THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Multi-bit Quanta Image Sensors

Eric R. Fossum

International Image Sensor Workshop (IISW)
Vaals, Netherlands
June 10, 2015

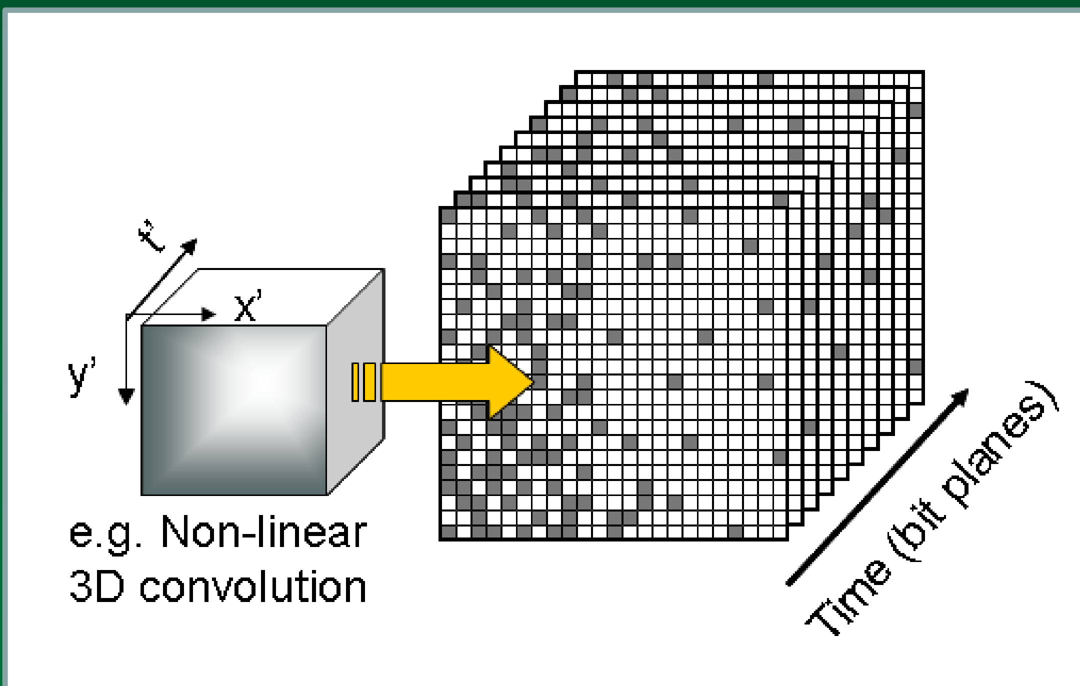
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Quanta Image Sensor

"Count Every Photoelectron"

Single-Bit QIS

Jot = specialized SDL pixel, sensitive to a single photoelectron with binary output, "0" for no photoelectron, "1" for at least one photoelectron.



Many jots are needed to create a single image pixel.

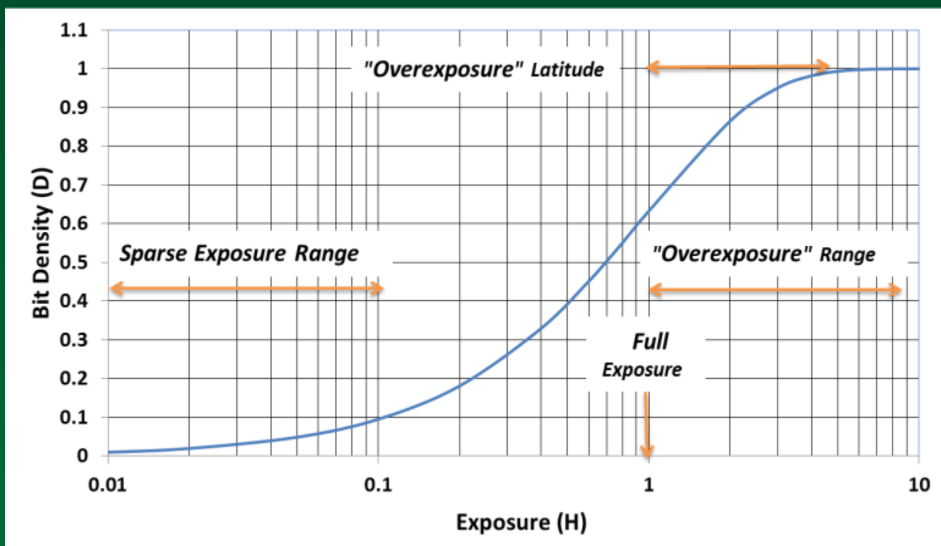
e.g. 16x16x16 = 4,096

A QIS might have 1G jots, read out at 1000 fields/sec or 0.5 Tbits/sec

Film-like Exposure Characteristic for Single-Bit QIS

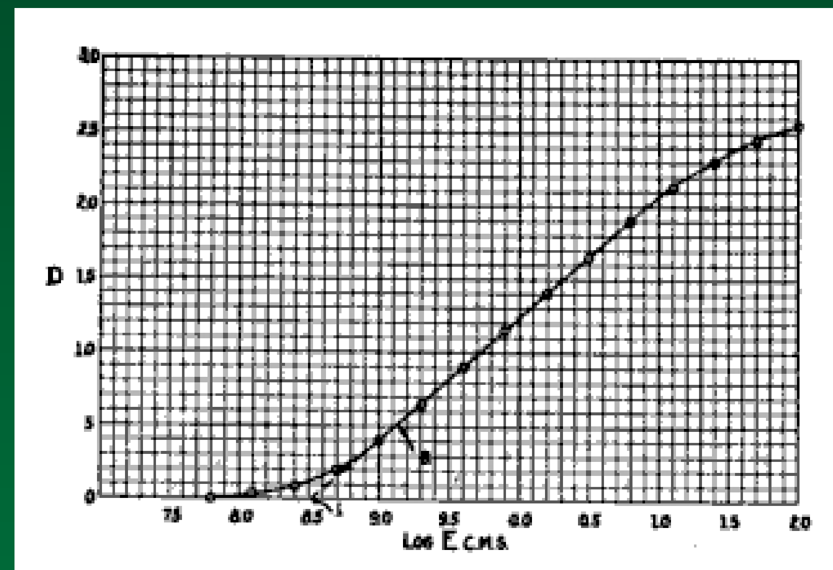
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

QIS D – log H



Bit Density vs. Exposure

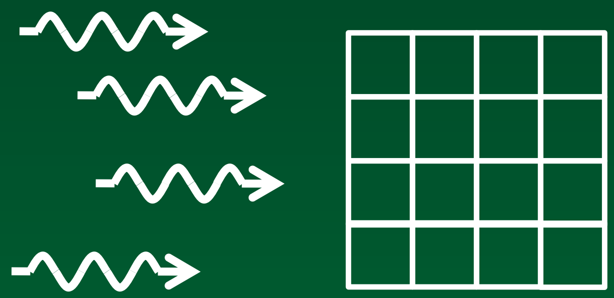
Film D – log H



Film Density vs. Exposure
1890 Hurter and Driffield

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Figure of Merit: Flux Capacity ϕ_w



At the flux capacity, there is an average of one photoelectron per jot

$$\phi_w = j f_r / \sigma \bar{\gamma}$$

$j = jot\ density\ (per\ cm^2)$

$f_r = field\ readout\ rate\ (per\ sec)$

$\sigma = shutter\ duty\ cycle$

$\bar{\gamma} = average\ quantum\ efficiency$

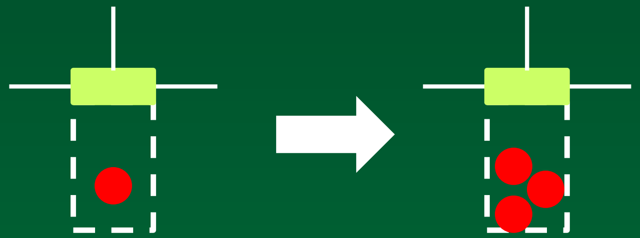
- At 500nm jot pitch, 1000fps, 100% duty cycle and 35% QE, $\phi_w \cong 10^{12}/cm^2 s$
- Corresponds to ~100lux (555nm, F/2.8, RT=80%)

➔ Drives high jot density and field readout rate so can handle normal lighting conditions
➔ And improve SNR per sq. cm of sensor area.

Multi-bit Jot Increases Flux Capacity

At the flux capacity, there is an average of $2^n - 1$ photoelectrons per *n*-bit jot

$$\phi_{wn} = jf_r(2^n - 1)/\sigma\bar{\gamma}$$



Single bit jot
0, 1 electrons

Multi-bit (2b) jot
0, 1, 2, 3 electrons

➔ Can increase flux capacity at same jot density and field readout rate
➔ Or, relax field readout rate and/or jot density for same flux capacity

Little impact on detector and storage well. Little impact on FD CG or voltage swing (e.g. 1mV/e -> 31mV swing for 5b jot.

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Flux Capacity Comparison

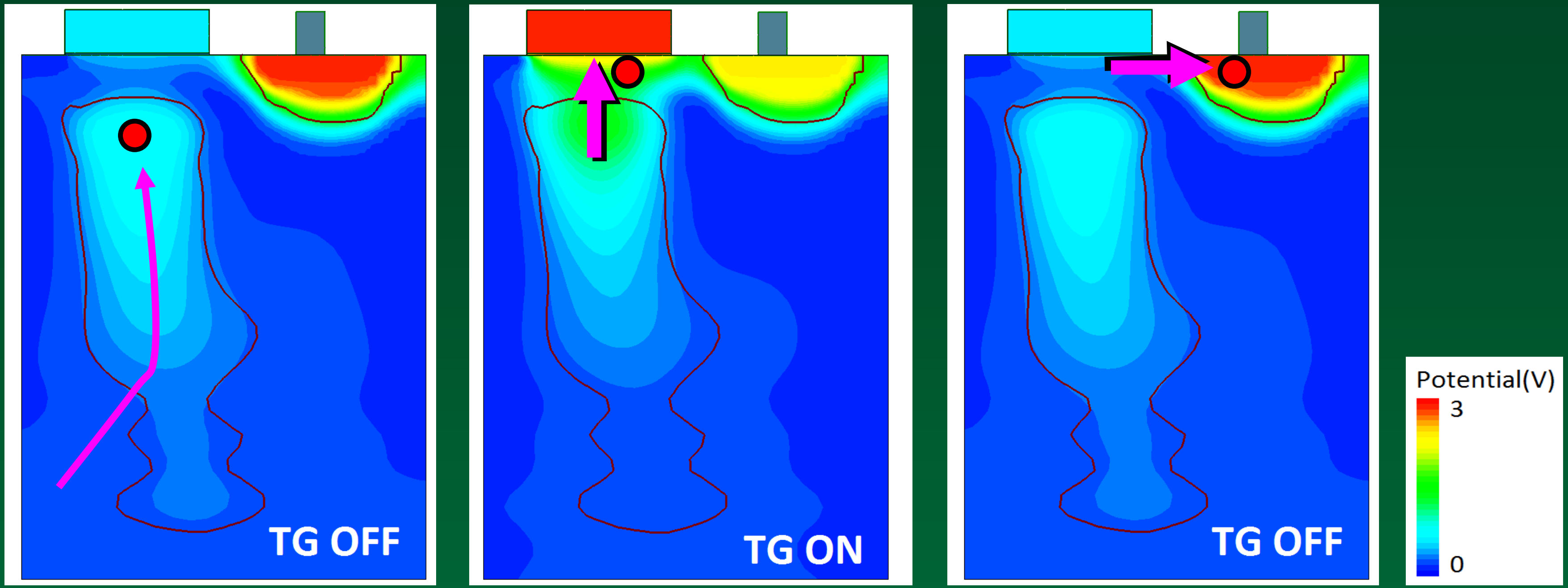
	QIS 1b	QIS 3b	CIS	SPAD
Pitch	0.5 um	0.5 um	1.1 um	8 um
Full Well	1 e-	7 e-	5,000 e-	1 e-
Readout	1,000 fps	1,000 fps	60 fps	4,000 fps*
QE	35%	35%	35%	35%x30%FF
Flux Cap.	$1x10^{12}/cm^2/s$	$7x10^{12}/cm^2/s$	$7x10^{13}/cm^2/s$	$6x10^{10}/cm^2/s$
Exp. Latitude	5x	2x	1x	5x
Adj. Flux Cap.	$5x10^{12}/cm^2/s$	$1.5x10^{13}/cm^2/s$	$7x10^{13}/cm^2/s$	$3x10^{11}/cm^2/s$
	Concept	*Concept*	*Commercial*	*R&D demo*

