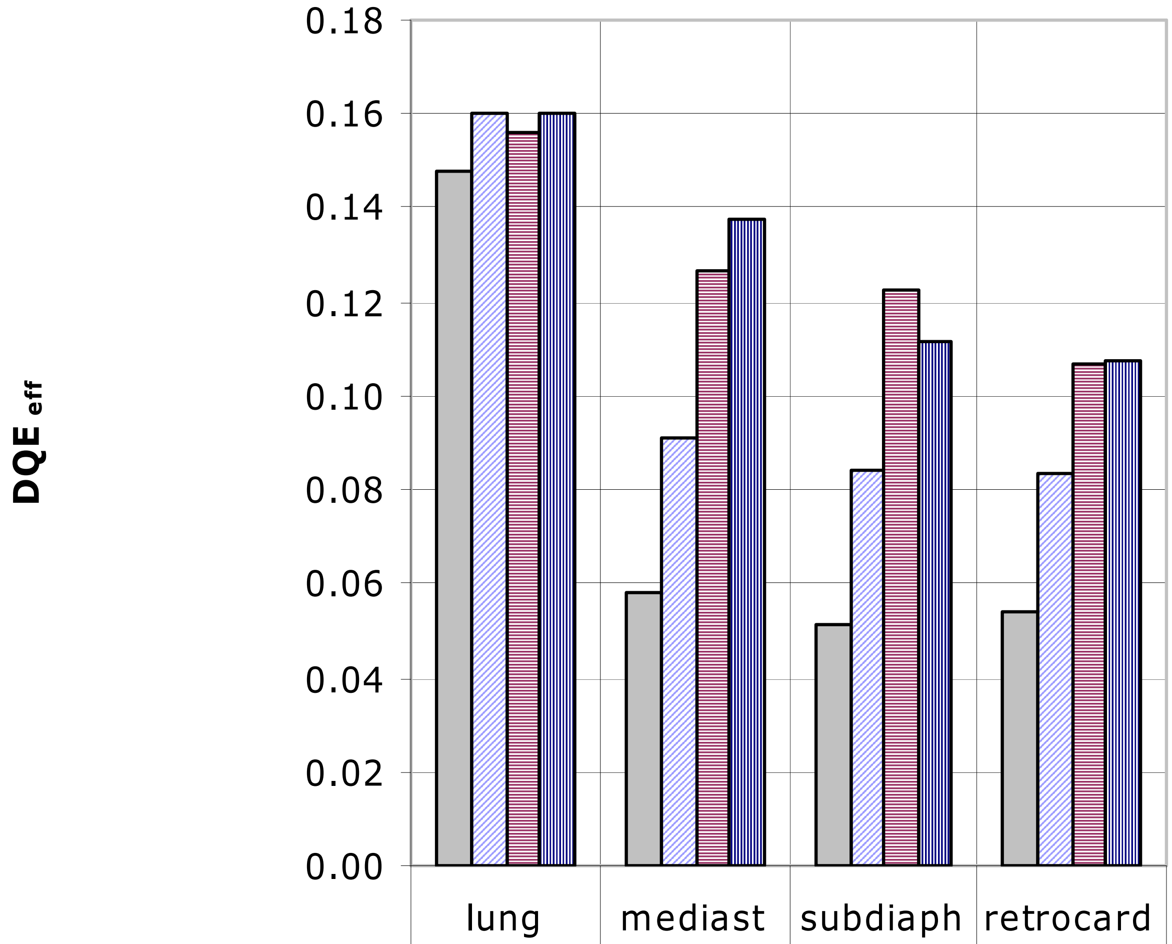
SF = 67-89% (w/o grid)
45-71% (w/ grid, t=0.65)

Slot-scan (SS) CCD-based detector

DQE(0) = 18%

SF = 13-32%

?




| | lung | mediast | subdiaph | retrocard |
|---|---|---|---|---|
| WB 120, no grid | 0.148 | 0.058 | 0.051 | 0.054 |
| WB 120 | 0.160 | 0.091 | 0.084 | 0.083 |
| SS 117 | 0.156 | 0.126 | 0.123 | 0.107 |
| SS 140 | 0.160 | 0.138 | 0.111 | 0.107 |

**region**

# Basic descriptors of the digital image

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# Speed

**Analog systems**

- Defined in terms of exposure required to achieve good analog image quality (i.e., OD)

$$S = 1 / K_S$$

$K_S$ = air kerma in uGy to achieve unit OD (ISO 9236-1, 2004)

**Digital systems**

- OD is irrelevant
- Image quality = SNR
- Speed should be defined in terms of exposure required to achieve good digital image quality (i.e., SNR)

# Digital speed ($S_d$)

- eDQE => $SNR^2$ per unit exposure

$$S_d = \frac{S_0}{eDQE_0(0)} eDQE(0)$$

$S_0$ and $eDQE_0$ = speed and eDQE of an anatomy-specific "standard" film radiographic system

# Digital speed ($S_d$)

Example, Chest radiography:

$S_0 = 400$

120 kVp

12:1 grid => $S_d = 400 / 0.075$ eDQE

$t = 0.5$

$SF_0 = 0.4$

$DQE_0 = 0.2$

# Basic descriptors of the digital image

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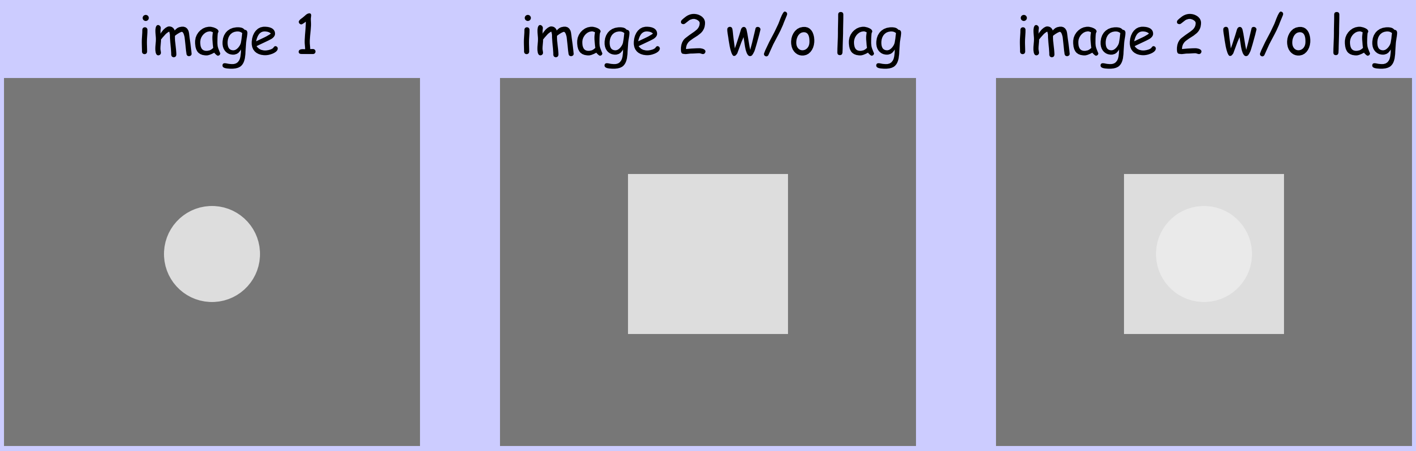
4. Latitude
5. Spatial resolution
6. Noise
7. Efficiency
8. Scatter sensitivity
9. Speed
10. Lag

# Lag

a) Residual signal
b) Sensitivity fatigue

# a) Residual signal

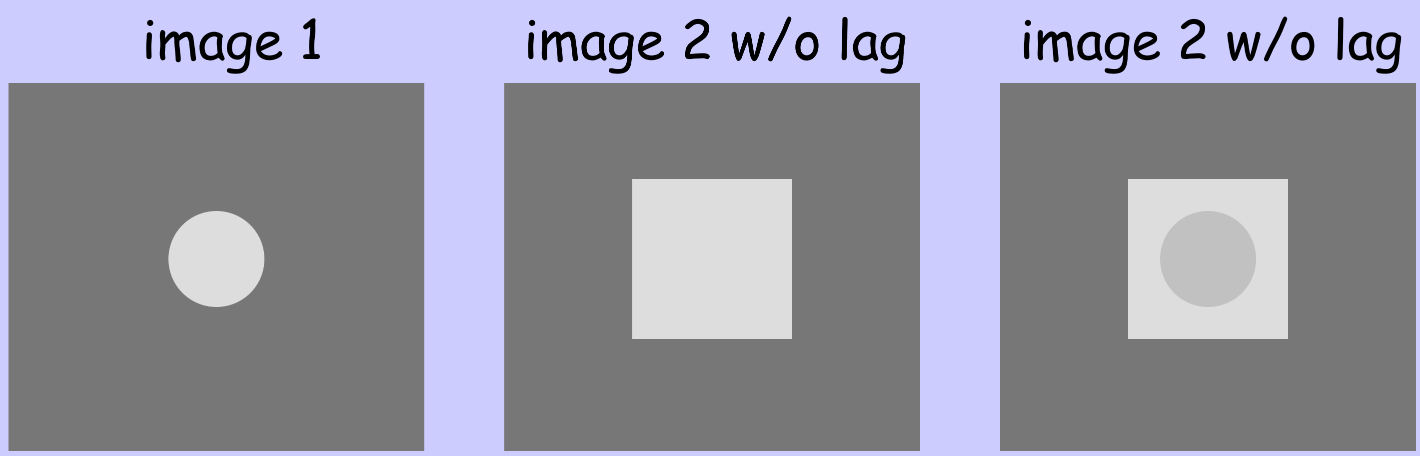
- Incomplete read-out of charge from the detector
- Residual **positive** contrast shadows




Can be corrected by **subtracting** a fraction of last image

# b) Sensitivity fatigue

- Due to reduced sensitivity after an exposure has been acquired
- Residual **negative** contrast shadows on subsequent images



