Henry Ford Health System

RADIOLOGY RESEARCH

CR/DR Image Noise
Part 1

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Henry Ford Health System

Image Noise

- Image noise associated with quantum mottle limits the detection of large low contrast features.
- When evaluating the performance of CR/DR systems, the noise amplitude and texture should be consistent with the incident exposure and the detector type.

Learning Objectives

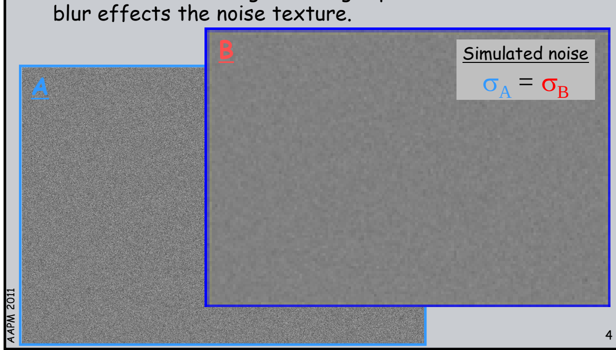
A. Appreciate the value of the Noise Power Spectrum (NPS) in comparison with the pixel Standard Deviation (SD).

B. Understand how to acquire and analyze image data to measure the NPS of a CR/DR system.

C. Understand how to relate the NPS to the input exposure.

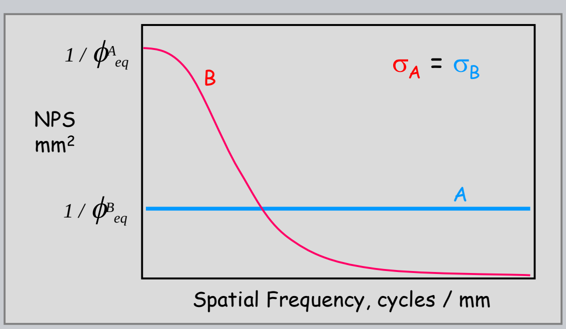
A - Noise texture

- Statistical fluctuations in the number of x-rays detected in each pixel cause image noise.
- Correlation of the signal amongst pixels from detector blur effects the noise texture.



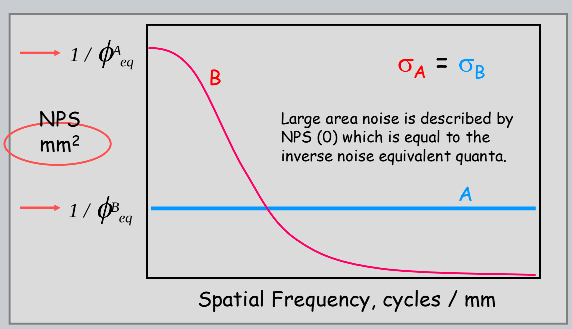
A - Noise Power Spectrum, NPS

The relative strength of various spatial frequencies in a noise image is referred to as the noise power spectrum, NPS.



A - NPS and Noise Equivalent Quanta

The units of the NPS are mm^2/quanta. This is the inverse of the noise equivalent number of quanta per mm^2 (NEQ, ϕ_{eq}).



A - Signal to Noise Ratio

Consider a target region and various background regions in an image with area A_t

SNR² at low frequency is equal to $(A_t \phi_{eq})$

- Signal Proportional to the number of photons
- Standard Deviation Equals Square root of the number of photons.

$$\frac{\text{Signal}}{\text{Noise}} = \frac{A\phi_{eq}}{\sqrt{A\phi_{eq}}} = \sqrt{A\phi_{eq}}$$

The size and contrast of just visible targets is determined by $(\phi_{eq})^{1/2}$

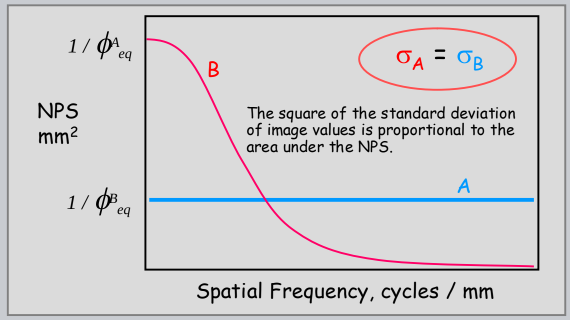
The product of the relative contrast, C_r, and the dimension of the target, $(A_t)^{1/2}$, is the contrast-detail product

$$\frac{\text{Contrast}}{\text{Noise}} = C_r \frac{S}{N} = C_r \left(A_t \phi_{eq}\right)^{1/2} = k_t$$