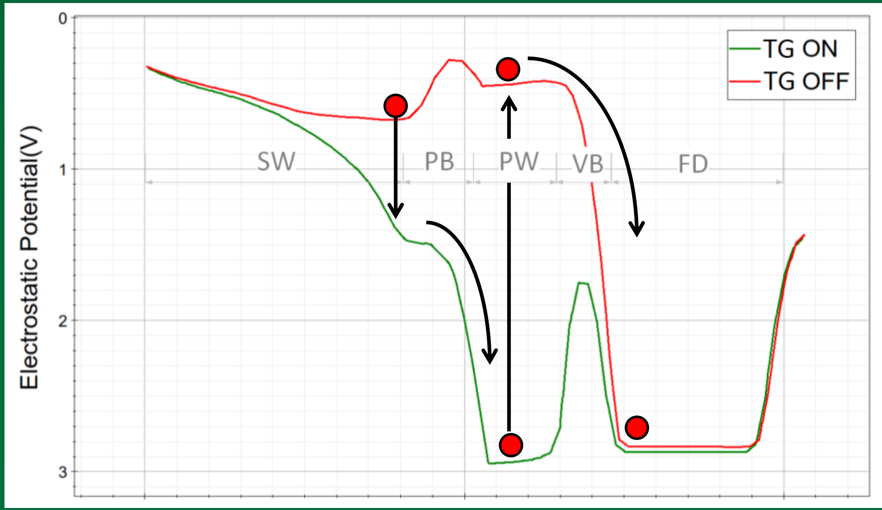
QIS has issue with flash photography

*16,000 fps in 320x240 demonstrated by STM

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Pump-gate Jot Device with Distal FD and Tapered RG

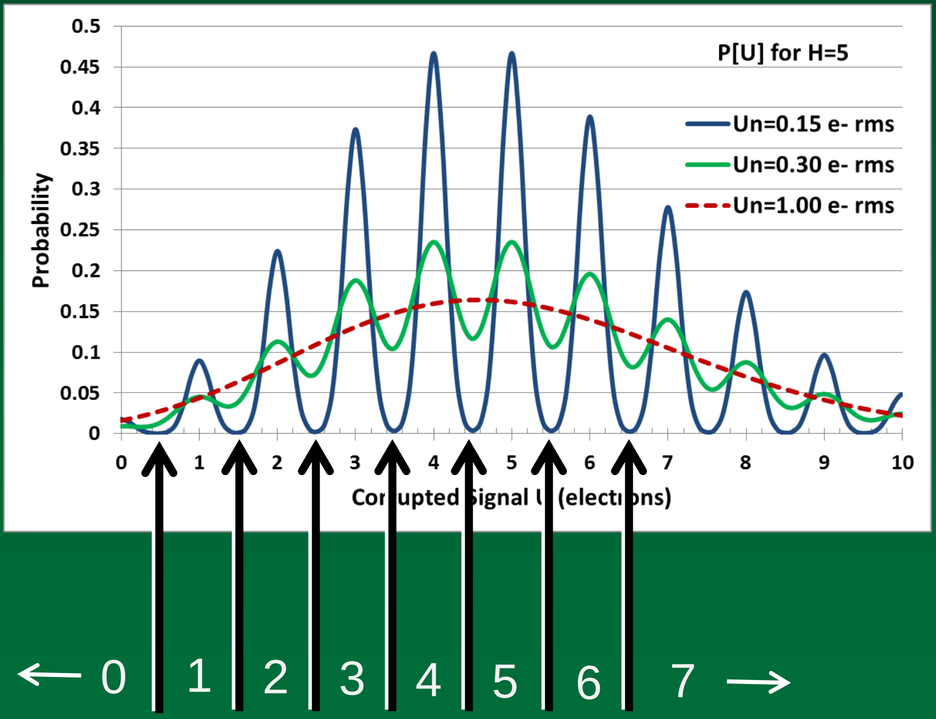




J.J. Ma and E.R. Fossum, A Pump-Gate Jot Device with High Conversion Gain for Quanta Image Sensors, IEEE J. Electron Devices Society, Vol. 3(2), pp. 73-77, March 2015.

Need an *n*-bit ADC to discriminate between levels

Ideally, 1 LSB corresponds to 1 photoelectron.

