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Advanced Radiography for EOD

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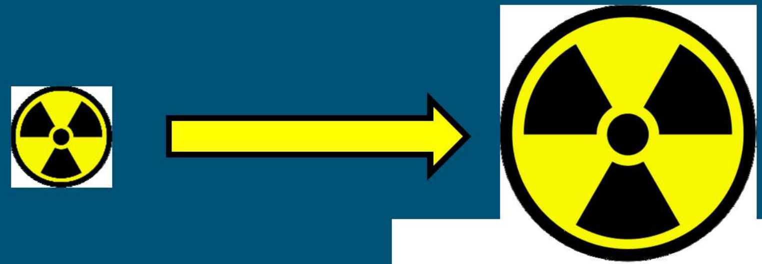
High Energy Radiography Techniques



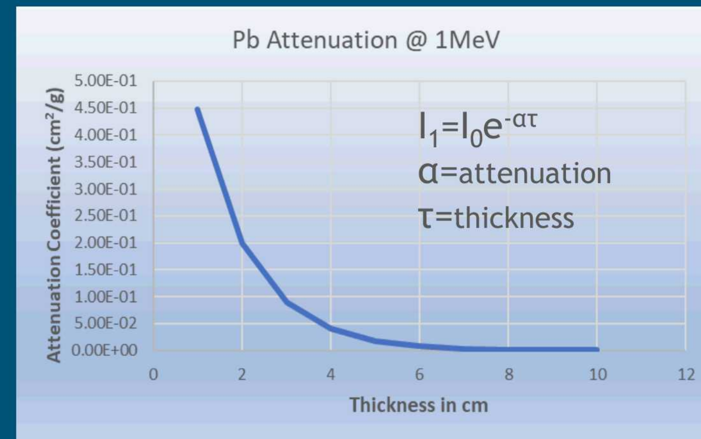
- Lexicon –What do you call it?
- Penetration – high energy to the rescue!
- SNR – winning the battle!
- Scatter – why do we care?
- Image processing – what else can we do?

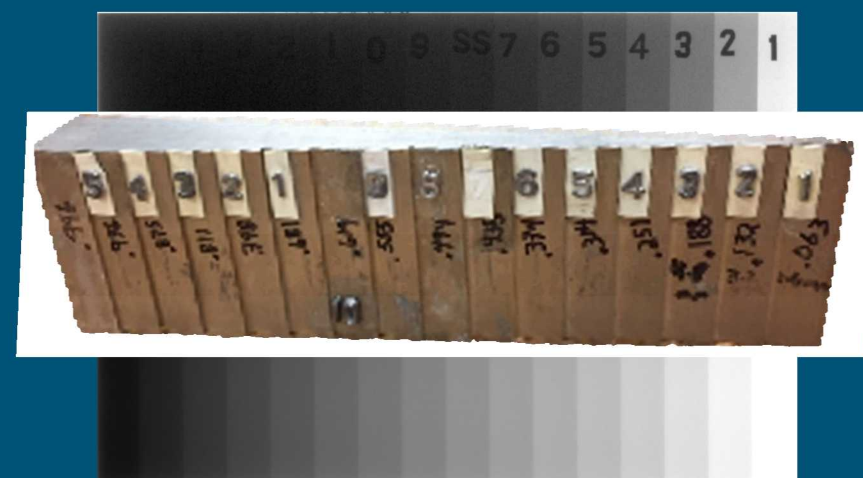
Lexicon

- RGD – *Radiation Generating Device*
- DR Panel – *Digital Radiography Panel (flat panel)*
- CR Plate – *Computed Radiography (PSP photostimulable phosphor plate)*
- Low Energy – *Peak energy <1MeV*
- High Energy – *Peak energy >1MeV*
- SNR – *Signal to Noise Ratio*
- Field Of View –*The object region visible in the image*
- Z Number – *Number of protons in nucleus (not density)*

Penetration Fundamentals

- Increasing thickness quickly reduces x-ray penetration
  - Energy
  - Z number of material
  - Density of material
- Thicker denser objects force us to use higher energy
  - Low Energy photons have a higher probability of interaction and attenuate more
  - High Energy photons have a lower probability of interaction which results in more penetration





