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Author(s): Watson, Scott

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Go Pink! - The Effect of Secondary Quanta on Detective Quantum Efficiency

by

Scott A. Watson (NEN-2)

LA-UR-ABDCE

Abstract

Photons are never directly observable. Consequently, we often use photoelectric detectors (eg CCDs) to record associated photoelectrons statistically. Nonetheless, it is an implicit goal of radiographic detector designers to achieve the maximum possible detector efficiency¹. In part the desire for ever higher efficiency has been due to the fact that detectors are far less expensive than associated accelerator facilities (e.g. DARHT and PHERMEX²). In addition, higher efficiency detectors often have better spatial resolution. Consequently, the optimization of the detector, not the accelerator, is the system component with the highest leverage per dollar.

In recent years, imaging scientists have adopted the so-called Detective Quantum Efficiency, or DQE as a summary measure of detector performance. Unfortunately, owing to the complex nature of the trade-space associated with detector components, and the natural desire for simplicity and low(er) cost, there has been a recent trend in Los Alamos to focus only on the zero-frequency efficiency, or DQE(0), when designing such systems. This narrow focus leads to system designs that neglect or even ignore the importance of high-spatial-frequency image components.

In this paper we demonstrate the significant negative impact of these design choices on the Noise Power Spectrum¹ (NPS) and recommend a more holistic approach to detector design. Here we present a statistical argument which indicates that a very large number (>20) of secondary quanta (typically visible light and/or recorded photo-electrons) are needed to take maximum advantage of the primary quanta (typically x-rays or protons) which are available to form an image. Since secondary particles come in bursts, they are not independent. In short, we want to maximize the pink nature of detector noise at DARHT.

Introduction

We start from well-established definitions of the Detective Quantum Efficiency³ (DQE), first proposed by Dainty & Shaw⁴, namely:

$$DQE(f) = \frac{SNR_{out}^2(f)}{SNR_{in}^2(f)} = \frac{MTF^2(f)}{NPS(f)N_{eq}} \quad (1)$$

where SNR_{out} is the signal-to-noise ratio as a function of spatial frequency, f , that is recorded by a linear imaging system whenever, SNR_{in} , is incident upon that system. This DQE can also be written in the alternate form which incorporates more commonly measured linear-system functions, the Modulation Transfer Function^{5,6} (MTF), and the Noise Power Spectrum (NPS) normalized by a constant of proportion, N_{eq} , or the number of equivalent quanta⁷. To maximize

¹ Sometimes called the Wiener Spectrum in the literature after the 20th century mathematician Norbert Wiener.

the $DQE(f)$, we want to minimize the $NPS(f)$. What follows is a discussion about how the $NPS(f)$ is degraded when the statistical variations from secondary quanta are neglected.

The degradation of the zero-frequency detective quantum efficiency, $DQE(0)$, can be completely described by the number of secondary quanta by the following⁸:

$$DQE(0) = A \frac{n}{n+1} \quad (2)$$

Where A is the absorption efficiency of primary particles, and n is the number of secondary quanta. If $n \gg 1$, the $DQE(0)$ becomes equal to the absorption efficiency. For $n < 1$, the efficiency of the system is completely dominated by the statistics of the secondary particles in what is referred to as a, “quantum sink”⁹. While this criterion is a good guide for detector design, it does not fully account for the degradation of higher spatial frequencies. Furthermore, no amount of post-detection amplification can compensate for the loss of secondary particles. The shape of the NPS (or DQE) is determined by the mean number of secondary quanta, while the absolute magnitude of the DQE is determined by equation 2.

We give a simple, qualitative example, proposed by Hanson¹⁰ et al. to illustrate these effects. Imagine an imager which records exactly one visible light photon per absorbed x-ray photon. Because each visible photon is an independent sample of the imager’s Point Spread Function (PSF), the NPS is white², regardless of shape or extent of the imager PSF. Now imagine an otherwise identical imager where a very large number of visible light photons are recorded for every absorbed x-ray. In this latter case, the imager PSF is perfectly sampled and indeed the NPS is equal to the imager MTF squared. These two limiting cases bound the problem, namely, how does the NPS change as a function of the number of visible light photons per x-ray?

Intuitively, this change in the NPS is a rather straightforward concept. However, despite efforts by Barrett¹¹ et al., the closed-form, analytic solution to this problem has never been fully resolved¹² for the general case. The present state-of-the-art is summarized in Monnin, 2016¹³.

We therefore turn to numerical methods to illustrate the issues. While the computation of particle-by-particle noise images is computationally intensive, and therefore too slow for iterative optimization models like those used in the BIE, it is nonetheless straightforward to implement. Two IDL codes used here, “pink.pro”, and “nps_calc.pro” are included in appendix A.

