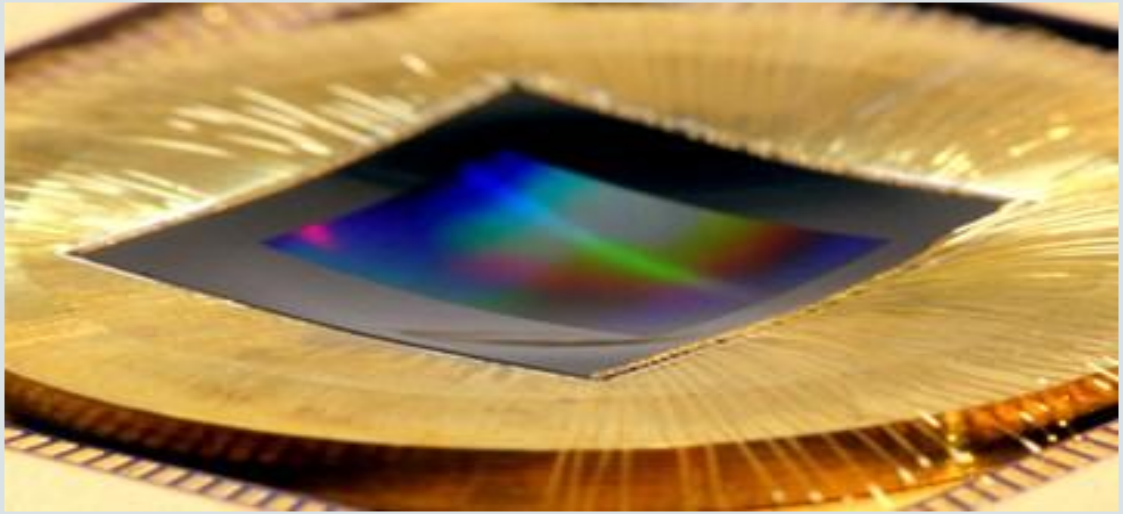
A Novel Technique for Low Cost Imaging in Light-Deficient Environments

EXPLOITING OF THE VERSATILITY OF CMOS



JOHN RICHARDSON

Digital Imaging: History in Brief

- ***1960s***: Birth of solid-state visible image sensing
- Two distinct approaches: **With** / **without** in-pixel MOS transistors
- **Passive Pixel Sensor (PPS):** One transistor (switch) to read out the photocharge (*Weckler*, ***1967***)
- **Active Pixel Sensor (APS):** Amplifier and reset transistors added (*Noble*, ***1968***). First "3T" sensor
- **Charge-coupled device (CCD):** MOS capacitors used to accumulate and read out photocharge (*Boyle/Smith*, ***1969***)

Digital Imaging: History in Brief

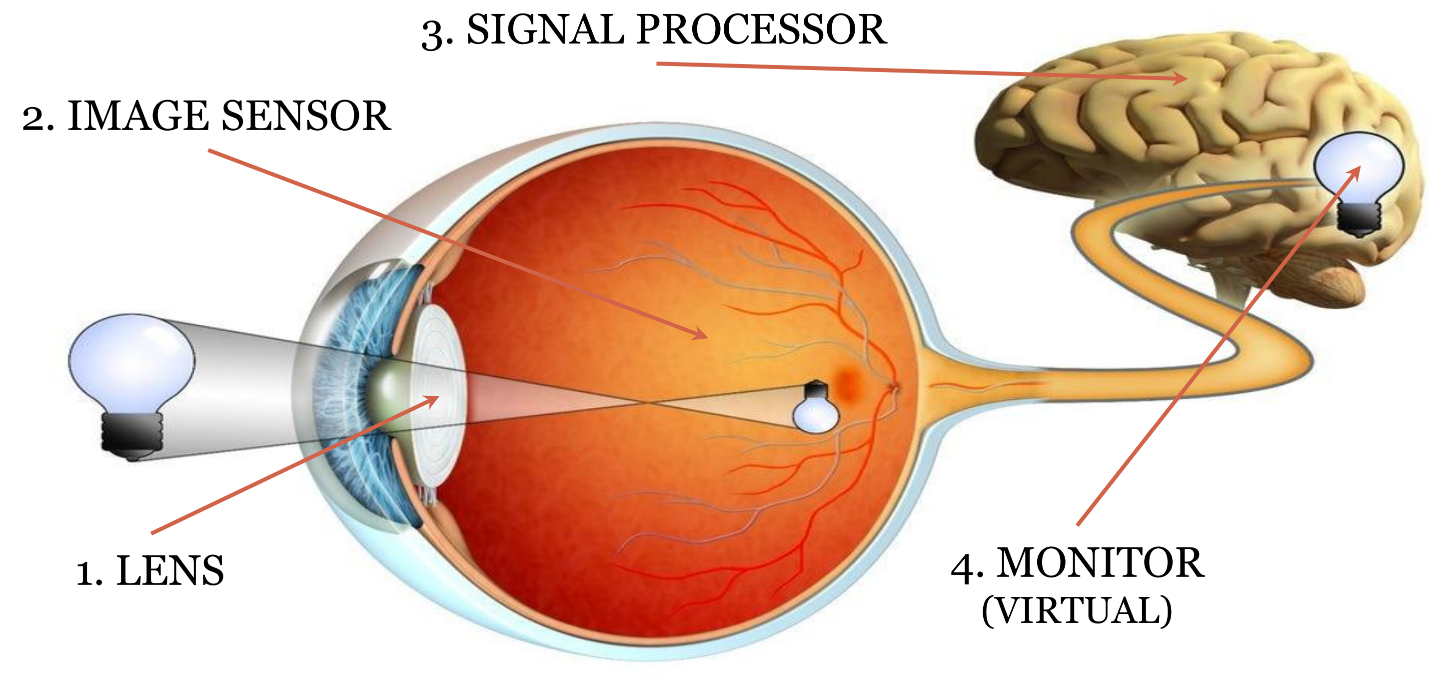
- Passive Pixel Sensor: **High read-noise and offset dispersion (pixel FPN)**. Poor final image quality. Used for OCRs etc. in the ***'60s***
- Partly addressed by 3T architecture
- CCD: **Much better image quality**
- Reigned supreme over the solid state imaging world throughout the ***'70s, '80s*** and ***'90s***
- Technology continued to be **honed throughout those decades**. Processing **highly specialized** and **exclusive**
- **Dominated** ~all visible imaging realms: Consumer, military, scientific, security, broadcast, studio, cinema, machine vision etc.