Rose'74 pg 26 $\quad C_r (A_t)^{1/2} = k_t (\phi_{eq})^{1/2} \cong 4(\phi_{eq})^{1/2}$

A - NPS and Spatial Variations

- Smoothing operations reduce SD but not NPS(0).
- SD is NOT a good measure of low contrast detection when image texture and the NPS shape are different



A - Parseval's theorem

Parseval's theorem

Loosely stated, Parseval's theorem says that the sum (or integral) of the square of the spatial function is equal to the sum (or integral) of the square of it's Fourier transform.

$$\int_{-\infty}^{\infty} |f(x)|^2 dx = \int_{-\infty}^{\infty} |F(s)|^2 ds$$

$$\sum_{n=0}^{N-1} |f_n|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |F_k|^2$$

Pixel SD and the NPS

We will see next that the NPS is computed from the relative noise of linear signals. The area of the NPS is equal to the relative SD for linear pixel values. For log pixel values, it is equal to the product of the SD and a scaling factor.

Parseval presented this theorem without proof in 1799, http://en.wikipedia.org/wiki/Parseval's_theorem

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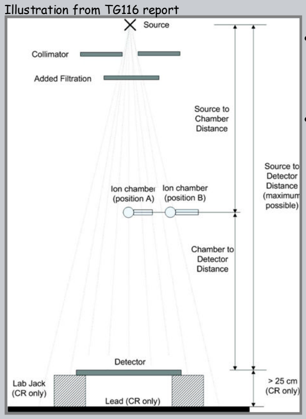
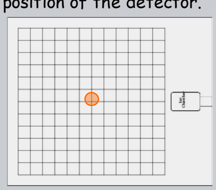
B – NPS measurement - exposure conditions

Illustration from TG116 report



- For NPS measurements, the exposure to the center of the detector for a uniform field is measured.
- The chamber is placed midway between the source and the detector and the measurement corrected for distance and offset to produce an estimate of the exposure in air at the position of the detector.



B- NPS measurement - Radiographic Technique

IEC and AAPM have recently released documents on Exposure Indices that include a standard beam condition similar to RQA5.

	HVL	kV	Added Cu	Added Al
IEC 62494	6.8 ± .3	70 ± 4	0.5 mm	2 mm
AAPM TG116	6.8 ± .25	70 ± 4	0.5 mm	0-4 mm

IEC Standard Radiographic Conditions (1st ed.)

Most previously published work has used IEC standard beam conditions.

#	added Al Filtration	HVL mm Al	nominal kVp	typical kVp
RQA5	21 mm	7.1	70	72-77
RQA9	40 mm	11.5	120	120-124

It is now common to measure NPS over a range of exposure values. Suggested Nominal Exposures

.1	.3	.6	1.0	3.0	6.0	10.0	mR
-	.3	-	1.0	-	6.0	-	mR

B – Linear Systems Analysis

Prerequisites for Fourier Analysis

- Linearity
  - For many inputs to a system, the output corresponds to a the sum of the outputs that would occur if each input was separately applied.
  - Multiplication of the input by a constant multiplies the output by the same constant.
- Spatial invariance
  - The image resulting from a point input is the same for all input positions.
  - For some systems, the response may be large scale invariant with respect to the response sample by output detector elements, but small scale variant with respect to input positions within one detector element.

B – Linear 'For Processing' image data

- Ideally, we would like to obtain image data that is linear with exposure but include
  - Defective pixel corrections
  - Gain and offset corrections (flat field)
- Systems often export 'For Processing' images data that include these corrections but are proportional to the log of the detector input exposure, E. If the pixel value relationship is known, a linear approximation for small signal deviations can be used.

$$\bar{I}_p = A + B\ln(\bar{E})$$

$$\bar{I}_p + \Delta I = A + B\ln(\bar{E} + \Delta E)$$

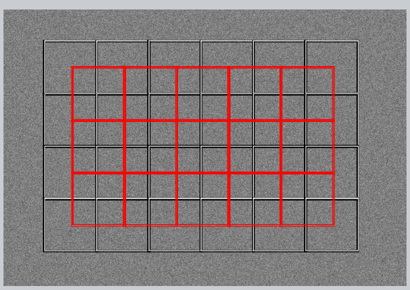
$$\Delta I = B\ln\left(1 + \frac{\Delta E}{\bar{E}}\right) \cong B\left(\frac{\Delta E}{\bar{E}}\right)$$

AAPM TG116 recommends that exported 'For Processing' images have pixel values with $I_p = 1000\log_{10}(K_{std})$ where K_{std} is the standard beam input air kerma in nanoGray units.