² The terms, “pink” and “white” noise are commonly used to distinguish spectrums with larger number of long (spatial) wavelength noise (aka “pink”), from those spectrums with a uniform distribution across wavelength (aka “white”. Sometimes “pink” noise is also referred to as “correlated” noise because of the correlation of the noise signal over short distances. Correlated noise is itself commonly referred to as, “quantum mottle”.

Analysis

We simulated images with the following parameters 0.2mm pixels, 50 binomially distributed, primary quanta per pixel, and secondary quanta $n=\{1,2,5,10 \text{ and } 20\}$ per primary quanta with a Gaussian PSF with a width of 5 pixels. These values were somewhat arbitrarily chosen, but are nonetheless illustrative of the statistical nature of the NPS with pink, quantum mottle. Figures 1-5 illustrate these noise images showing purely white noise (Figure 1), and increasingly pink noise (Figure 5). It is important to realize that the primary photon statistics in each of these images is identical. The only significant difference results from the secondary quanta (photons).

Somewhat counterintuitively the more mottled, pink-noise image (Figure 5), has a substantially better DQE than the white noise image (Figure 1). This effect is illustrated in Figure 6 with lineouts of the white and pink images respectively.

Because their point-wise, noise-variance is different, one might believe that these two images have different zero-freq DQE. In fact, the $DQE(0)$ is identical in both images; the differences are at high spatial frequencies. We emphasize this difference because it is a common misconception to use the noise-variance as a simple measure of signal-to-noise ratio. It isn't! The $SNR(f)$ is a function of spatial frequency as equation 1 implies.

Another way to display this difference is by plotting the corresponding NPS of each image. We use the method of Hanson¹⁴ to calculate the NPS in each case. These spectrums are plotted in Figure 7.

The implications of the NPS character illustrated in Figure 7 are profound for detector design. We illustrate the magnitude of this effect using planned, present and historic DARHT detectors which are all light starved. Put another way, the number of secondary quanta recorded at DARHT is severely limited and represents an important parameter in the overall trade space.

It has been shown¹⁵ that the mean number of photo-electrons (a typical secondary quanta), n , on a lens-coupled system like the ones at DARHT can be expressed by the following relation:

$$n = \frac{T_{lens} QE_{CCD} G M^2}{8 F_{\#}^2 \eta_i^2 (1 + M)^2} \quad (3)$$

Where $F_{\#}$, M , and T_{lens} are the lens F#, optical magnification and transmission respectively, G is the scintillator gain in photons per primary particle absorbed, n_i is the scintillator index of refraction, and QE_{CCD} is the quantum efficiency of the CCD.

If we take representative numbers at DARHT (using the 5-camera array), we have $T_{lens}=0.9$, $QE_{CCD}=0.6$, $G=10,000$, $M=0.2$ ¹⁶, $n_i=1.7$, and $F_{\#}=1.2$ we find that $n \sim 5$, roughly corresponding

to the green NPS in Figure 7. We can refer to measurements on this same system^{17,18} and see that the correspondence is good within the error bars of those measurements.

Two things have changed at DARHT since those DQE measurements were made. First, the original BGO scintillator was exchanged for the newer, LSO scintillators, and the 5-camera-array was replaced with a single, larger camera. The former change in secondary quanta, moved the NPS from “green” to “red” in Figure 7, and the latter change reduced the secondary quanta moving it back, from “red” to “blue-green”.

An alternative configuration has been suggested where we still utilize the larger CCDs, but maintain the 5-camera array arrangement. Under this configuration, we might expect an NPS more like that depicted in cyan.

NPS measurements of storage phosphor screens by Kauppila et al.¹⁹ using megavolt (primary) photons suggests that the visible light transport, and therefore the number of visible photons recorded, is large – at least using the Fuji, BAS-1500 scanner. This outcome should come as no surprise because most storage phosphor scanners use large photomultiplier tubes and light pipes to record the photostimulated light on a pixel-by-pixel basis. Furthermore, because they are designed for medical imaging, where a typical primary photon only carries ~10-50keV of energy, they must be extremely efficient or fail to achieve the desired DQE(0) necessary for clinical use.

It is important to recognize that the NPS differences described here are significant from an image quality perspective. We note that Figure 7 is a log-log plot. So, by implication, if we are rectify the high-frequency loss in DQE(f) associated with the change from a 5-camera array to a single camera, we require a factor of two or more enhancement in machine dose. The zero frequency DQE, which has been the driving factor in the detector design until now, is nearly identical in both cases.