Digital Imaging: History in Brief

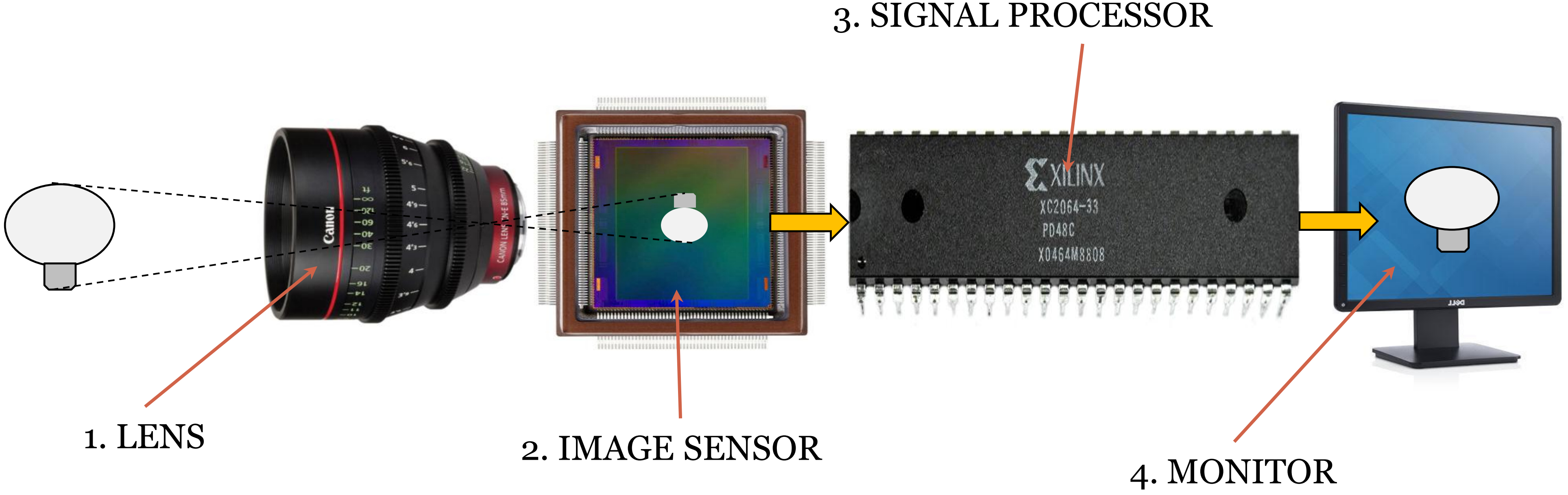
- ***1990s***: **New focus** on MOS transistor-based approach
- Prospect of better performance arising from **processing refinements** and greater integration (Imaging System on Chip concept, iSoC): **CMOS technology**
- Lower cost & Accessible: Pure-play foundry paradigm, MOSIS etc.
- ***End of '90s:*** Greatly improved performance but **still inferior** to **CCD**
- ***2004***: Sony announces they "**have to win in CMOS**"
- ***Late '00s***: Huge capital injection from burgeoning high-volume markets drove greater refinement.
- ***'10s:*** **Explosion of CMOS**. Market dominance over CCD
- Today: Ubiquitous