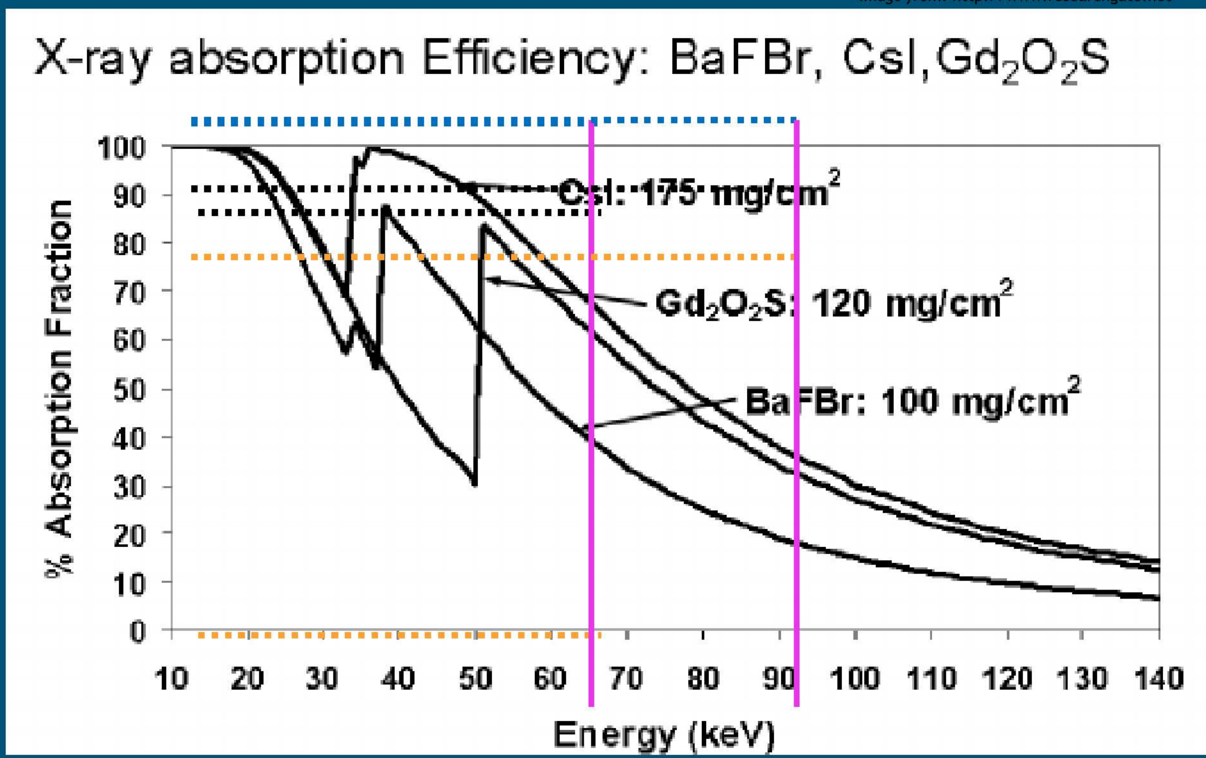
6 MeVp

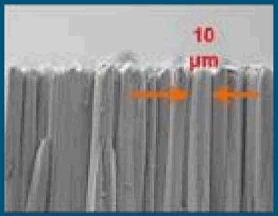
Penetration Fundamentals

- Material differentiation = worse at high energy (contrast)
  - Scatter can be bad for image quality
- Detector efficiency decreases at higher energy, lowering image SNR
- Do we care?

Why don't we always use High Energy?

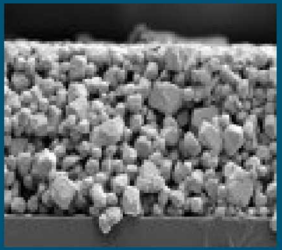
Image from: http://www.researchgate.net





CsI

Image from: http://www.rmdinc.com



Gadox

Image from: http://www.researchgate.net

BaFBr

Image from: http://www.pubs.rsc.org

Signal to Noise Ratio

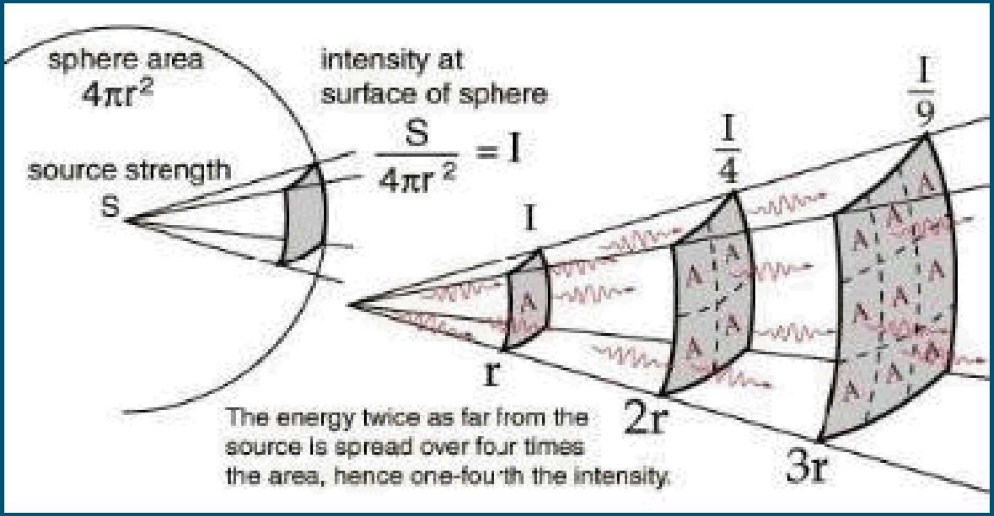
- Signal – desired information (photon attenuation)
  - sum of original photons reaching the detector unaltered
- Noise – any information that obscures the signal
  - Scatter --any photon reaching the detecting medium that has been altered from its original form
  - Systematic --noise associated with the system such as defects in the detector or imaging plate
  - Electronic --noise inherent to the electronics such as thermal and read noise

Signal – How do we get more of it?

- Get a more powerful RGD

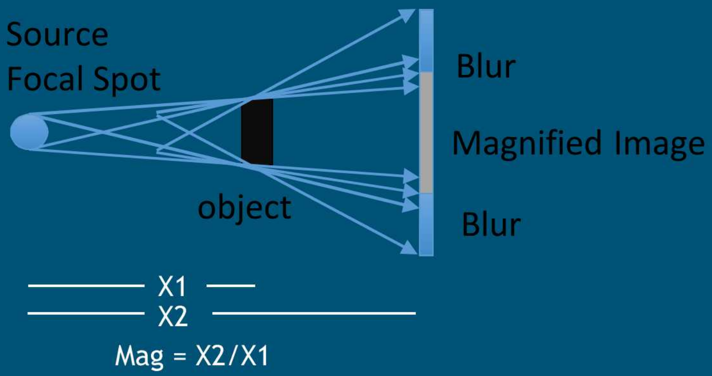
OR….

- Move the RGD in --provides increased photon count per surface area (inverse square law)
- Careful! –it can reduce spatial resolution due to blur

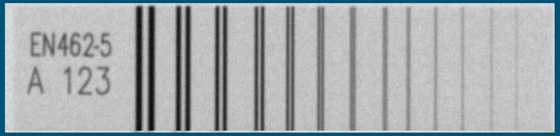


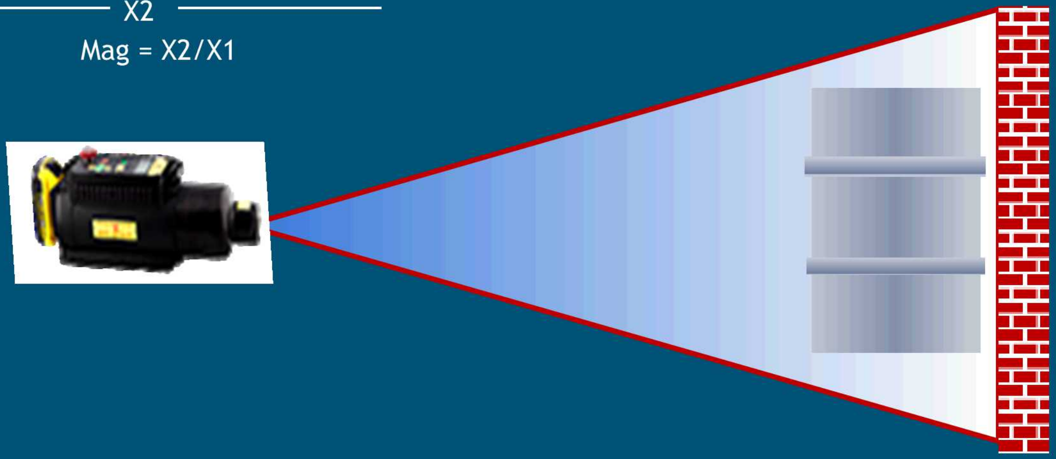
The Distance Compromise

- Moving the RGD in
  - Increased photon intensity per surface area
  - Collimating effect (source cone illuminating fewer objects)