B – NPS: 2D Block Average

To reduce noise in the estimate of the NPS at the expense of spectral resolution, the 2D NPS is computed for many small blocks using a 2D FFT and the results are averaged.

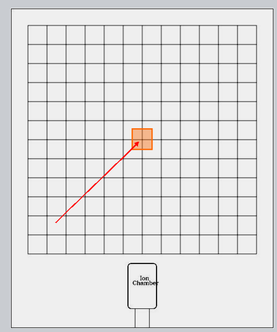
Additional improvement in the noise of the NPS estimate can be achieved by computing the 2D FFT from overlapping blocks.



•Flynn, Med. Phys., V 26, N 8, 1999

B – NPS adjustment for non-uniformity

- The linear signal mean in each block is used to correct the NPS of each block to the exposure at the center of the detector.
- This accounts for variations in the input signal due to the x-ray tube heel effect.



B – FFT estimate of the NPS

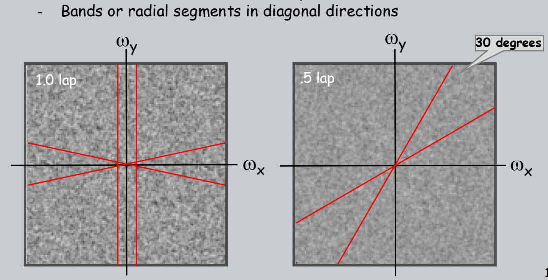
The estimate of the NPS for each block is done using a Fast Fourier Transform, FFT, as described in Flynn1999.

1. A bi-quadratic surface is fit to the block values to obtain the mean value and low frequency trend (see Zhou, MedPhys 2011).
2. Relative noise deviations are computed based on whether the data is linear or logarithmic.
3. Values are adjusted for image pixel area.
4. Block values are modified by a spectral window function (Hamming).
5. The NPS is computed as the magnitude squared of the Fourier transform.

•Flynn, Med. Phys., V 26, N 8, 1999

B – NPS: 1D Results from 2D NPS

- The 2D NPS can be displayed as an image with values proportional to the log of the NPS.
- An 1D estimate can be derived from the 2D NPS by averaging all values within;
  - Horizontal/Vertical bands about the ω_x / ω_y axis
  - Radial segments about the ω_x / ω_y axis
  - Bands or radial segments in diagonal directions



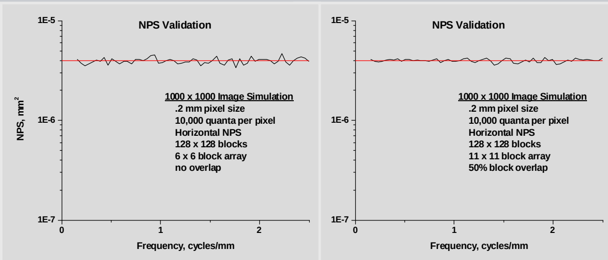
B – NPS: Benchmark verification

NPS for a simulated image

uncorrelated gaussian noise

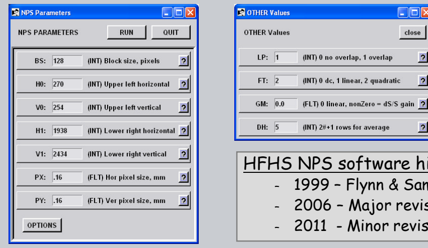
10,000 #/pixel x 25 pixels/mm^2 = 250,000 #/mm2

1/250,000 = 4E-6 mm^2



B – HFHS NPS software

Parameters specified by Macro groups that can be defined for specific CR/DR detectors.