Figure 1 – 1024x1024 pixel image with 1 secondary quanta for each of 50 primary quanta

Figure 2 – 1024x1024 pixel image with 2 secondary quanta for each of 50 primary quanta

Figure 3 – 1024x1024 pixel image with 5 secondary quanta for each of 50 primary quanta

Figure 4 – 1024x1024 pixel image with 10 secondary quanta for each of 50 primary quanta

Figure 5 – 1024x1024 pixel image with 20 secondary quanta for each of 50 primary quanta

Figure 6 – Row plot of white noise (black curve), and pink noise (pink curve) with exactly the same number of primary quanta (mean =50), but different number of secondary quanta (1 vs 20)

Figure 7 – NPS for various mean numbers of visible, secondary particles. Note that the number of primary particles is fixed in each case, Poisson distributed with a mean of 50.

Conclusions

The cost-benefit-ratio of using more elaborate detector hardware (e.g. 5-camera arrays, or MOXIE^{20,21}) is clear. Because equivalent changes in machine dose on large flash-radiographic facilities like DARHT require hardware upgrades that can run into tens or even hundreds of millions of dollars, we recommend more cost-effective changes in detector geometry, which typically cost an order of magnitude less to achieve. It is also worth noting that the 5-camera arrays provide redundant data not captured with the single-camera counterparts. This redundant data requires additional processing, but that processing is modest compared to the overall analysis scheme. Finally, both the chip yield and charge transfer efficiency are higher with smaller chips like those used in the 5-camera arrangement.

Appendix A

IDL Codes Used To Simulate And Estimate The Detector NPS

```

function pink, sz

;This program creates sz x sz, "pink" correlated noise images to test NPS issues
;Eliminated "edge" effects by using interior +/- 3 sigma of image overall... August,
2017
;-Watson

print,'Enter mean number of gamma-ray photons per pixel'
read,g
print,'Enter mean number of visible-photons per pixel'
read,n
print,'Enter spread in pixels'
read,s
s=FIX(s)
im = FLTARR(sz+6*s,sz+6*s)

seed=57

r=RANDOMN(seed,sz+6*s,sz+6*s,POISSON=g)

for x=0,sz+6*s-1 do begin
    for y=0,sz+6*s-1 do begin
        for q = 0, r(x,y) do begin
            for z=0,n-1 do begin
                dx=s*randomn(seed)      ;Assume Gaussian MTF blur for simplicity...
                dy=s*randomn(seed)
                if ((x+dx) LT sz+6*s) AND ((y+dy) LT sz+6*s) AND ((x+dx) GE 0) AND
((y+dy) GE 0) then begin
                    im(x+dx,y+dy)=im(x+dx,y+dy) + 1.
                endif
            endfor
        endfor
    endfor
endfor

return,im(3*s:sz+3*s-1,3*s:sz+3*s-1)
;Use just "interior" +/- 3 sigma to eliminate edge effects...
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
pro nps_calc, fn, dpixin, sp, freq, sperr

; calculates radial nps using Gaussian pyramid
; using kernels convolved with decimated versions of image
; fn = input noise image with pixel spacing dpix (mm)
; sp = output spectrum at radial frequency values freq
; with estimated rms dev of sperr

time0 = systime(1) ; for timing

```

```

dpix = dpixin

nfrq = 7 ; number of freqs
sp = make_array(nfrq)
sperr = make_array(nfrq)
freq = make_array(nfrq)

f = fn ; store input image in working array
res=size(f)
if res[0] ne 2 then print,"SPEC_CALC: not an image"
ni = res[1]
nj = res[2]
;print, "size of image: ni,nj",ni,nj
; assume square image, i.e., nj tacitly assumed to be same as ni
print, "ni, pixel spacing",ni,dpix

i = 0
gen_b2,kern,ki,kj ; generate kernel for highest freq.

kie=(ki+1)/2 ; useless edge width + 1 after convolution
kje=(kj+1)/2
g0f = convol(f,kern,/edge_truncate)
;print,size(kf)
;fconv = ff[kie-1:ni-kie,kje-1:nj-kje]
f = f - g0f ; original image - convolution of original with b2
varf = variance(f[kie-1:ni-kie,kje-1:nj-kje])

sp[i] = varf*dpix*dpix ; full-sized image, 12n
freq[i] = 0.92/(2*dpix)
; approximate rms uncertainty
gen_12,kdif ; generate kernel for normalization and uncertainty
sp[i] = sp[i]/total(kdif*kdif)
fact=sqrt(total(conv2d(kdif,kdif)^2))/total(kdif^2)
sperr[i] = (2*sp[i]*fact)/sqrt(2.*(ni-2*kie+2)*(nj-2*kje+2))

print, "ni, freq, nps, nps_err", ni, freq[i], sp[i], sperr[i]
if i ge nfrq-1 then goto, ending

i = 1
gen_b2,kern
; two convolutions with b2 same as one with b4
g1f = convol(g0f,kern,/edge_truncate)
l1f = g0f - g1f
print,"mean g1f",mean(g1f)
print,"mean l1f",mean(l1f)
kie = 2*kie - 1
kje = 2*kje - 1
varf = variance(l1f[kie-1:ni-kie,kje-1:nj-kje])
sp[i] = varf*dpix*dpix ; full-sized image, 12n
freq[i] = 0.56/(2*dpix)
; approximate rms uncertainty
gen_14,kdif ; generate kernel for uncertainty
print,total(kdif*kdif)
sp[i] = sp[i]/total(kdif*kdif)
fact=sqrt(total(conv2d(kdif,kdif)^2))/total(kdif^2)