Blur= Fs(X2-X1)/X1
Fs = Focal Spot Size



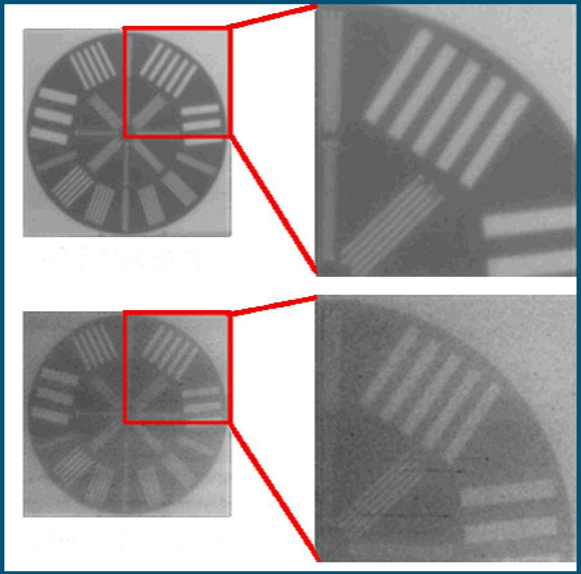


Signal – How do we get more of it?

- Increase phosphor or scintillator stopping power and efficiency (DQE)
  - Higher density = capture of more x-ray photons (signal)
  - Higher light output per x-ray photon captured= more signal sent to photodiodes
- Lower X-ray energy
  - Higher energy photons pass through lighter density phosphors and scintillators (lost signal)
- Increased dose = more signal (sometimes)

DQE

- Filter/Intensification Plates
  - Increases detector quantum efficiency
  - Enhances probability of photon interaction by providing high density/high Z material prior to detector
  - Photons interact with the denser material creating lower energy x-rays and electrons
  - The detectors are more efficient at detecting these lower energy photons and electrons
  - The plates need to be in very close proximity (compression) to the imaging plate to reduce detector blur from angular scatter
  - The front and back plates filter other low energy scatter



Increased Dose

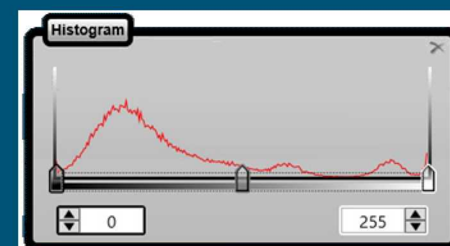
- Some examples of SNR curves with dose change only (CR)

- Why does this work?
  - We are outracing non-scatter noise

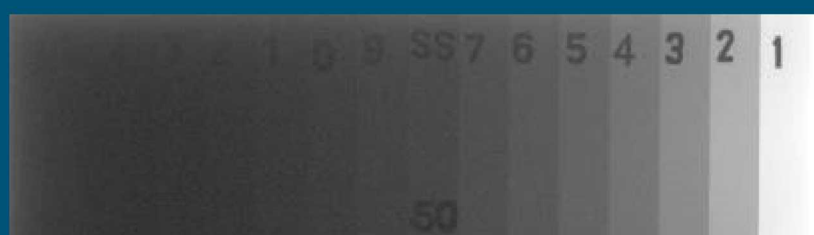
Increased Dose: Example

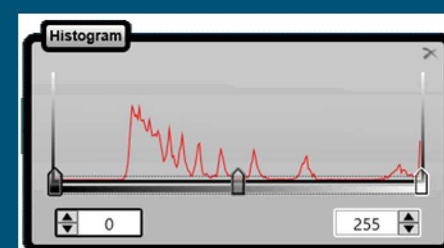
- Simple experiment with all factors the same except dose
  - More dose utilizes more of the available dynamic range leading to better image discrimination
  - Low dose becomes dominated by electronic noise

1x dose



20x dose





Noise –Know your enemy

- Noise can be broken down into to three groups
  - Scatter (dynamic photon interaction)
    - Increases with dose linearly
  - Random noise (dynamic noise)
    - Increase with dose as a function of 1/√
    - Poisson (statistical)
    - Electrical (detection electronics)
  - Fixed pattern noise (static noise)
    - Constant over time
    - Damaged pixels or CR plate

Scatter: Why Do We Care?

- Most high energy photon interactions are scatter

And…

- Scattered photons contain false information (noise)

And…

- Scatter can cascade through all materials exposed

But…

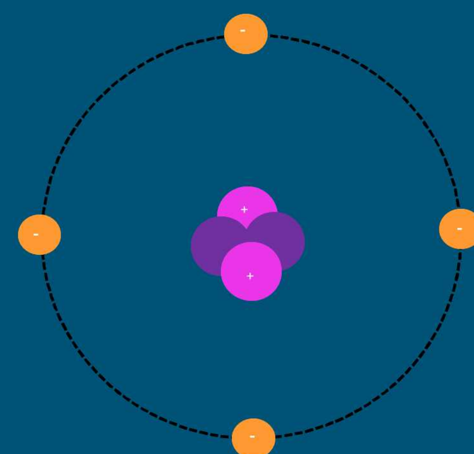
- We only care if it reaches the detector

In Fact…

- In high energy, scatter is the primary image forming attenuation (signal)

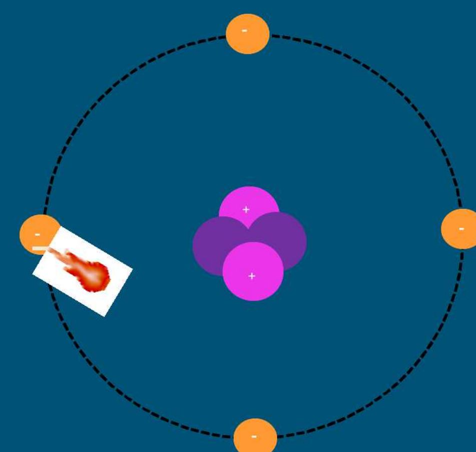
Scatter: Photoelectric Absorption

- Attenuation without scatter
- At "low" energies…
  - On the order of binding energies
- Photon is absorbed by electron
- Electron is ejected from orbit
- Ejected electron can generate secondary scattered photons