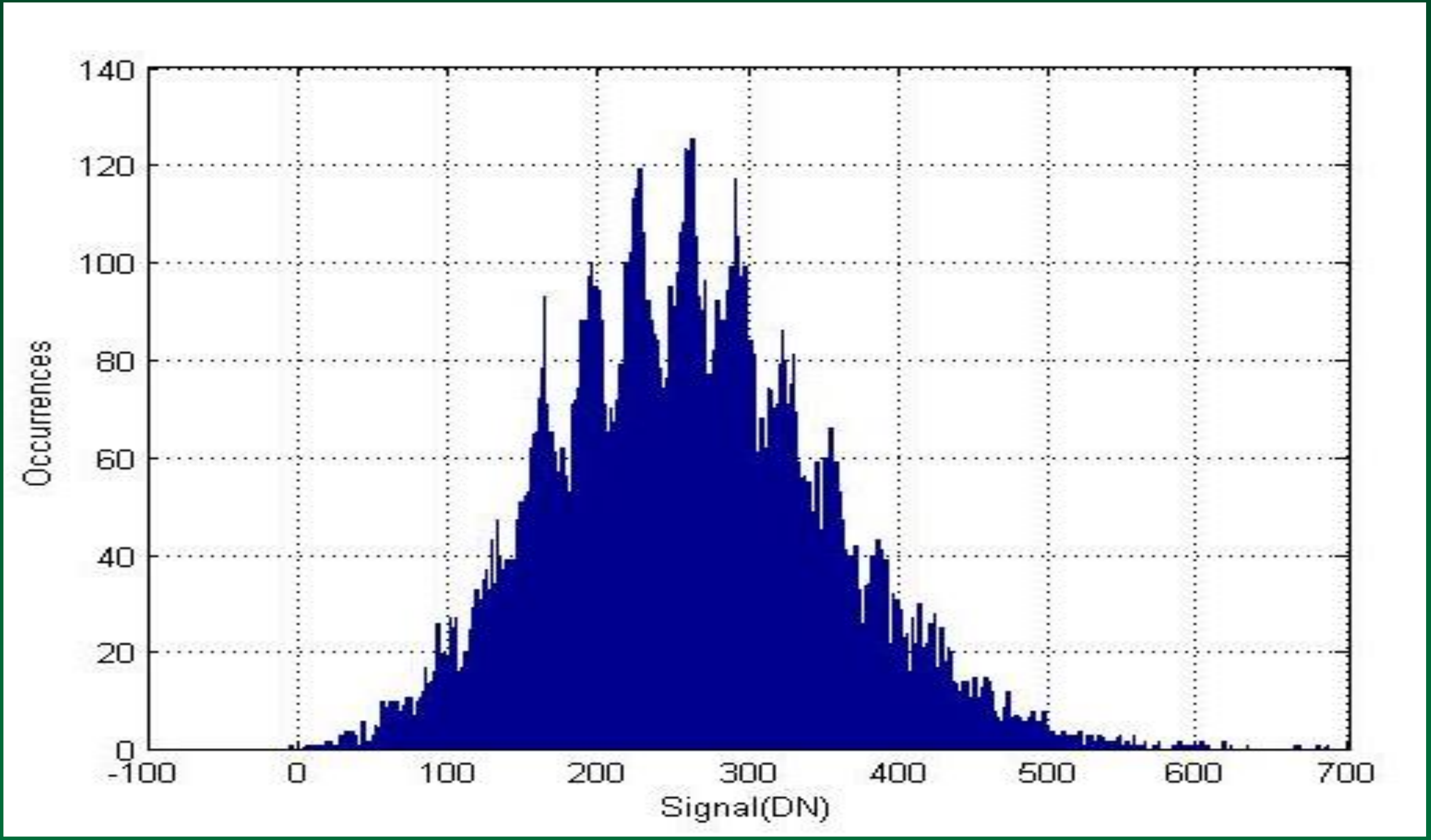


Example: 3b quantizer thresholds

MINI-PAPER IN A PAPER

Recent Results: Jiaju Ma and E.R. Fossum

First Photoelectron Counting without Avalanche Gain



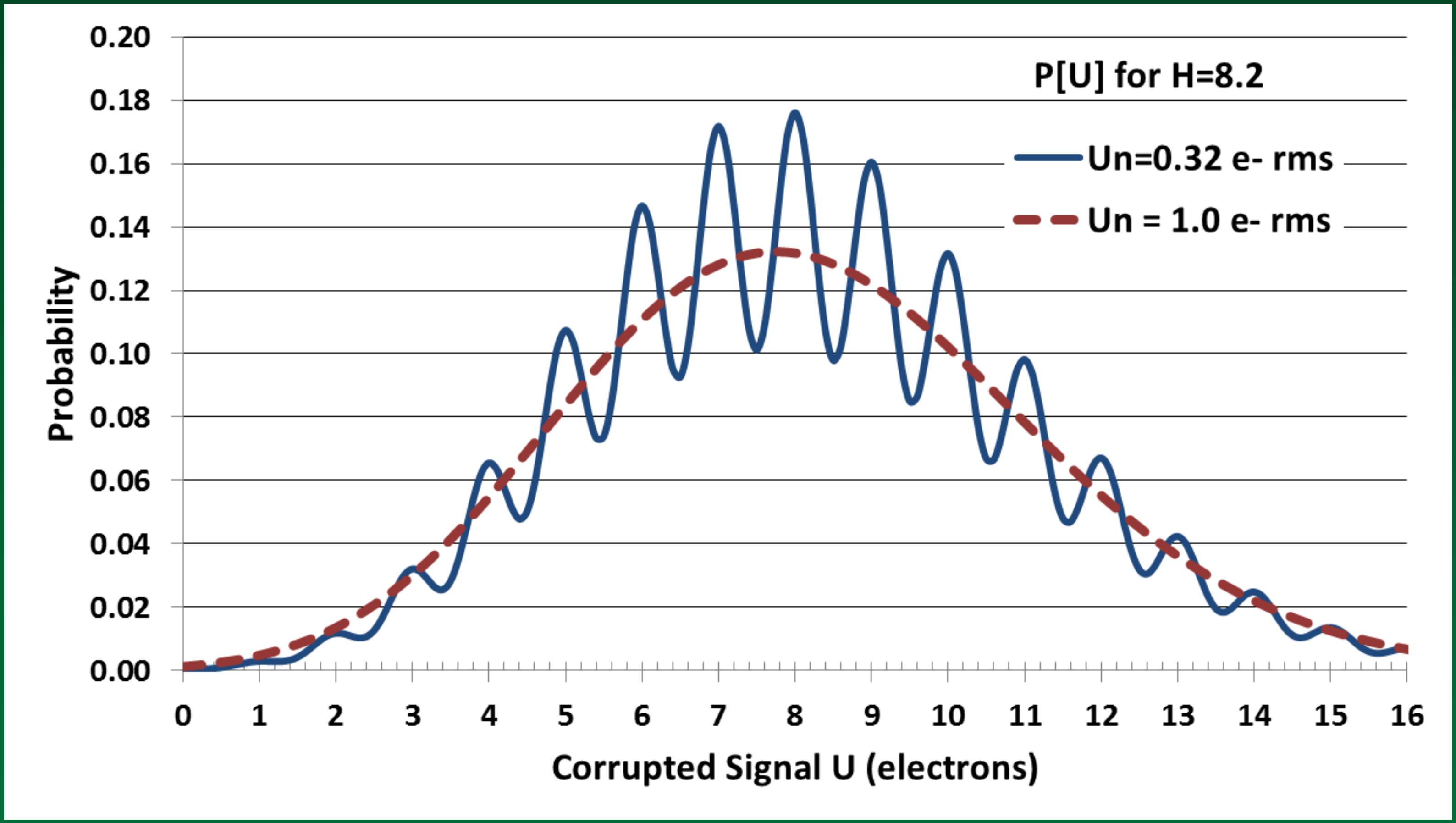
Jiaju Ma and ER Fossum, 6-June-2015 unpublished.

CG=242 uV/e-

27.4DN/e- using external ADC

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

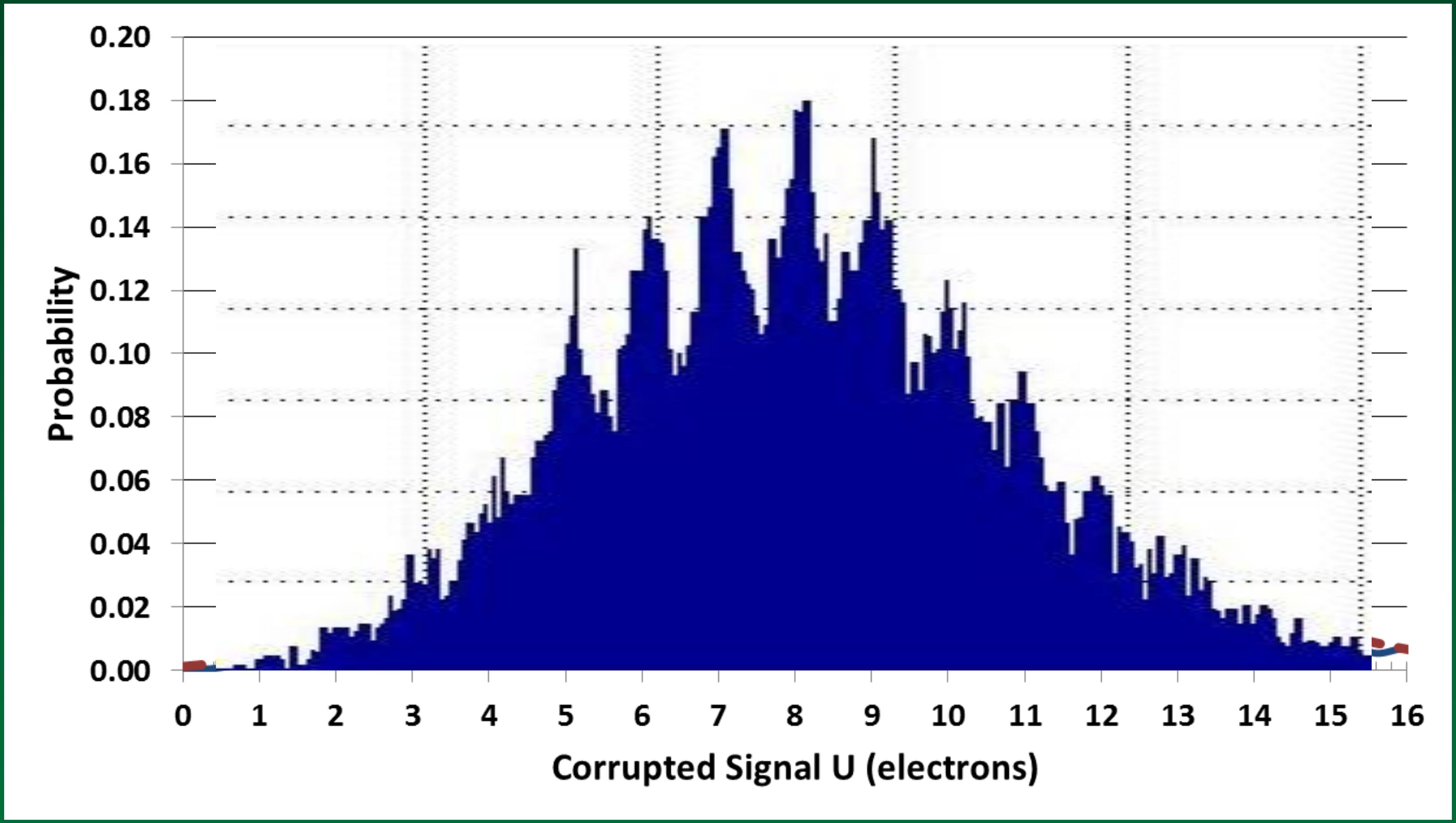
Photoelectron Counting Histogram (PCH) Model



This fit is quite good with mean of 8.2, std. of 2.86 e-, read noise of 0.32 e- rms.

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Photoelectron Counting Histogram (PCH) Model

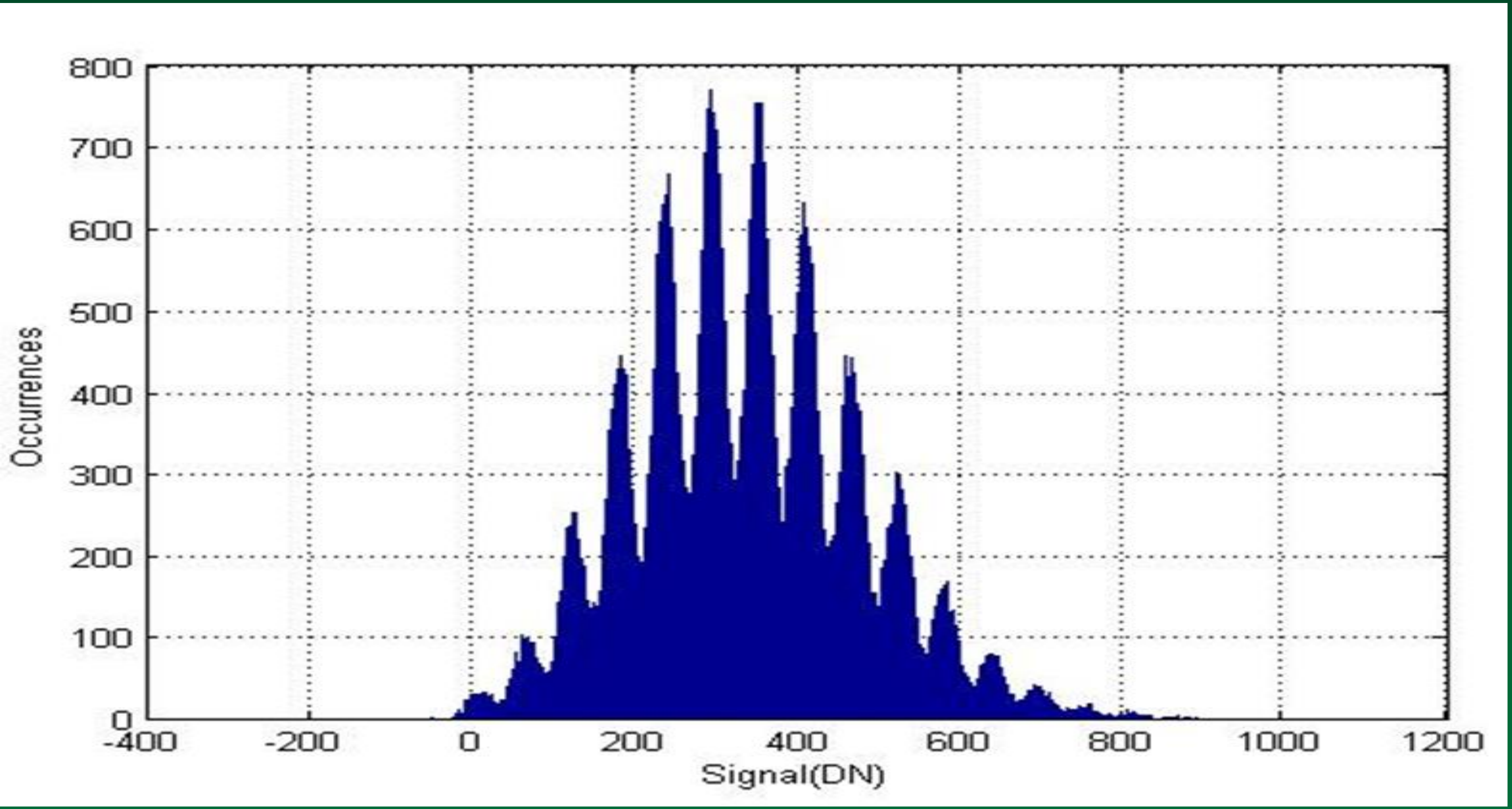


Jiaju Ma and ER Fossum, 6-June-2015 unpublished.