HFHS NPS software history

- 1999 – Flynn & Samei, Med.Phys. 1999
- 2006 – Major revision for Windows
- 2011 - Minor revisions for QC use

Other Software

(http://dailabs.duhs.duke.edu/imagequality.html)

- Saunders & Samei
- Maindment

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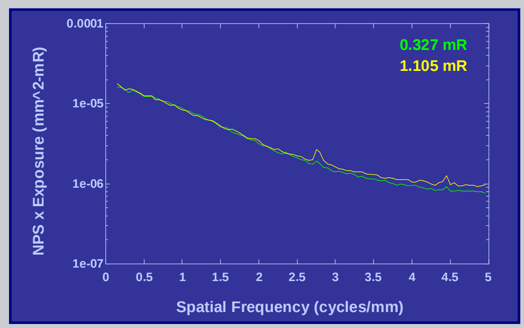
V.C.3 – NPS: NPS exposure product

The comparison of results made at different exposures can be done by plotting the product of NPS and exposure

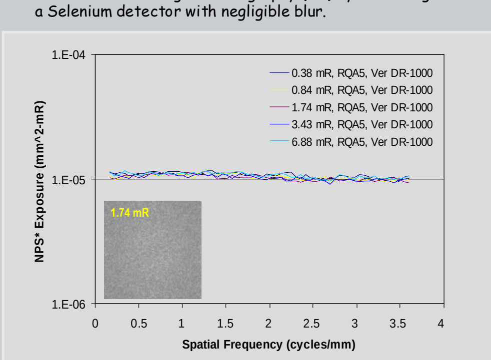


NPS for a Computed Radiography (CR) system

Samei & Flynn, SPIE, 1997

V.C.3 – NPS: Se DR detector

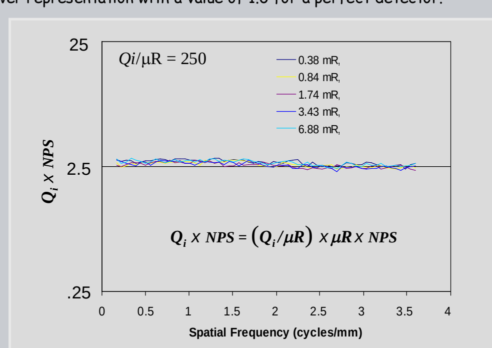
NPS for a direct digital radiography (DR) system using a Selenium detector with negligible blur.



Samei & Flynn, Med.Phys., 2003

V.C.3 – NPS: Se DR detector

Multiplying the NPS (mm2/quanta units) by the quanta/mm2 incident on the detector (i.e. ideal NEQ) results in a dimensionless noise power representation with a value of 1.0 for a perfect detector.



Samei & Flynn, Med.Phys., 2003

DQE: Detective Quantum Efficiency

- An ideal energy integrating detector defined is one that detects all of the energy of all of the incident radiation. If it also has no blur, the ideal $SNR(f)^2$ is constant for all spatial frequencies and equal to the noise equivalent quanta, Q_i.
- A popular figure of merit (FOM) is to compare the measured SNR(f) to the ideal SNR(f). This frequency dependant FOM is known as the Detective Quantum Efficiency;

$$DQE(f) = SNR^2_{meas} / SNR^2_{ideal}$$

$$DQE(f) = \frac{\left(MTF^2(f)/NPS(f)\right)}{Q_i}$$

$$DQE(f) = \frac{MTF^2(f)}{\{(Q_i / X_{mr}) \times X_{meas}\} \times NPS(f)} = \frac{MTF^2(f)}{nNPS(f)}$$

Note: DQE(f) is seen above to be just the ratio of the MTF(f) squared to the normalized NPS obtained by using the ideal quanta per mR.
It is usually more informative to report the MTF and normalized NPS separately rather than combining them into one FOM.

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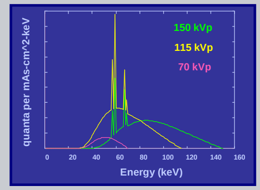
25

NPS for an ideal detector

For experimental use, values of Q_i .and exposure, X , are computed using a model of the spectral shape and expressed as Q_i / X in relation to kVp and filtration.

$$Q_i = \frac{\left(\int_0^{kVp} E\Phi(E)dE\right)^2}{\int_0^{kVp} E^2\Phi(E)dE}$$



- Values for X_f are obtained by computing the energy absorbed in air for the spectrum $\Phi(E)$ using mass energy-absorption coefficient data obtained from the National Institute of Standards and Technology.
- The energy absorbed in air is then converted to charge using a W value of 33.97 J/C (i.e. eV/ion pair) (Boutillon 1987).

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26

III.A.4 – Radiation Exposure – air kerma, ergs/gm

- Exposure can be estimated by computing the energy absorbed in air using the differential radiation energy fluence, $\Psi(E)$ in ergs/cm²/keV and the linear attenuation coefficient describing the absorption of energy in air, $\mu(E)/\rho$ in cm²/gm;

$$K_{air} = 10^{-4} \int \Psi(E) \frac{\mu_{en}(E)}{\rho} dE \quad , \quad (J/kg)$$

where the factor 10^{-4} is used to convert from ergs/gm to J/kg. This quantity is the air kerma (Kinetic Energy Released per unit Mass). The special name for the unit of kerma is Gray (Gy).