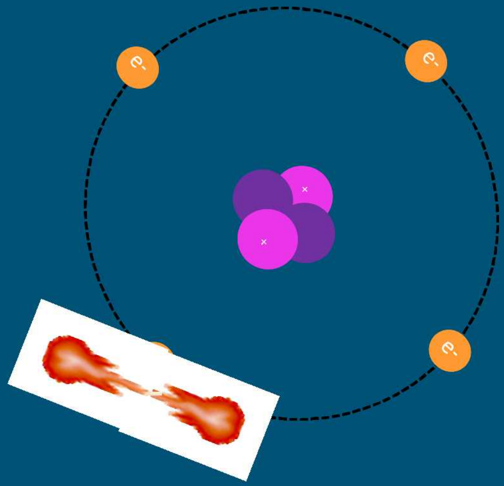
Scatter: Compton

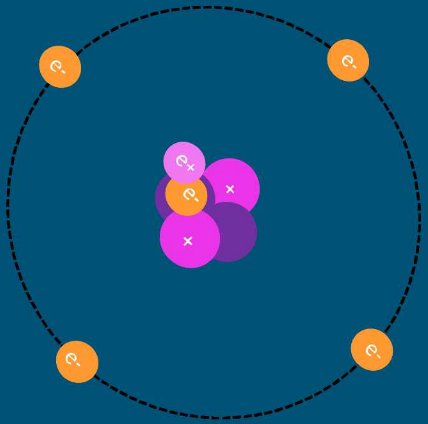
- Attenuation At "higher" energies…
  - Significantly higher than binding energy
- Photon transfers some energy to an electron
- Electron is ejected at some angle
- Photon is scattered at some angle with lower energy
- This is the most common scatter for XRS and low energy Betatron



Scatter: Pair Production

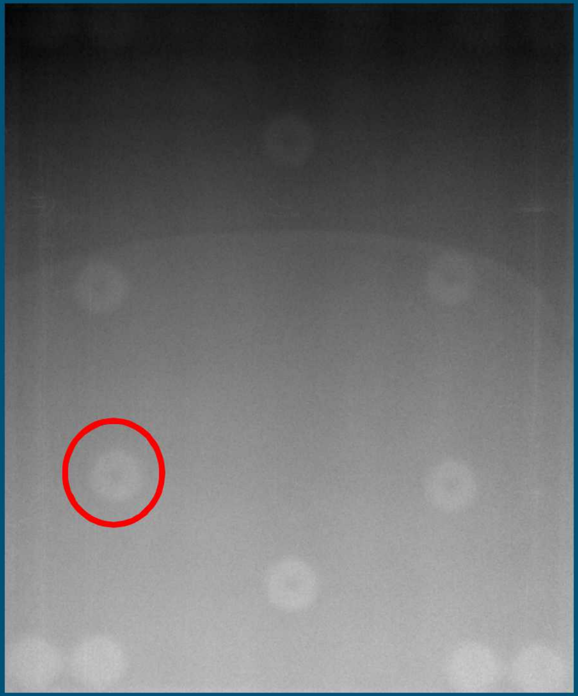
- E > 1.02 MeV
- Photon interacts with nucleus generating electron and positron
- Positron eventually disintegrates and releases 2 510keV photons
- Becomes common at energies above 5 MeV for dense materials

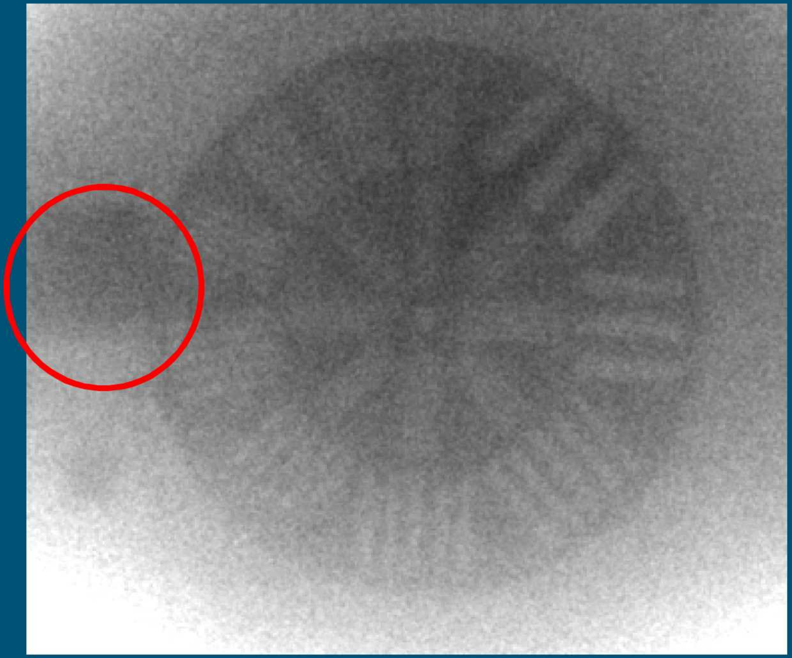




Scatter: Effects

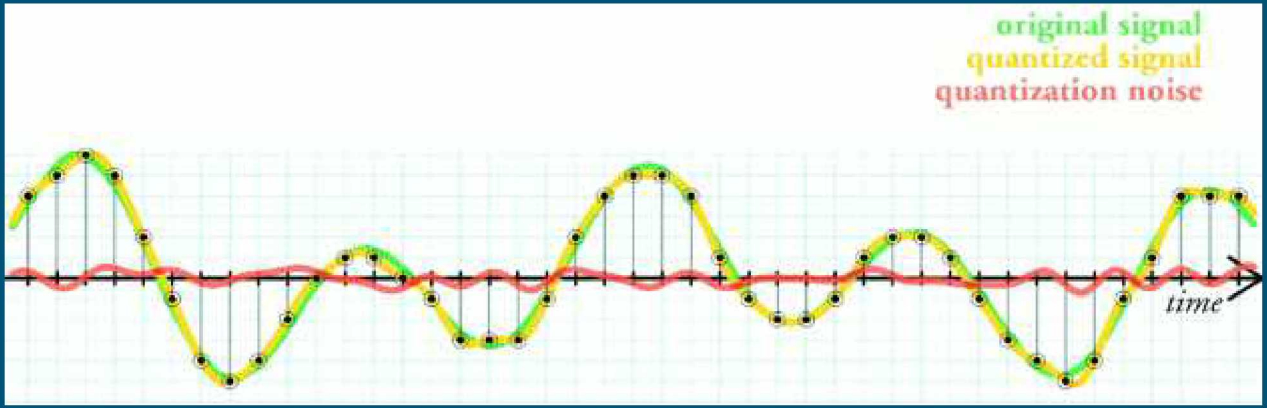
- Example of real world scatter/noise dominated images