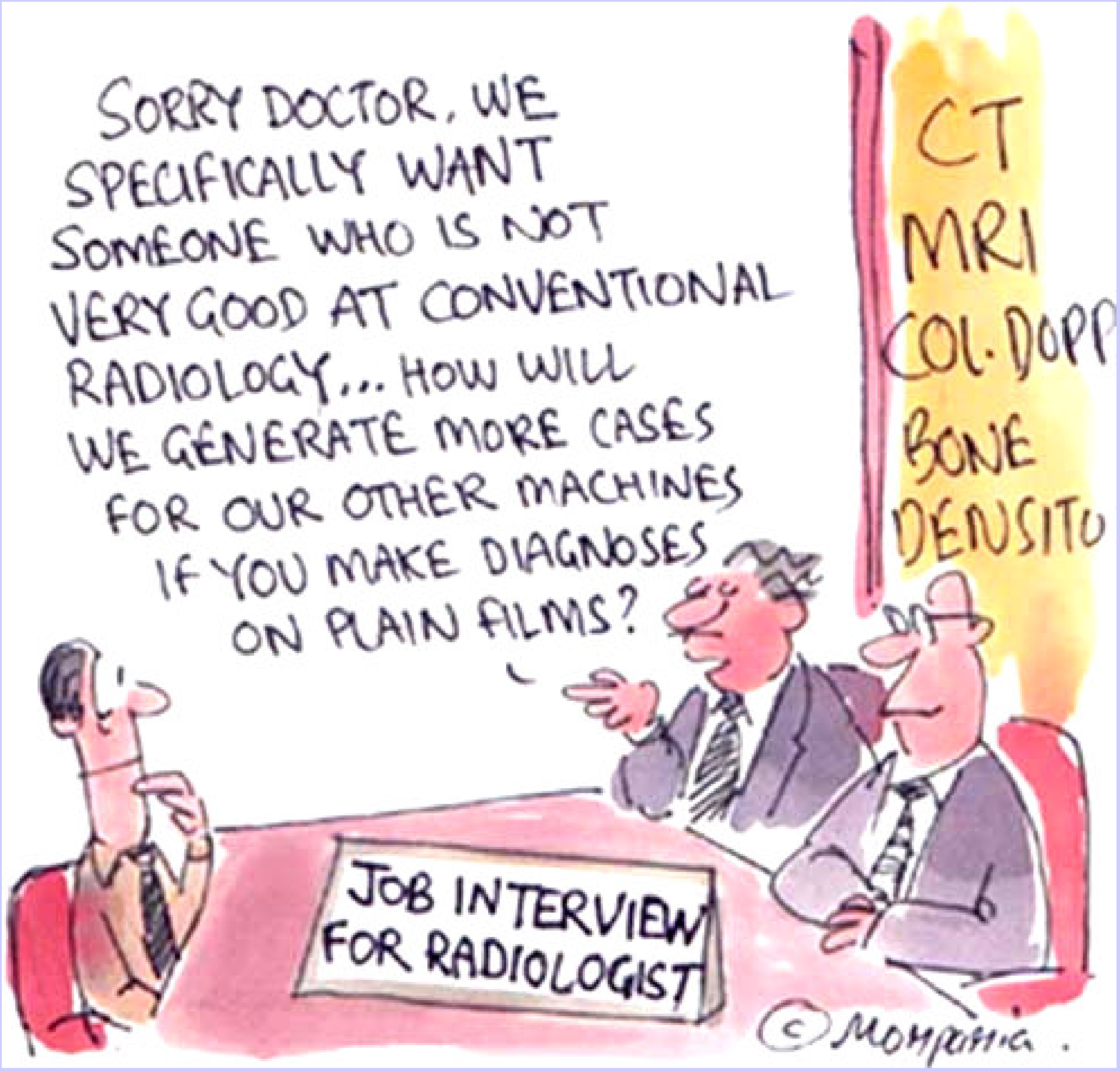

Can be corrected by **adding** a fraction of last image

# Summary

1. Decoupling of capture and display in digital imaging offers potential as well as challenges for improved image quality
2. Lag, uniformity, and artifacts are unique attributes/challenges of digital rad/fluoro systems
3. MTF, NPS, and DQE use slightly new definitions and metrology for digital systems

# Summary

4. The primary image quality factor for digital radiographic systems is the SNR per unit exposure (i.e., DQE) taking into account scattered radiation
5. Neglecting scatter sensitivity can misrepresent the clinical performance of imaging systems
6. DQE and scatter sensitivity can be used as the basis for defining speed for digital imaging systems


SORRY DOCTOR, WE SPECIFICALLY WANT SOMEONE WHO IS NOT VERY GOOD AT CONVENTIONAL RADIOLOGY... HOW WILL WE GENERATE MORE CASES FOR OUR OTHER MACHINES IF YOU MAKE DIAGNOSES ON PLAIN FILMS?
CT
MRI
COL. DOPP
BONE DENSITO
JOB INTERVIEW FOR RADIOLOGIST
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