- The energy absorbed per gram, K_{air} (J/kg), is then converted to exposure using a conversion factor of 33.97 Joules/Coulomb along (i.e. eV/ion, Boutillon, PMB, 1987);

$$X_{SI} = K_{air}/33.97 \text{ , C/kg}$$

- The traditional unit of exposure has been the Roentgen, R, for which the conversion is given by 1 R = 2.58 x 10^{-4} C/kg. Thus;

$$X_R = K_{air}/0.0087643 \text{, Roentgens}$$

1 J/kg = 10^4 ergs/gm

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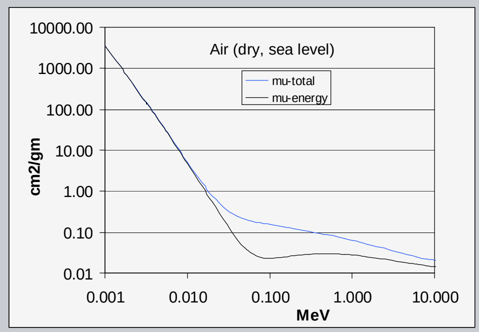
27

III.A.4 – Radiation Exposure – air μ_{en}

The photon mass attenuation coefficient and the mass energy absorption coefficient for air from NIST tables based on calculations by Seltzer (Radiation Research 136, 147; 1993).



http://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html

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28

Ideal Noise Equivalent Quanta

[ ] denotes converted values

Reference	Beam Conditions	Added Filtration	Method	Q, #/mm2 per μR	Q, #/mm2 per nG
Dobbins ... MedPhys 1992	70 kVp -	0.5 mm Cu	Provided by Manf.	270	[30.8]
Kengylelics ... MedPhys 1998	75 kVp -	1.5 mm Cu	Photon fluence	[310]	35.4
Stierstorfer ... MedPhys 1999	70 kVp 7.1 mm HVL	21 mm Al	NEQ (energy intgr. detector)	[258]	29.4
Flynn & Samei MedPhys 1999	70 kVp 6.3 mm HVL	19 mm Al	NEQ (energy intgr. detector)	262	[29.9]
Samei & Flynn MedPhys 2002	70 kVp -	19 mm Al	NEQ (energy intgr. detector, HVL adj.)	246-249	[28.1-28.4]
Granfors ... MedPhys 2003	75 kVp 7.0 mm HVL	20 mm Al	Photon fluence	[261]	29.8
IEC 62220-1 1st ed. 2003	77 kVp 7.1 mm HVL	21 mm Al (RQA 5)	Photon fluence	[264]	30.2
Samei & Flynn MedPhys 2003	74-78 kVp 7.1 mm HVL	21 mm Al	NEQ (energy intgr. detector, HVL adj.)	256-259	[29.2-29.6]
Samei MedPhys 2003	70 kVp 6.4,6.5 mmHVL	19 mm Al	NEQ (energy intgr. detector, HVL adj.)	255-258	[29.1-29.5]
Siewerdsen ... MedPhys 2005	60, 80 kVp -	4 mm Al 0 .6 mm Cu	Photon fluence	259, 283	[29.6,32.3]

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Q per μR for TG116/IEC beam conditions

Noise equivalent quanta compute from a spectral model.

- Qi/μR E integr: Ideal energy integrating detector
- Qi/μR Fluence: Ideal counting detector
- Qd/μR dDR: Direct DR detector (.5mm Se)

XSPECT 3.5b

kV	Added Cu Filtration	Added Al Filtration	HVL	Qi/μR E integr.	Qi/μR Fluence	Qd/μR dDR
70	0.5 mm	0.0 mm	6.6	251	(258)	145
70	0.5 mm	2.0 mm	6.8	255	(262)	144
70	0.5 mm	2.0 mm	7.0	258	(265)	144

- Within the range of added filtration and HVL acceptable for AAPM EI beam conditions, the Qi per mR varies by about +/- 1.5%
- The Qi per mR for an ideal counting detector is about 2.7% higher that that for an ideal energy integrating detector.
- The noise equivalent quanta, and therefor NPS(0) for a DR detector varies little with beam conditions.

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30

Questions?