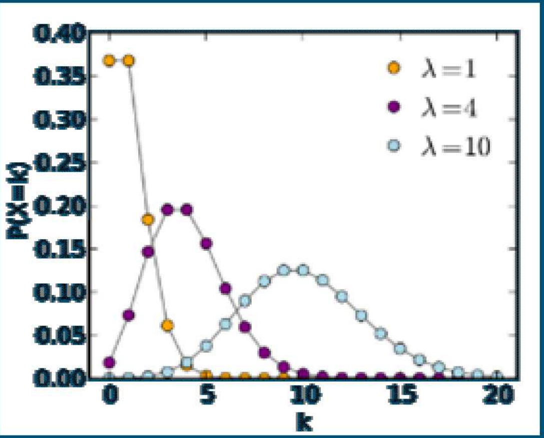
Random Noise

- Quantization noise – Errors arising due to digitization or conversion of analog or continuous signal to a discrete signal.



https://en.wikipedia.org/wiki/Quantization_(signal_processing)

- Poisson Noise– Low numbers of photons (x-ray or light) will fluctuate statistically in terms of the counts received over a given time frame.
  - Photodiode response is more uniform with higher photon counts.



https://en.wikipedia.org/wiki/Shot_noise

Random Noise

- Nyquist noise -- random fluctuations in charge carriers causing fluctuations in electrical signal.
- Dark Current Noise – random generation of electrons in photo diodes due to reverse bias leakage current.
- Conductive and Inductive interference or a failing electrical circuit with random fluctuations

Fixed Pattern Noise

- Physical Defects
  - Scratched phosphors
  - Defects in scintillating crystals or the panel itself
- Latent images or phosphor burn-in
  - Un-erased phosphors
  - Scintillators that fluoresce past their normal decay time
- Bad Photodiodes
  - Charge carriers that no longer respond at the same rate as others
- Can be calibrated out or detector replaced
  - Offset (dark current)
  - Flat Field (empty image normalization)

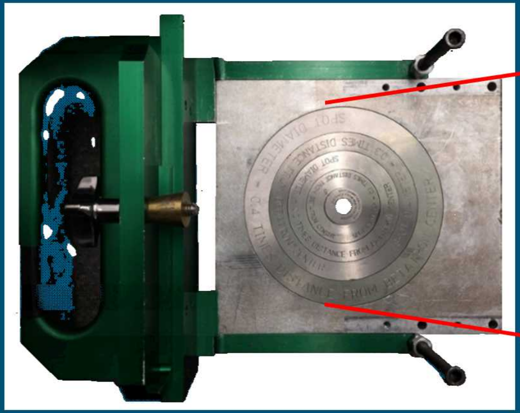
Noise –How do we get rid of it?

- Energy selection
  - Low Energy or High Energy
- Distance –push in
- Collimation –illuminate only what is necessary
- Detector selection for high energy
  - CR less noisy during long integration times
  - CR more efficient with intensification plates
  - DR easier to correct (gain, dark, averaging)

Betatron Beam Collimation

Collimation Rings

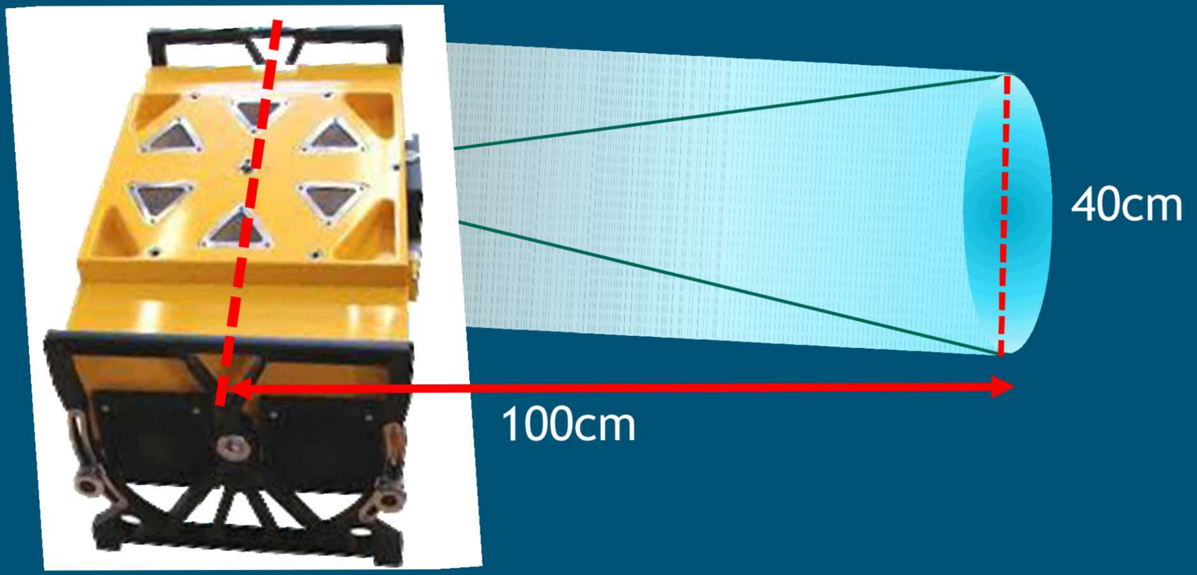
- 5 nested rings
- Each ring has a multiplication factor
  - 0.4x (fixed in holder)
  - 0.3x, 0.2x, 0.1x, 0.05x inserts
- Rings held in place by a front plate
- Rings are 65mm thick tungsten



Betatron Beam Collimation

Calculating Illumination Spot Size

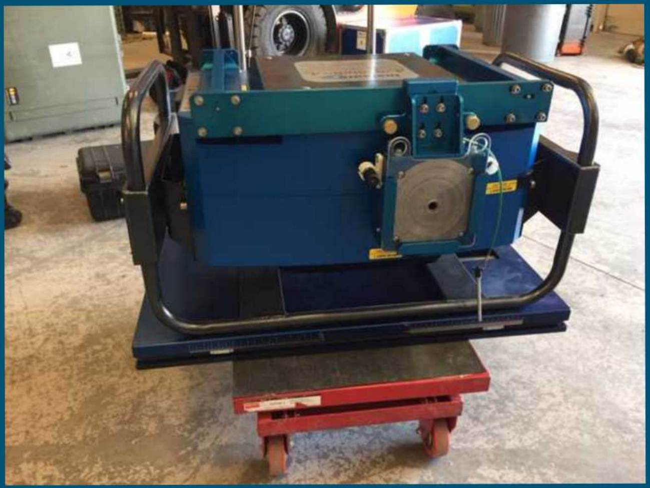
- Field of view diameter= (*factor*)x (source to object distance)
- Source to object distance measured from middle of head
- Example:
  - Field of view diameter = 0.4 x 100cm = 40cm