CG=242 uV/e-

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Pump Gate Jot with Tapered Reset Gate*



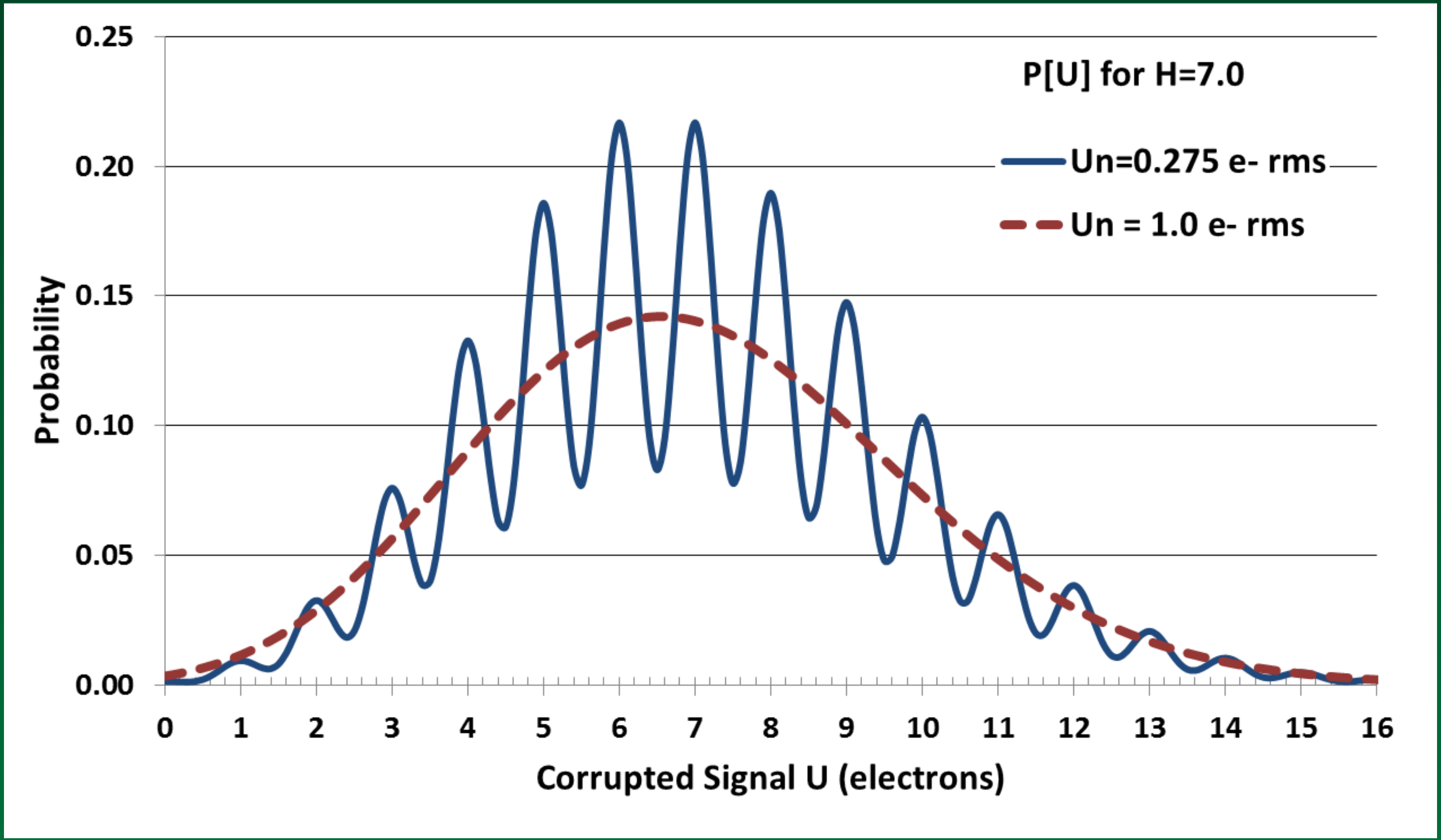
56DN/e- external ADC
CG=403 uV/e-

Jiaju Ma and ER Fossum, 7-June-2015 unpublished.

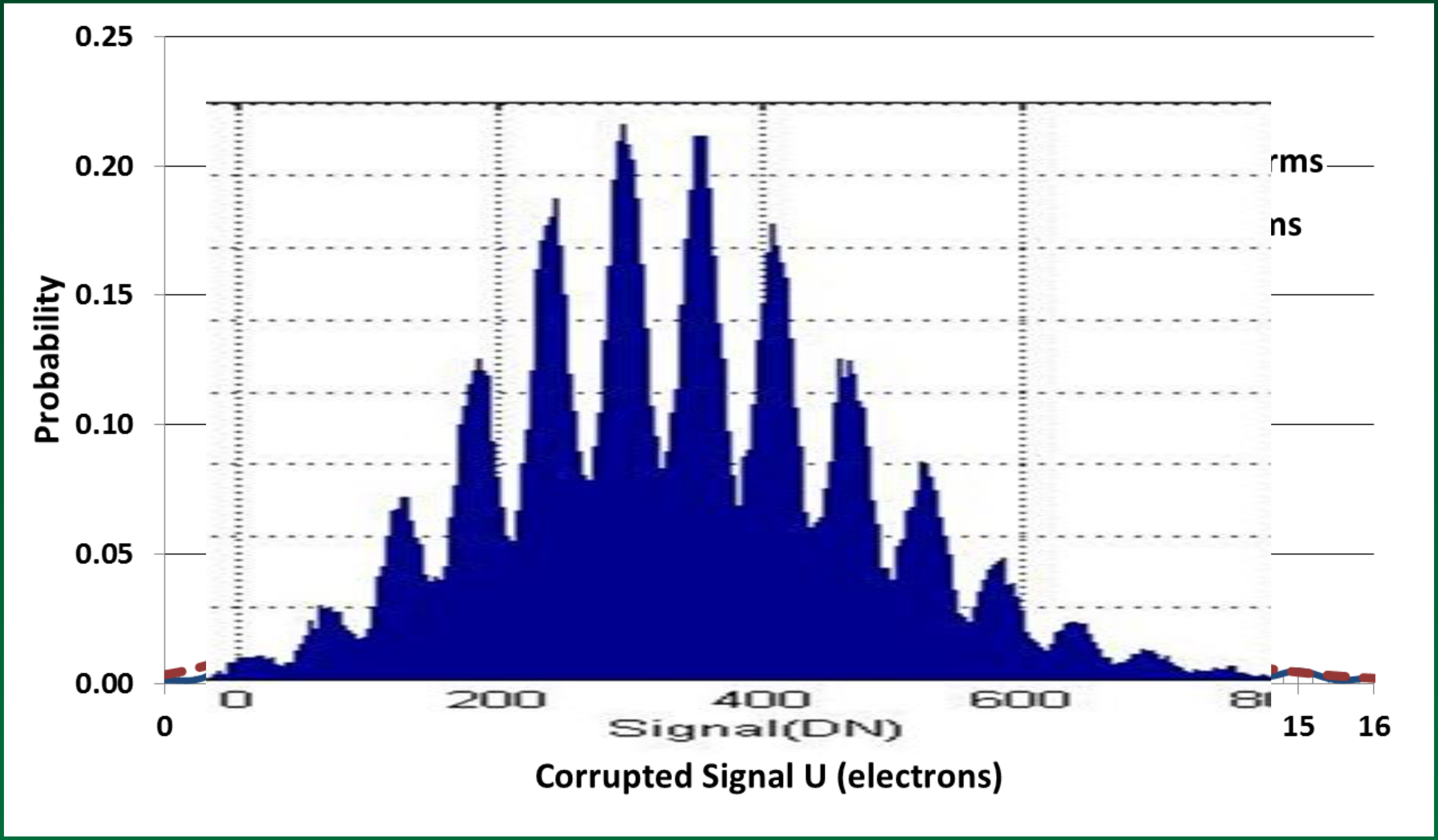
*Tapered reset suggested by Mike Guidash

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Pump Gate Jot with Tapered Reset Gate



Pump Gate Jot with Tapered Reset Gate

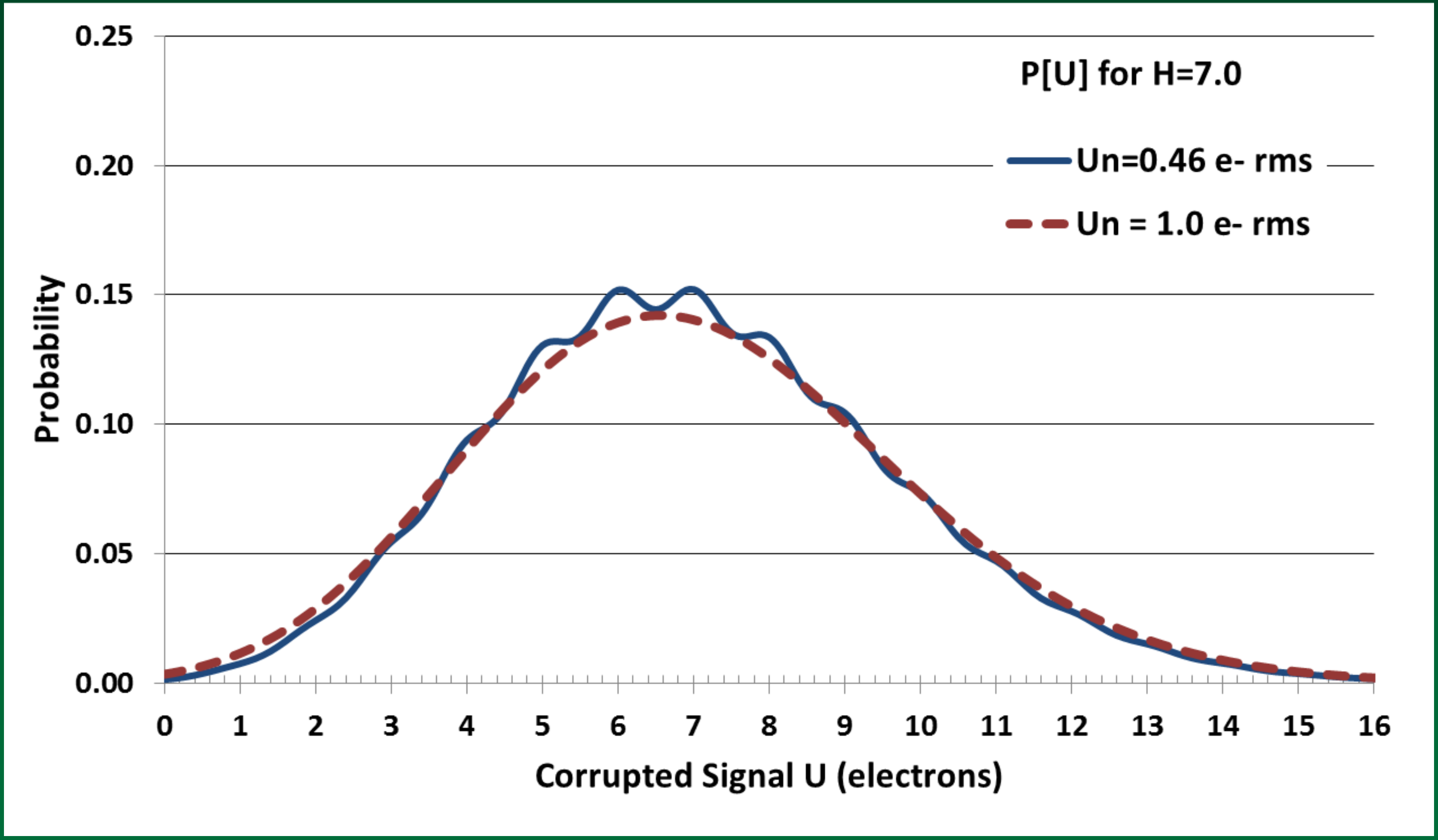


Jiaju Ma and ER Fossum, 7-June-2015 unpublished.