```

```

sperr[i] = (2*sp[i]*fact)/sqrt(2.*(ni-2*kie+2)*(nj-2*kje+2))

print, "ni, freq, nps, nps_err", ni, freq[i], sp[i], sperr[i]
if i ge nfrq-1 then goto, ending

gen_b2,kern,ki,kj    ; generate b2
kie=(ki+1)/2    ; useless edge width + 1 after convolution
kje=(kj+1)/2
kie = 2*kie - 1    ; for b4 & l4 (two colvolutions by b2)
kje = 2*kje - 1
spnorm=0.95/(0.152262)    ; nps normalization for remainder
spfact=1.37    ; factor used to account for higher level filters
gfprev = g1f
for i = 2,nfrq-1 do begin
    ni=ni/2                ; decimate image by factor of two
    nj=nj/2
    dpix = 2*dpix
    if ni ge ki then begin    ; check that image is larger than kernel
        gftmp = rebin(gfprev,ni,nj,sample=1)    ; decimate previous image
        print,"rebin gfprev, continue",mean(gftmp)
        gftmp2 = convol(gftmp,kern,/edge_truncate)    ; effectively convolved with b2
        gfprev = convol(gftmp2,kern,/edge_truncate)    ; effectively convolved with b4
        gftmp = gftmp - gfprev    ; difference unconv., convov b4
        varf = variance(gftmp[kie-1:ni-kie,kje-1:nj-kje])
        sp[i] = varf*dpix*dpix    ; full-sized image, 12n
        freq[i] = 0.68/(2*dpix)
        ; approximate rms uncertainty
        print,"spnorm",spnorm
        sp[i] = sp[i]*spnorm
        spnorm=spnorm*spfact
        spfact=(spfact)^0.23
        fact=sqrt(total(conv2d(kdif,kdif)^2))/total(kdif^2)
        sperr[i] = (2*sp[i]*fact)/sqrt(2.*(ni-2*kie+2)*(nj-2*kje+2))

        print, "ni, freq, nps, nps_err", ni, freq[i], sp[i], sperr[i]

    endif
endfor
ending:
print, "time (sec) = ",systime(1) - time0
print, " "

; display spectrum
; display black on white
print, "nps",sp
print, "nps_err",sperr
print, "freq",freq

!p.background=16777215L
!p.color=0
plot, freq, sp, psym = 7,/xlog,/ylog, $
    xtitle = 'SPATIAL FREQUENCY (1/mm)', symsize=2,$
    ytitle = 'NOISE POWER SPECTRUM (mm^2)',charsize=2,charthick=2
oploterr, freq, sp, sperr
end

```

```

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
function conv2d, a, b

; calculates two 2D arrays a and b

res = size(a)
nax = res(1)
nay = res(2)
res = size(b)
nbx = res(1)
nby = res(2)
;print, "convolve: input array sizes", $
; nax," X",nay," and ",nbx," X",nby
ncx = nax + nbx - 1
ncy = nay + nby - 1
c = make_array(ncx,ncy) ; result

for ja = 0,nay-1 do for ia = 0,nax-1 do begin
  for jb = 0,nby-1 do for ib = 0,nbx-1 do begin
    jc = ja + jb
    ic = ia + ib
    c(ic,jc) = c(ic,jc) + a(ia,ja)*b(ib,jb)
  endfor
endfor
;print, "output array ",ncx," X",ncy
;print,c
return, c
end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
pro gen_b2, kern, ki, kj

; create kernel: 3X3 binomial, normalized to unit sum
; output is kernel image and its size

b1 = [[1,1],[1,1]]
b1 = b1/total(b1)
b2 = conv2d(b1,b1)

kern = b2
res=size(kern)
ki = res[1]
kj = res[2]

end

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
function mean, x

; returns mean value of x

mom = moment(x)
return, mom[0]