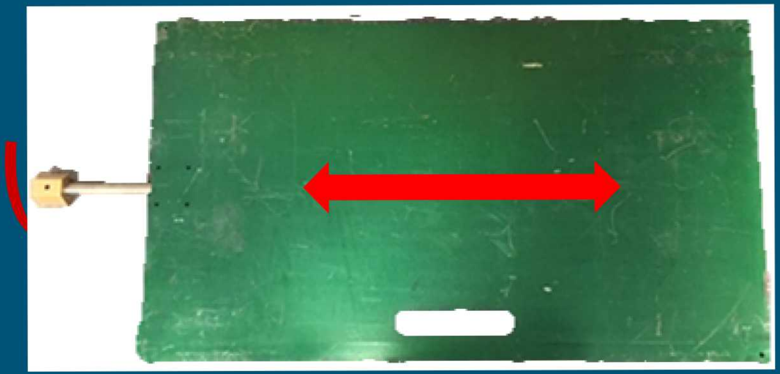


Betatron Beam Collimation

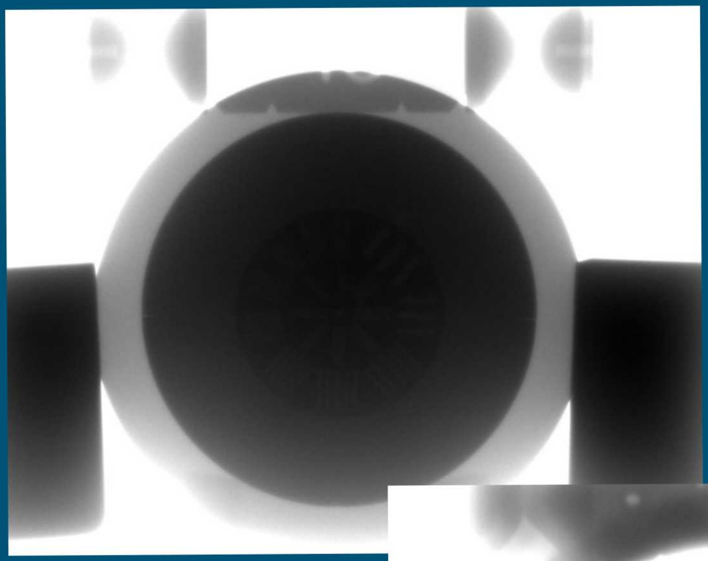
Aiming

- Alignment of beam is difficult for narrow apertures
- Start wide, adjust beam alignment and add rings
- Translation table for small adjustments

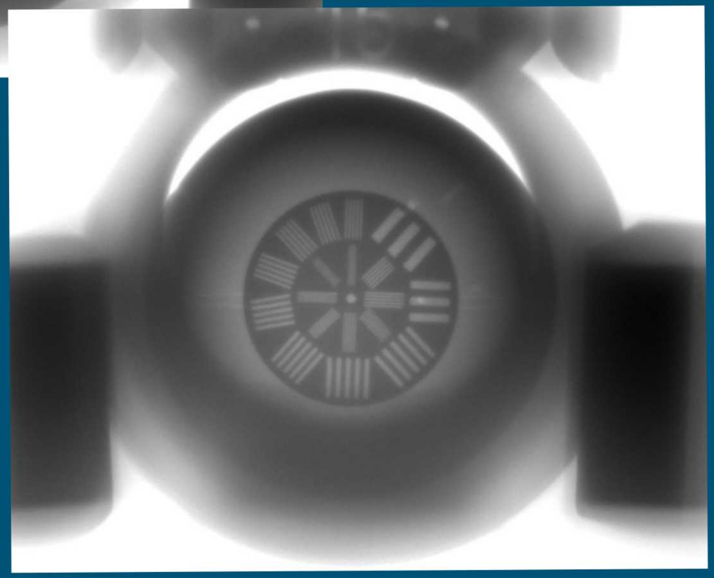




Betatron Collimation: Example



Un-Collimated

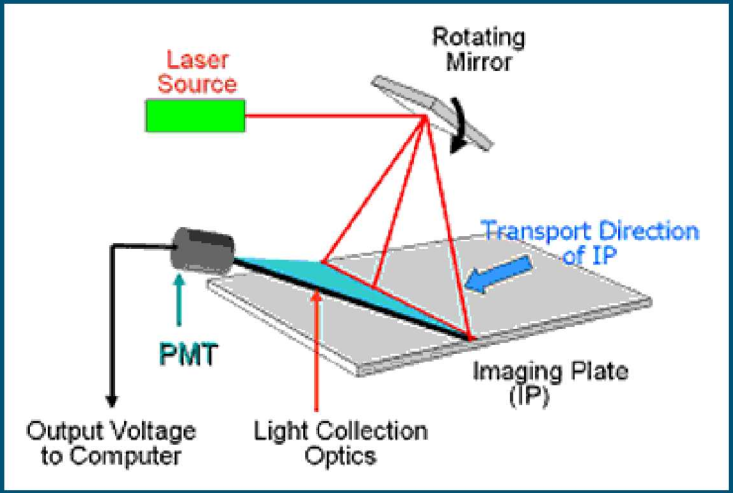


Collimated

Resolution gauge obfuscation device

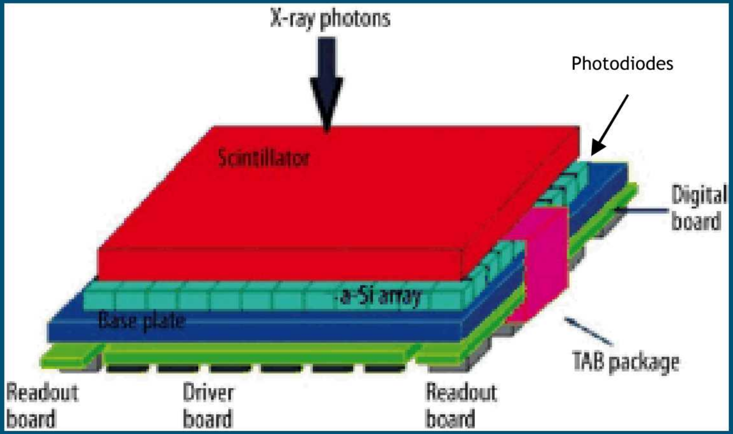
Detectors: Types

- Two Common Types in the Field
  - Imaging Plates (CR)
    - Single or line of light sensors that are rastered in a scanner after the shot
  - Flat Panels (DR)
    - Scintillator; TFT-Photodiode; Electronics
    - Analog to Digital Converter; Arranged in pixel groups