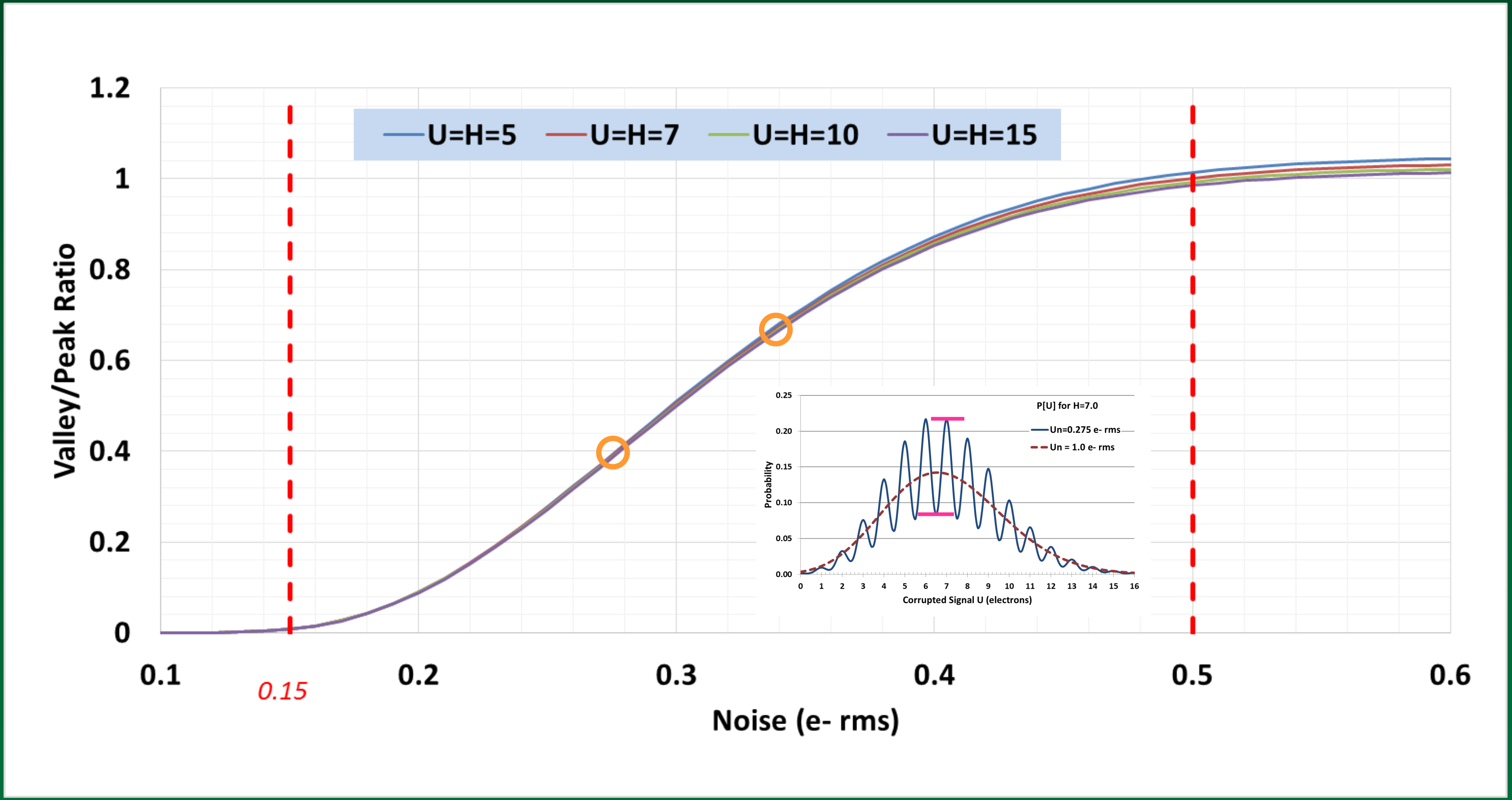
CG=403 uV/e-

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Read Noise of 0.46 e- rms (Tohoku Univ paper 5.10)



Quick Estimate of Read Noise Using Valley-Peak Ratio (VPR)



THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

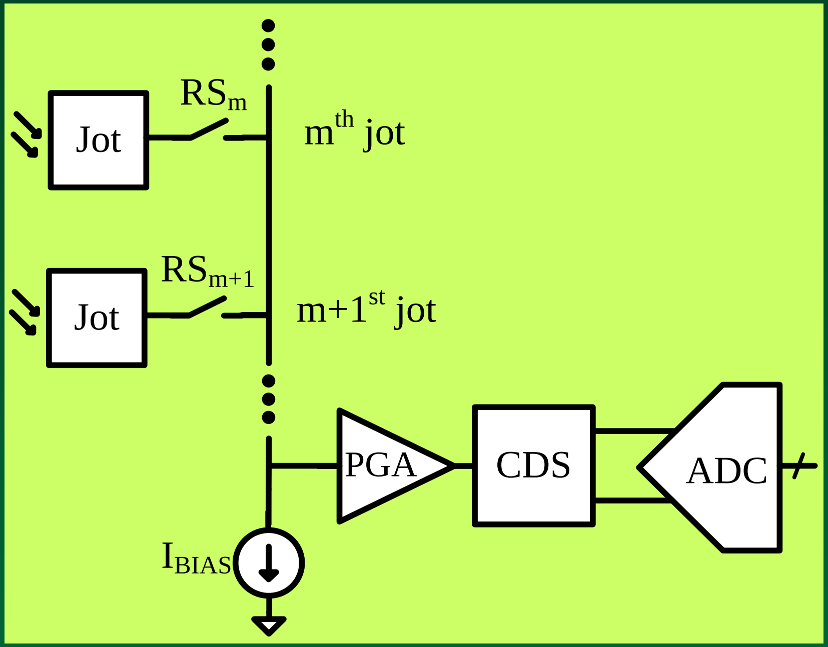
Late News Summary

	PG jot	Tapered PG jot
Pitch Size	1.4μm	1.4μm
PTC CG	241.7 μV/e-	403.0 μV/e-
Dark Read Noise	96.89 μV rms (0.40e- rms)	136.9 μV rms (0.34e- rms)
Jot SF Read Noise	96.06 μV rms	136.3 μV rms
PCH CG	255.8 μV/e-	426.2 μV/e-
VPR Read Noise	0.32e- rms	0.28e- rms
Full Well Capacity	288e-	210e-
RT Dark Current	<10e-/s	<10e-/s
Col. Bias Current	416nA	416nA

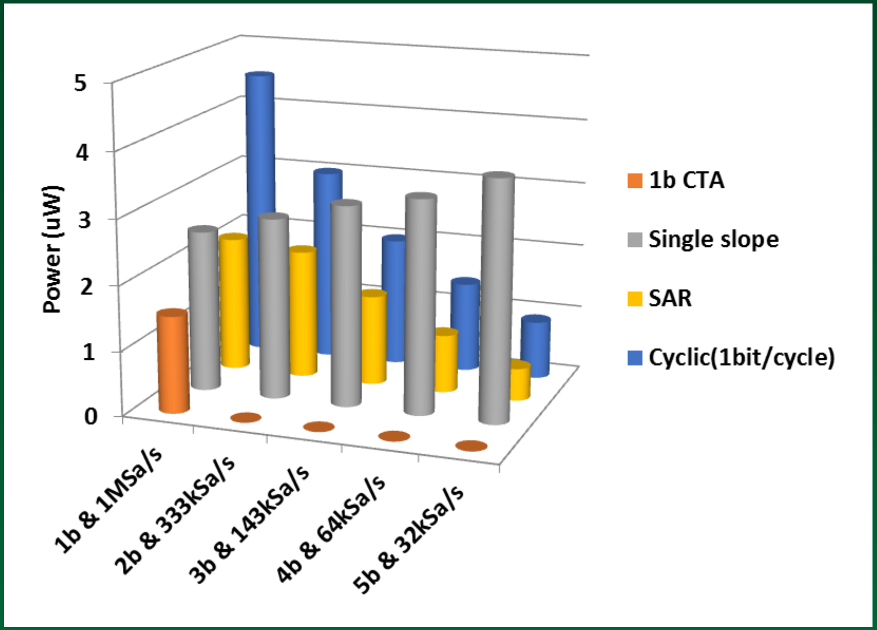
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

End of Mini-Paper

Multi-bit QIS ADC Trade Space

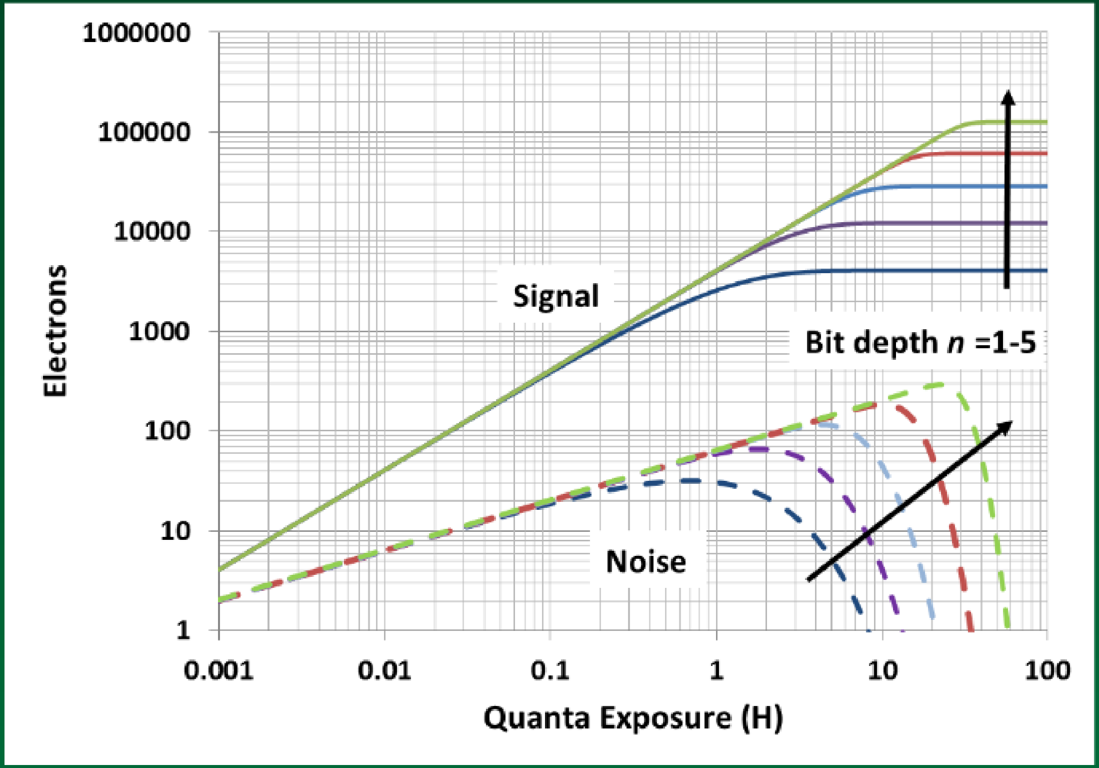


Block diagram of readout signal chain.