```



```

end
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
function variance, x

; returns variance of x

mom = moment(x)
return, mom[1]

end
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
pro gen_l2, kern

; create kernel 3X3 Laplacian

b1 = [[1,1],[1,1]]
b1 = b1/total(b1)
;print, b1

b2 = conv2d(b1,b1)
;print, b2

l2 = [[0,0,0],[0,1,0],[0,0,0]]
l2 = l2 - b2
;print,"L2"
;print,l2

kern = l2

end
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
pro gen_l4, kern

; create kernel 5X5 Laplacian

b1 = [[1,1],[1,1]]
b1 = b1/total(b1)
;print, b1

b2 = conv2d(b1,b1)
;print, b2

b4 = conv2d(b2,b2)
;print, b4

l4 = b4
l4[1:3,1:3] = l4[1:3,1:3] - b2
l4=-l4
;print,"L4"
;print,l4

kern = l4

end

```

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- ¹ Hawkins, D., et al.. Manhattan District History: Project Y - The Los Alamos Project. Los Alamos National Laboratory. LAMS-2532. 1961.
- ² Venable, D., et al.. PHERMEX: A Pulsed High-Energy Radiographic Machine Emitting X-Rays. Los Alamos Scientific Laboratory. LA-3241. 1967.
- ³ https://en.wikipedia.org/wiki/Detective_quantum_efficiency
- ⁴ Dainty, J., & Shaw, R.. Image Science – Principles, Analysis and Evaluation of Photographic-Type Imaging Processes. Academic Press. 1974.
- ⁵ Holst, G.. Electro-Optical Imaging System Performance. JCD Publishing. 1995.
- ⁶ Holst, G.. CCD Arrays Cameras and Displays. JCD Publishing. 1998.
- ⁷ Barret, H., and Myers, K.. Foundations of Image Science. Wiley Interscience. 2004.
- ⁸ Zweig, H.. Detective Quantum Efficiency of Photodetectors With Some Amplification Mechanisms. Journal of The Optical Society of America. Vol. 55, No. 5. 1965.
- ⁹ Cunningham, I., et al.. A Spatial-Frequency Dependent Quantum Accounting Diagram and Detective Quantum Efficiency Model of Signal and Noise Propagation in Cascaded Imaging Systems. Journal of Medical Physics. 1994.
- ¹⁰ Hanson, K.. Los Alamos National Laboratory. Private Communication. 2000.
- ¹¹ Barrett, H. & Swindell, W.. Radiological Imaging – The Theory of Image Formation, Detection, and Processing (Revised Edition). Wiley Interscience. 1981.
- ¹² <http://imaging.robarts.ca/~icunningham/SiteResources/publications/spie1896-82.pdf>
- ¹³ Monnin, P., et al.. A Comprehensive Model for Quantum Noise Characterization in Digital Mammography. Institute of Physics and Engineering in Medicine. 2016.
- ¹⁴ Hanson, K.. A Simplified Method Of Estimating Noise Power Spectrum. SPIE 3336. 1998.
- ¹⁵ Watson, S., et al.. Multiframe, High-Energy, Radiographic Cameras for Submicrosecond Imaging. Los Alamos National Laboratory. LA-UR-95-3570, 1995.
- ¹⁶ Watson, S., et al.. The DARHT Radiographic Camera Lenses: Design and Performance. Los Alamos National Laboratory DARHT Technical Note No. 100, LA-UR: 99-1112, 1999.
- ¹⁷ Watson, S., et al.. Quantum Efficiency, Noise Power Spectrum, Linearity and Sensitivity of the DARHT γ -ray Camera. Los Alamos National Laboratory, LA-UR-00-653. 2000.

¹⁸ Mendez, J.. Detective Quantum Efficiency of the DARHT 1st Axis Detector. Los Alamos National Laboratory. Unpublished Report. HX-3. 2006.

¹⁹ Kauppila, T., et al.. Detective Quantum Efficiency of a Storage Phosphor Pack Recording MeV X-Rays. Los Alamos National Laboratory. LA-UR-98-4505.

²⁰ Watson, S., et al.. MOXIE – Movies Of Extreme Imaging Experiments (2010 R&D 100 Winner). Los Alamos National Laboratory. LA-UR-10-01695. 2010.

²¹ Watson, S.. Ultra-fast 2D Detector For Megavolt X-Rays(U). ASNT Digital Conference. Los Alamos National Laboratory. LA-UR-10-03485. 2010.