CR Scanner

Image from: http://e-EdCredits.com

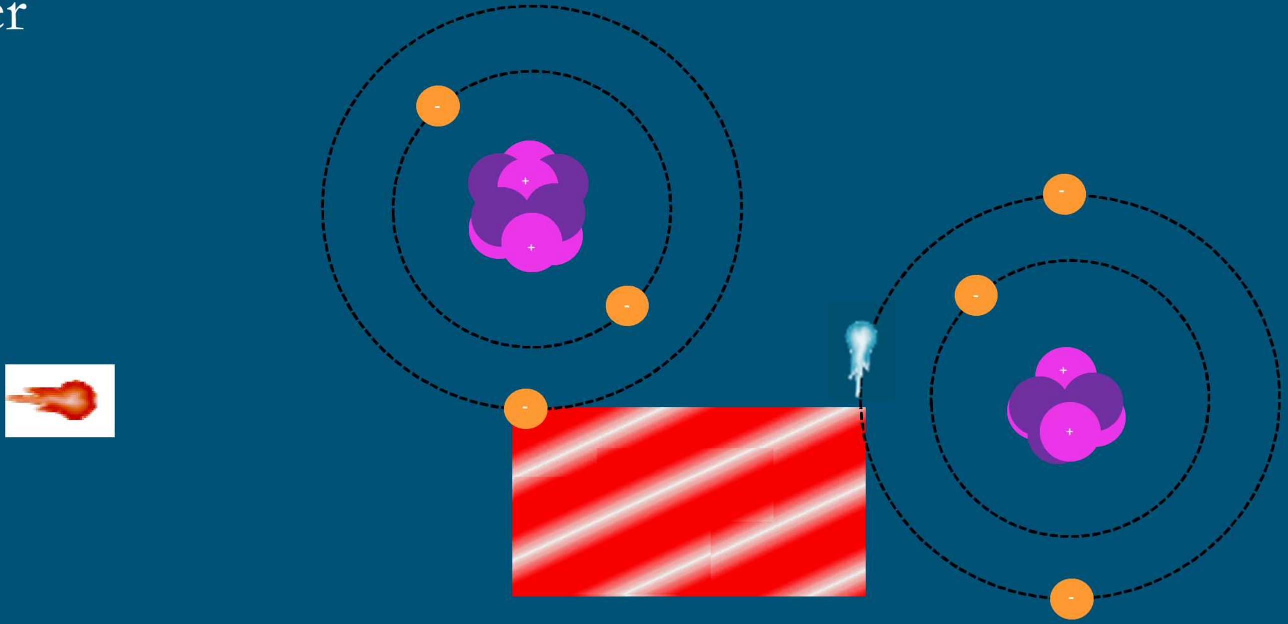


DR Panel

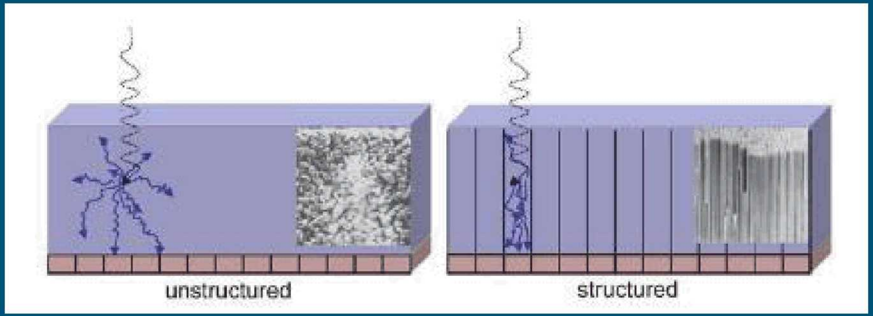
Image from: http://openi.nlm.nih.gov

Detectors: Phosphors and Scintillators

- Imaging panels have a stored charge that fluoresce when struck by a laser



- Scintillator reacts to x-rays by fluorescing visible light immediately
  - Common Types: Gd_2O_2S (Gadox), CsI



http://www.springer.com/978-1-4614-5066-5

Detectors: Selection

- CR
  - Bad for imaging radio-active materials
  - Bad for calibration and averaging
  - Good for long integration times
  - Incur less electronic noise naturally
  - Easier to mosaic multiple panels
- DR
  - Bad at long integration times
  - Expensive
  - Hard to mosaic
  - Good at calibrations and averaging
  - Fast at returning information

Detectors: Corrections

- Bright Field
  - Image with x-rays but no object (bright)
- Dark Current
  - Image with no x-rays (dark)
- Flat Field
  - Image corrected for non-uniform responses in the detector and x-ray field
- Bad Pixel Mapping
  - Selecting bad pixels and averaging with neighbors
- Averaging
  - Multiple images added together and divided by number of images