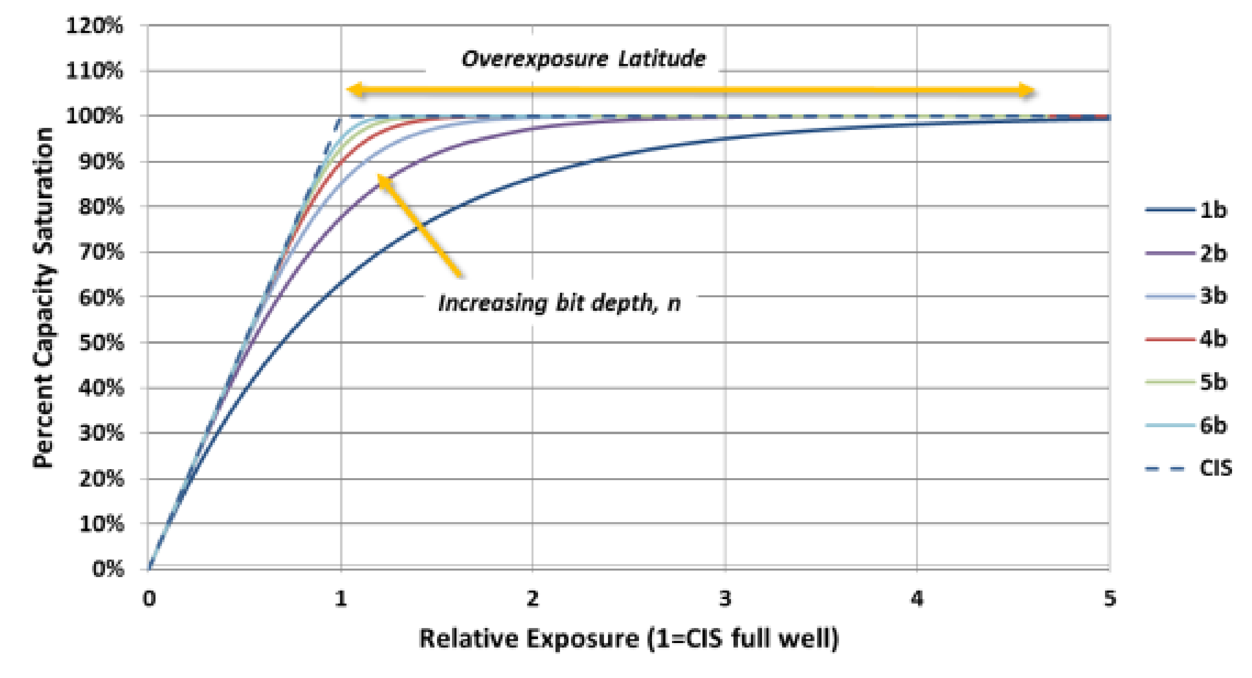
Power dissipation of single-bit and multibit QIS ADCs operating at different resolutions, and at different speeds for constant flux capacity. (From simulation of a chip in fab, S.Masoodian, D. Starkey, A. Rao, S. Chen, K. Odame and E.R. Fossum)

Signal and Noise for Multi-bit QIS



Log signal and noise as a function of log exposure for multi-bit QIS jots with varying bit depth. The signal is the sum over 4096 jots (e.g. 16x16x16). Saturation signal is $4096 \cdot (2^n - 1)$.

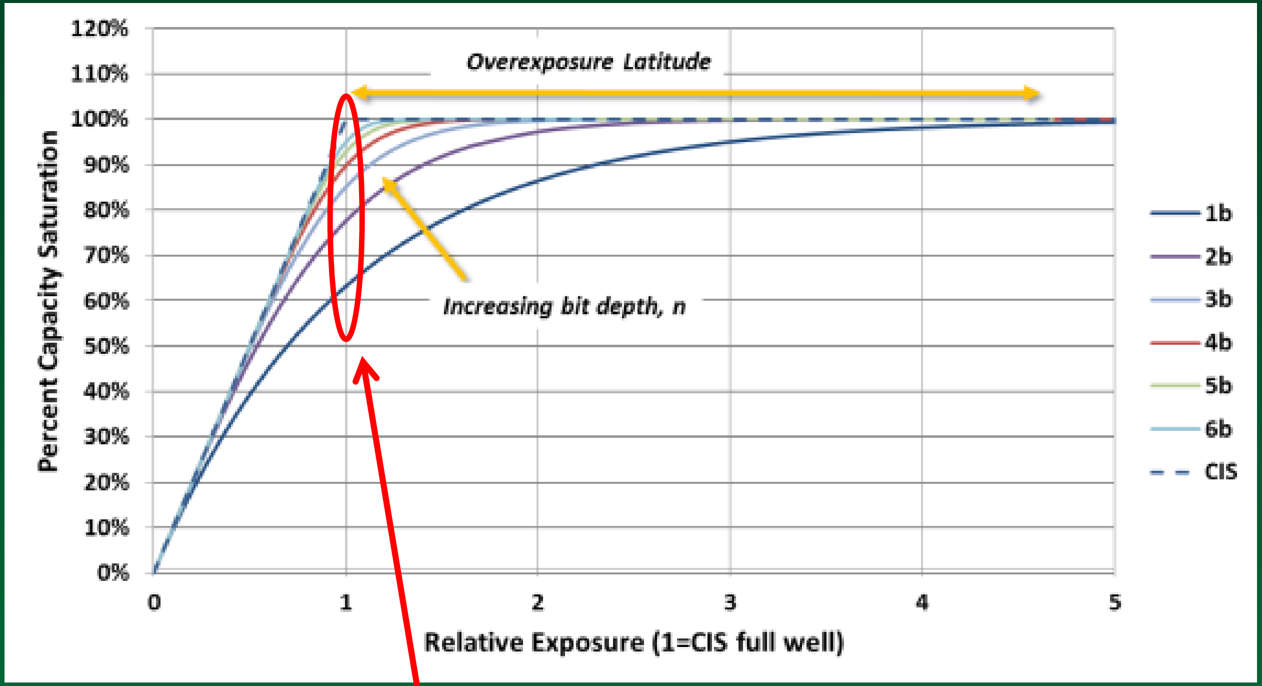
Signal Non-Linearity for Multi-bit QIS



Non-linearity and saturation characteristics of single-bit and multi-bit QIS for 1≤n≤6 bits. For the QIS, the capacity of the full well is given by FW=2^n-1. The relative exposure is the quanta exposure H (in photoelectrons) divided by the full well, and the percent saturation is calculated from the expected number of photoelectrons in the photosite. Generally for the QIS, a “cubicle” in x,y, and t might be summed.

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

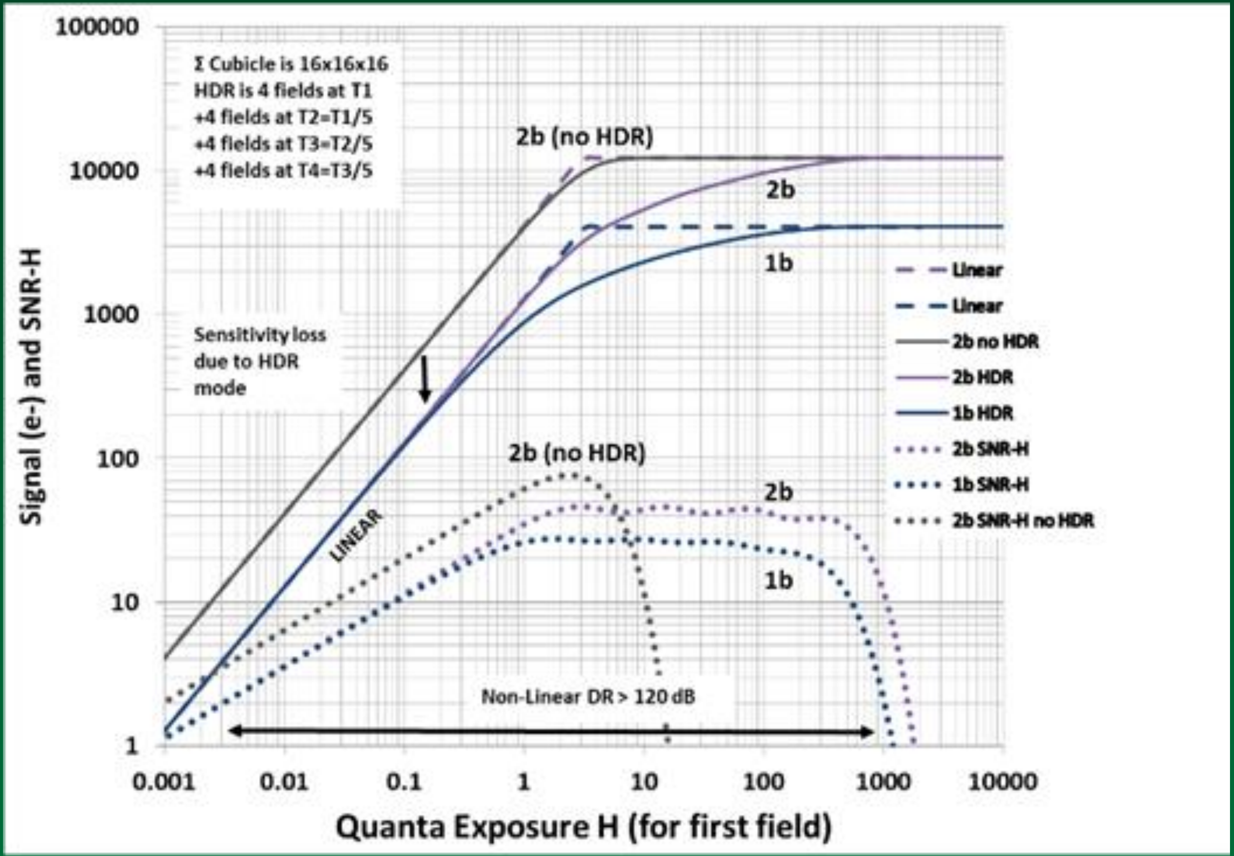
Signal Non-Linearity for Multi-bit QIS



$$\%Cap = 100\left[1 - \sum_{k=0}^{FW}\left\{1 - \frac{k}{FW}\right\}\frac{e^{-H}H^{k}}{k!}\right]$$