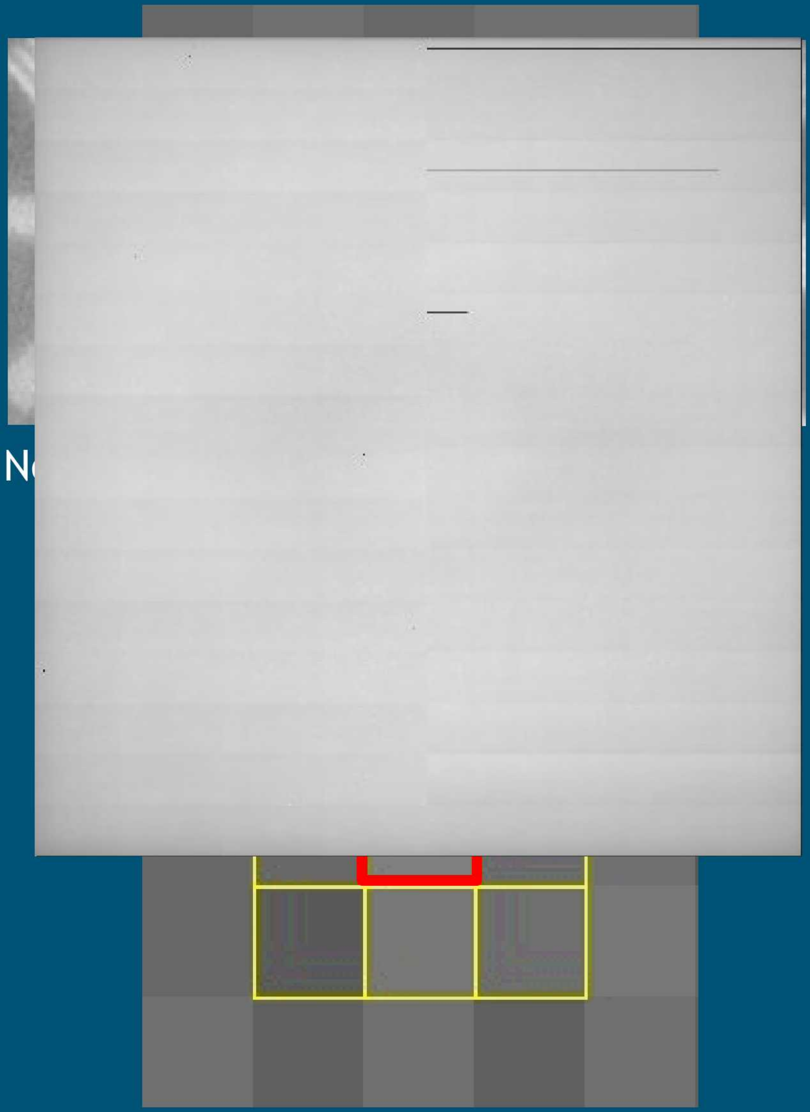
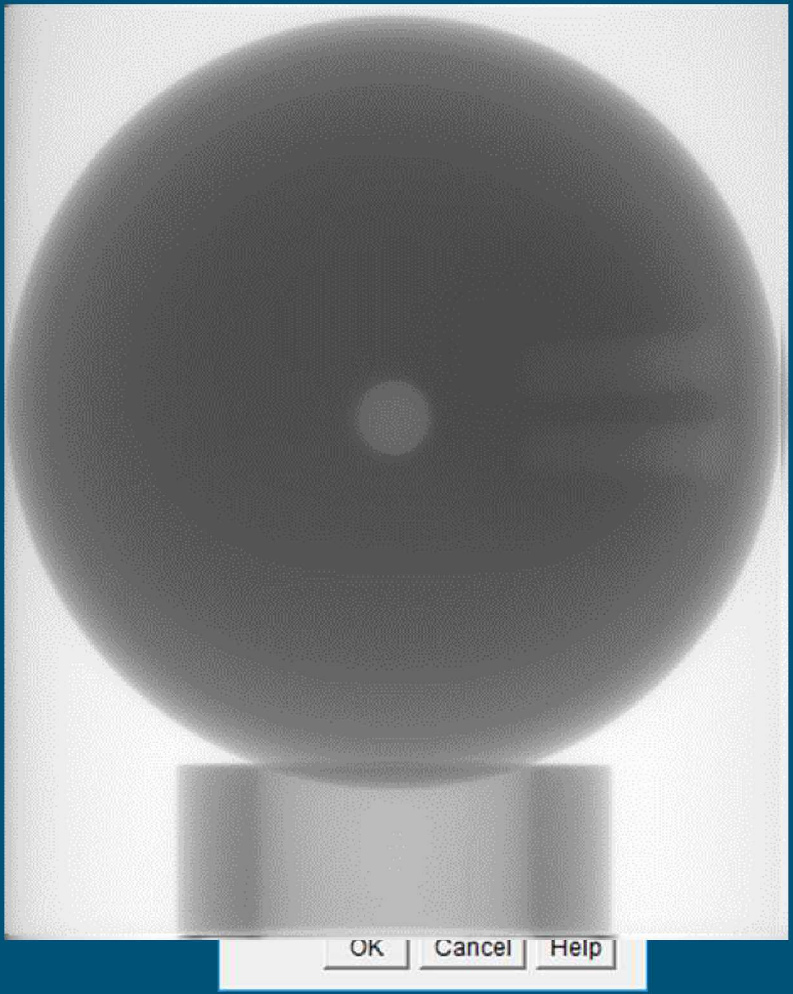


Image Processing –What else can we do?

- Window and Leveling
  - Adjust gray scale values displayed to match range of interest
- Histogram Equalization
  - Re-binning values based on frequency of appearance
- Contrast Limited Adaptive Histogram Equalization
  - Equalization of local regions with a limited amplification factor
- Outlier Removal
  - Averaging out statistical outliers
- Averaging
  - Averaging out varying data

Bowling ball image



Common Misconceptions

"Increasing dose always makes the image better"

- Increased dose will only make a difference up to a point
  - Scatter increases as dose increases and cannot be outpaced
  - The ratio of signal to electronic noise increases with the square root of the dose
  - Under saturation is typically better than over saturation
  - A pixel value of even a few hundred can be contrast stretched (not ideal)

"6MeV will penetrate 1' of steel, 4' of concrete, and 3' of aluminum"

- Not field reliable
- Environmental scatter plays a large role in the image quality at these thicknesses

"Stand-off of the detector will reduce scatter"

- Object scatter can be reduced but environment scatter increases and signal is lost due to inverse square law

"Betatrons require a 30 second ramp to get dose"

- This is not reliable and quite often will lead to oversaturation of images with CR
- Read the command console to determine dose manually
- Dose times less than 20 seconds are not reliable for CR

Key Concepts

- Winning the SNR is critical to high quality radiographs
- High Energy Radiography significantly decreases SNR due to scatter effects
- Select lowest energy setting that achieves desired penetration
- On high energy shots, filter scatter with lead or steel
- The exponent is your best friend for improving signal- use inverse square; four times the bang for half the cost along with a collimation effect
- Good spatial resolution is achieved by more standoff or smaller mag factor
- Illuminate only what is necessary - collimation increases SNR
- Increase DQE when necessary by using filter/intensifier plates
- Reduce random noise by averaging

Questions?

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Appendix A

Acknowledgements

I would like to thank the following individuals for their participation in the gathering of this data: Kyle R. Thompson (SNL), Matt Basner (DOD), Mark Monda (SNL), Justin Garretson (SNL).