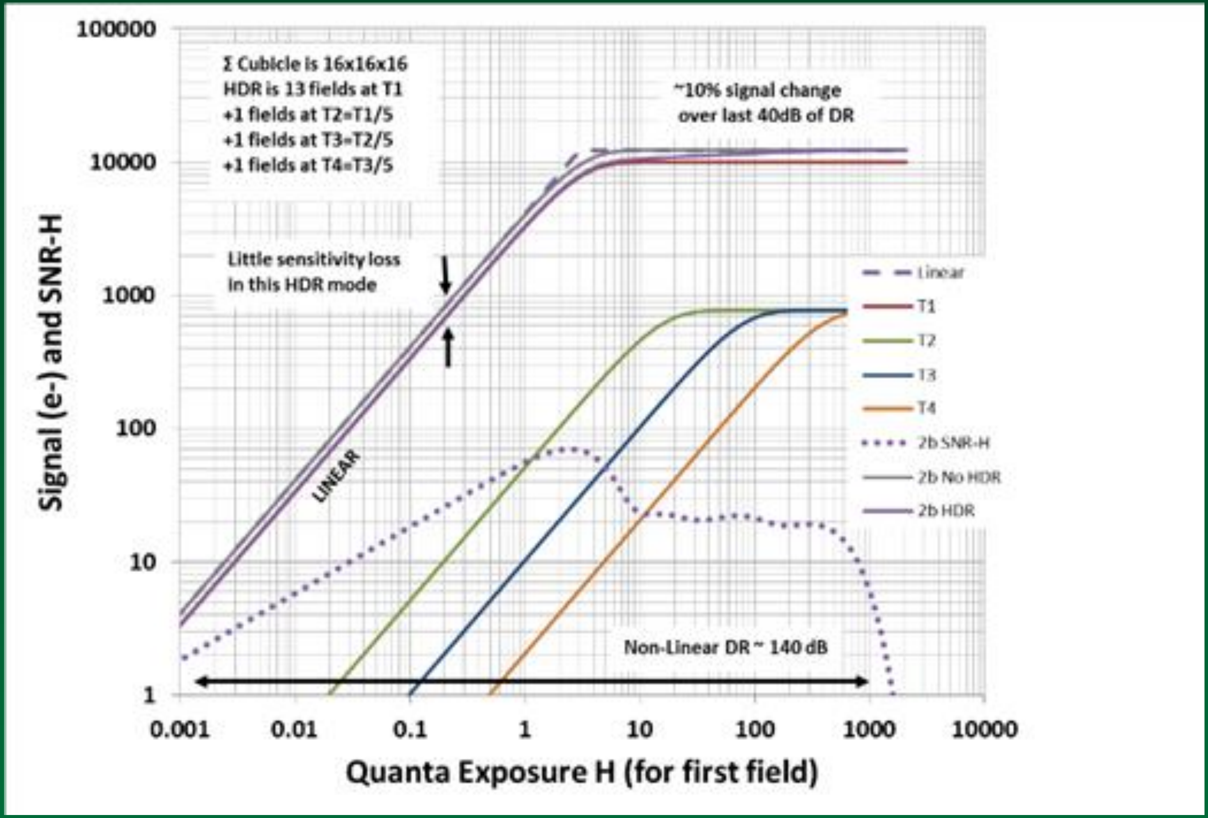
$$\%Cap \cong 100\left[1 - e^{-n^{0.6}}\right] \quad 1 \le n \le 6$$

HDR mode for Multi-bit QIS



Comparison of an HDR mode for 1b and 2b QIS. Cubicle is 16x16x16 fields, with 4 different shutter duty cycles. First 4 fields duty cycle is unity, next is 1/5, next is 1/25, and last group of 4 fields is 1/125. Signal is sum of cubicle data

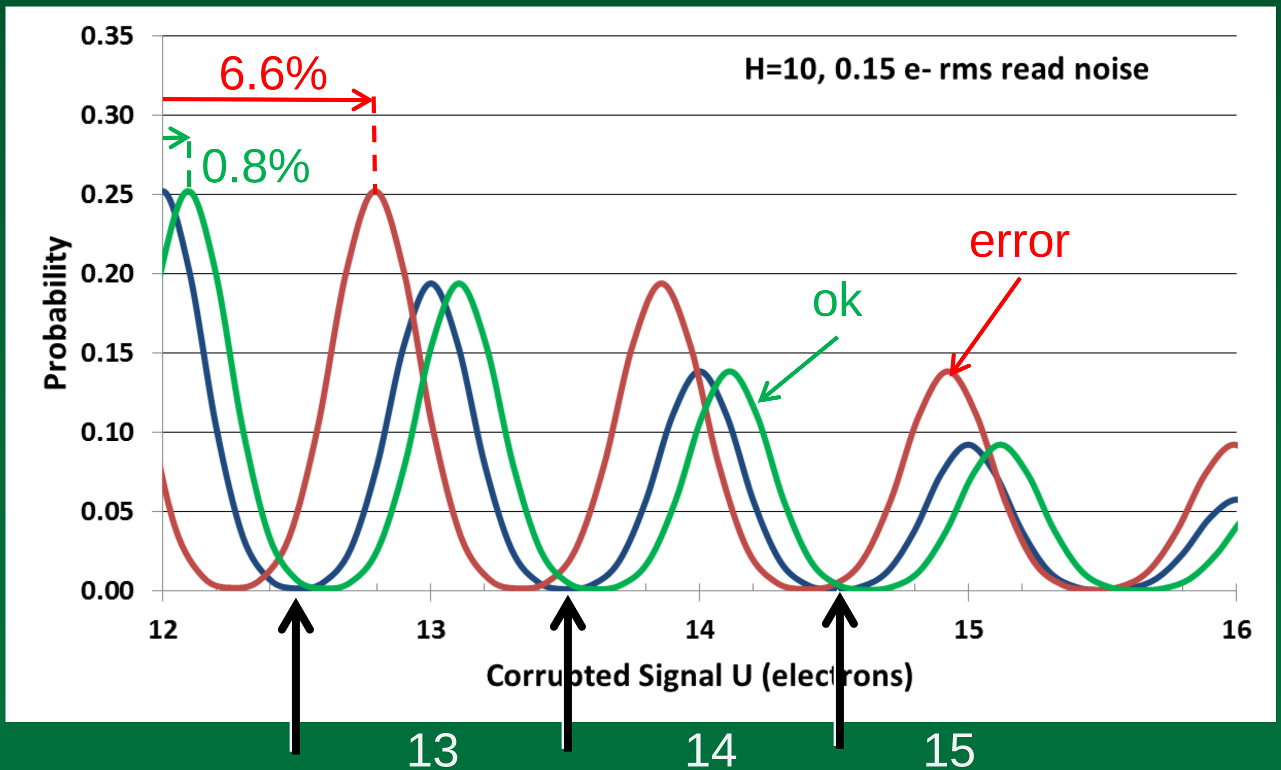
Alternate HDR mode for Multi-bit QIS



Alternate HDR mode that improves low-light sensitivity at expense of reduced SNRH at higher light levels. Note 10% of max signal change occurs over last 40 dB of DR. First 13 fields duty cycle is unity, next field duty cycle is 1/5, next field is 1/25, and last is 1/125. The contribution of each set of fields is also shown.

Gain Variation

- To have count error < 1 e-, want gain variation $\delta G/G \leq 1/(2^n - 1)$. Example, for $n = 4$ we want $\delta G/G \lesssim 6.6\%$
- For low BER, better to have $\delta G/G \leq 1/2^{n+3}$. For $n = 4$ that is 1/128 = 0.8%



THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Summary

- QIS goal: "count every photoelectron" in the sensor.
- "Flux capacity" as a figure of merit.
- Non-linearity is a function of bit depth *n*.
- Bit depth can be changed (downwards) during or after capture, and thus change linearity.
- First photoelectron counting without avalanche gain demonstrated.

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Discussion Points

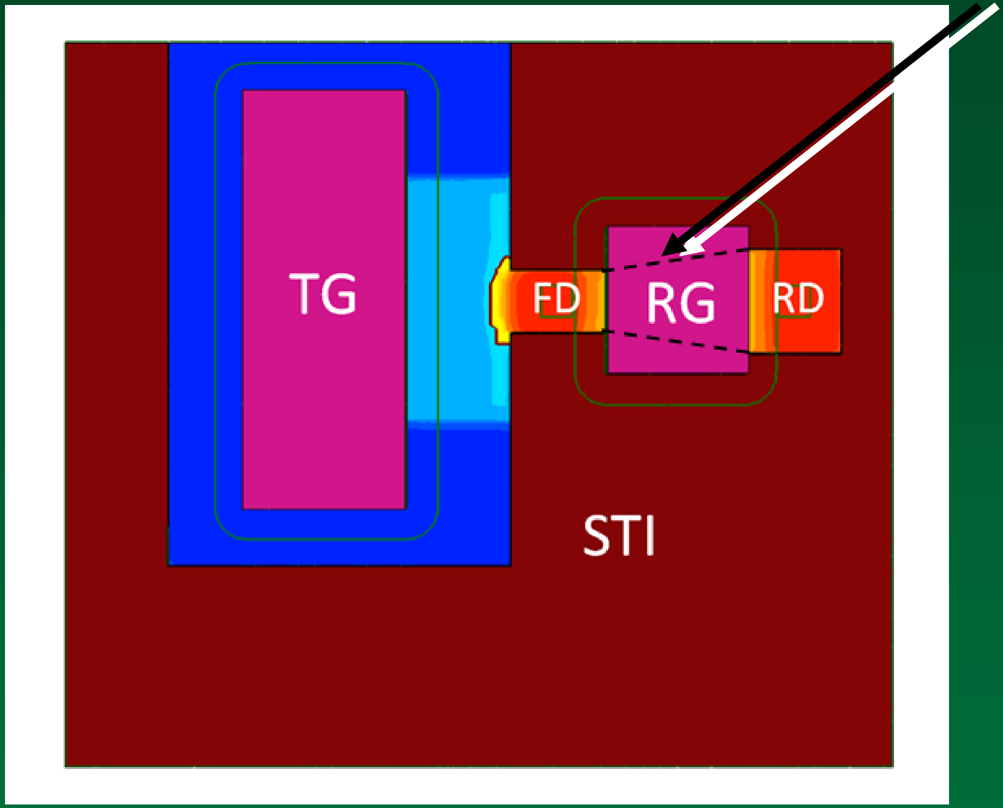
- Techniques and concepts such as high CG and digital integration will be applicable to many sensors.
- Concepts apply to larger jot/pixel sizes and slower readout speeds. It is CIS or QIS?
- How important is it, really, to discriminate accurately between 14 and 15 electrons?
- Combination with cascaded integration (or LOFIC) will be interesting.
- IoT will be light starved.

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

EXTRA SLIDES

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Tapered Reset Gate Geometry

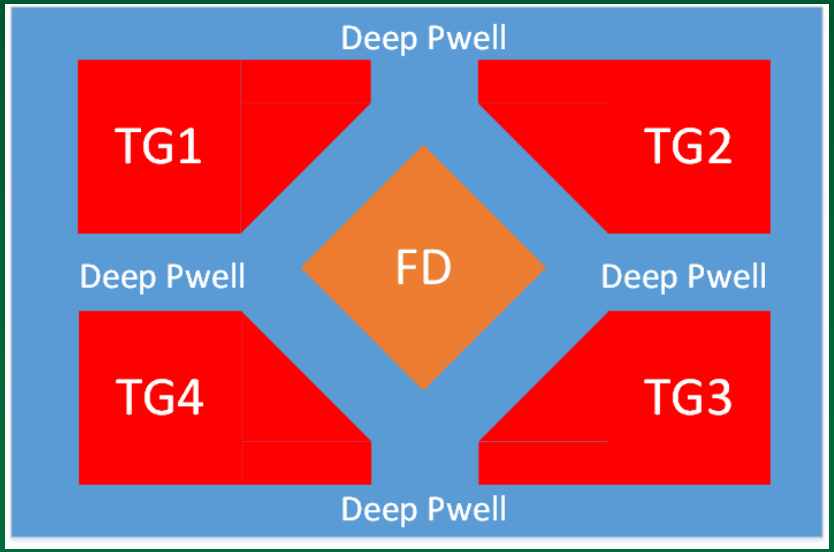


STI edge taper
To reduce RG overlap capacitance

Top view
Synopsys Sentaurus
SPROCESS output

Pump-gate Jot Device with Distal FD and 4-Way Shared Readout

With distal FD, shared readout does not increase FD capacitance due to multiple TG overlaps



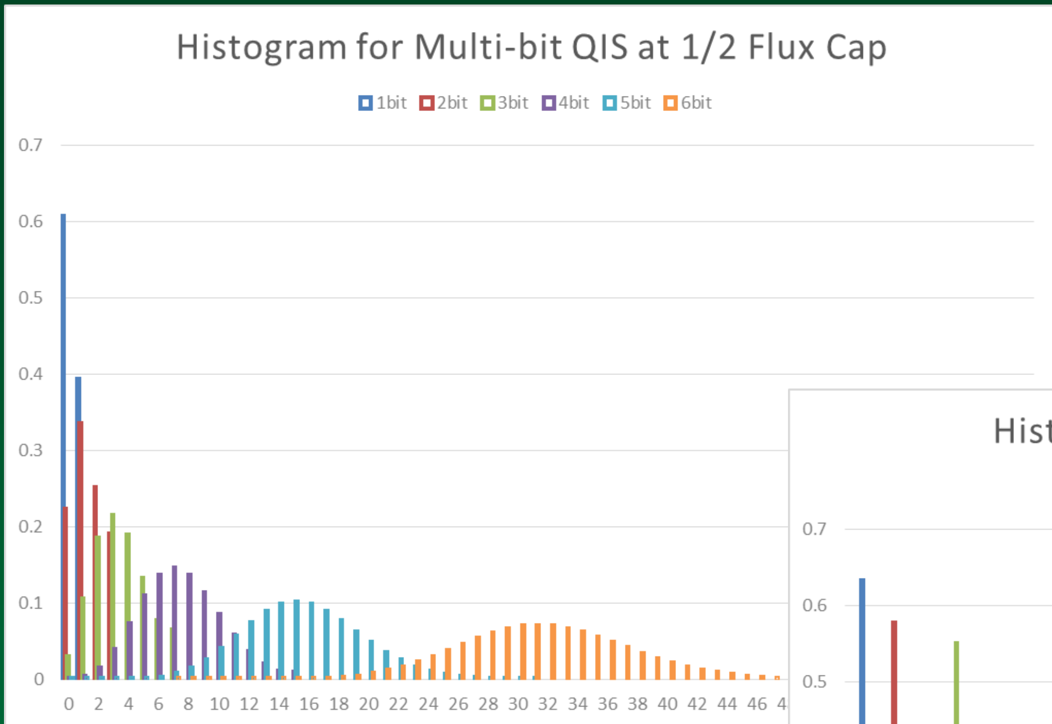
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

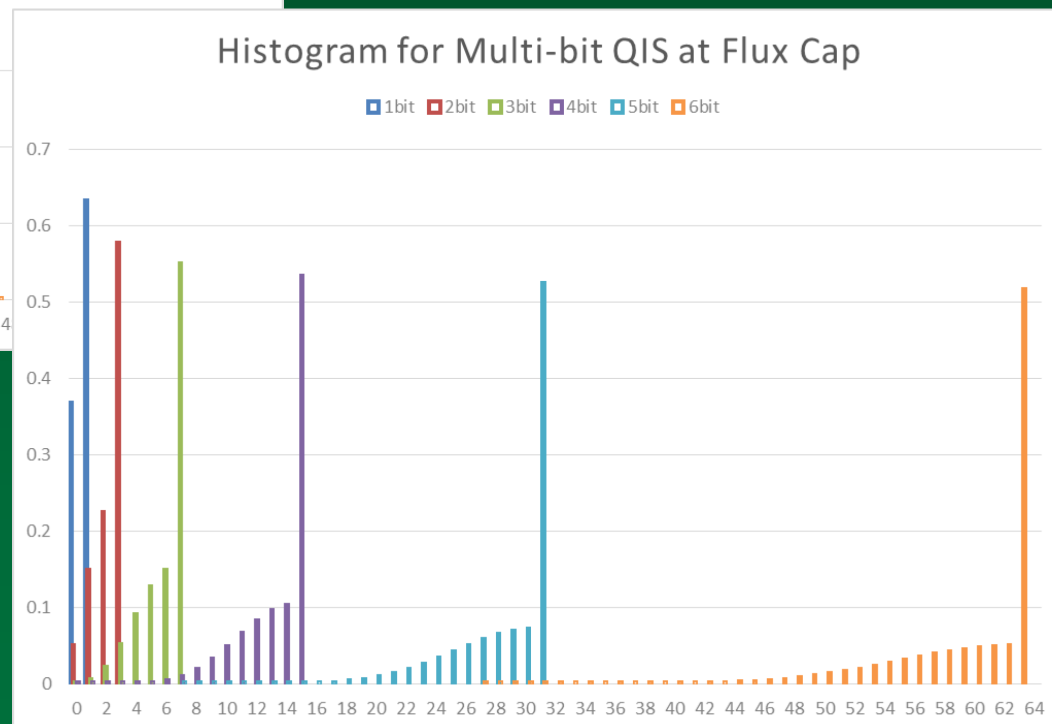
Pump-Gate Jot With Distal FD Status

- BSI CIS as baseline process.
- Test subarrays (32x32 each)
- No extra masks required
- Masks and Implants changed

	Non-Shared	4-Way Shared
Technology	65 nm BSI CIS	65 nm BSI CIS
Pitch	1.4 um	1.0 um
Full well	200 e-	200 e-
Baseline CG		170 uV/e- (1.4um)
Non-taper CG	250 uV/e-	250 uV/e-
Tapered RG + smaller SF CG	480 uV/e-	n/a
Future pitch @65nm?	1.2 um	0.8 um

Histograms of Photoelectrons

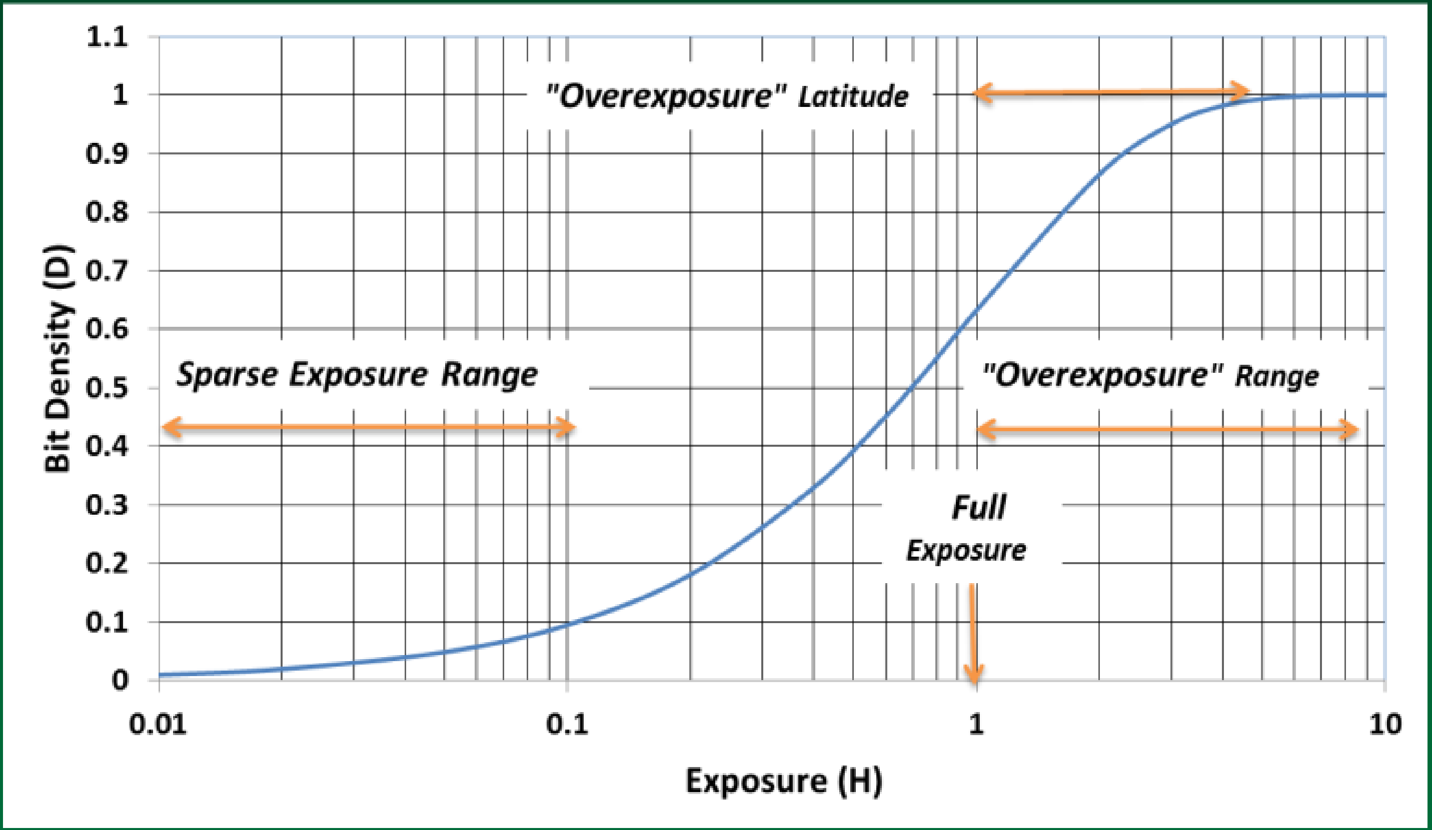




THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Bit Density

$$Bit\ Density\ D \triangleq \frac{M_1}{M} = 1 - e^{-H}$$



$$D \cong H \quad \text{(linear)}$$

Can determine H from measured D

$$\mathrm{H} = \ln\left[\frac{1}{1-D}\right]$$

Multi-Arrival Threshold (Not QIS)

Binary output of sensor ="1" when # of arrivals $k \geq k_T$
Results in reduced higher slope and less overexposure latitude