Camera System Architecture

- Essential function: **Mimic the human visual response system**



Camera System Architecture



“Image Quality”

- A simple handle given to a **highly complex and highly convoluted concept**
- Two principal approaches, individually inadequate:
- **Qualitative analysis:**
  - Quick and easy but requiring knowledge and experience
  - Accounts for “human aspect” but inherently, highly subjective
  - Difficult/impossible to benchmark
- **Quantitative analysis:**
  - Demands a consensual, mathematical description of each quality aspect
  - Demands much investment in infrastructure and *savoir-faire*
  - Provides for target performance definitions and comparison metrics
  - But, no intrinsic insight as regards final quality perception

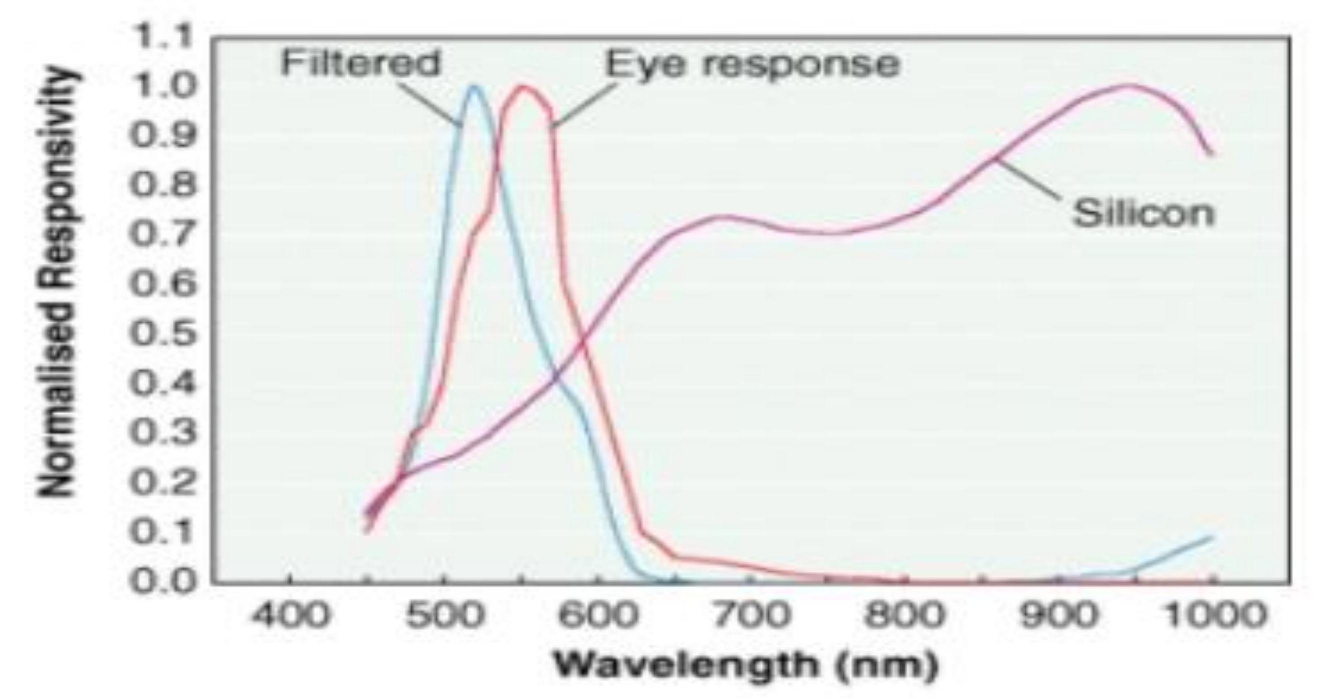
Digital Camera System Considerations

- **Image sensor**: Fundamental action: **relay spatial photon arrival rate information**
- Quality with which this action is performed may be quantitatively judged on the basis of **3 essential concerns**:

1. How efficiently are the incident photons captured and converted within visible range, i.e. **Quantum Efficiency**
2. To what extent and in what manner, the photon rate analog deviates from the ideal, i.e. **Noise and Dispersion**, and
3. The quotient of the largest allowed signal and the smallest detectable signal, i.e. the **Dynamic Range**

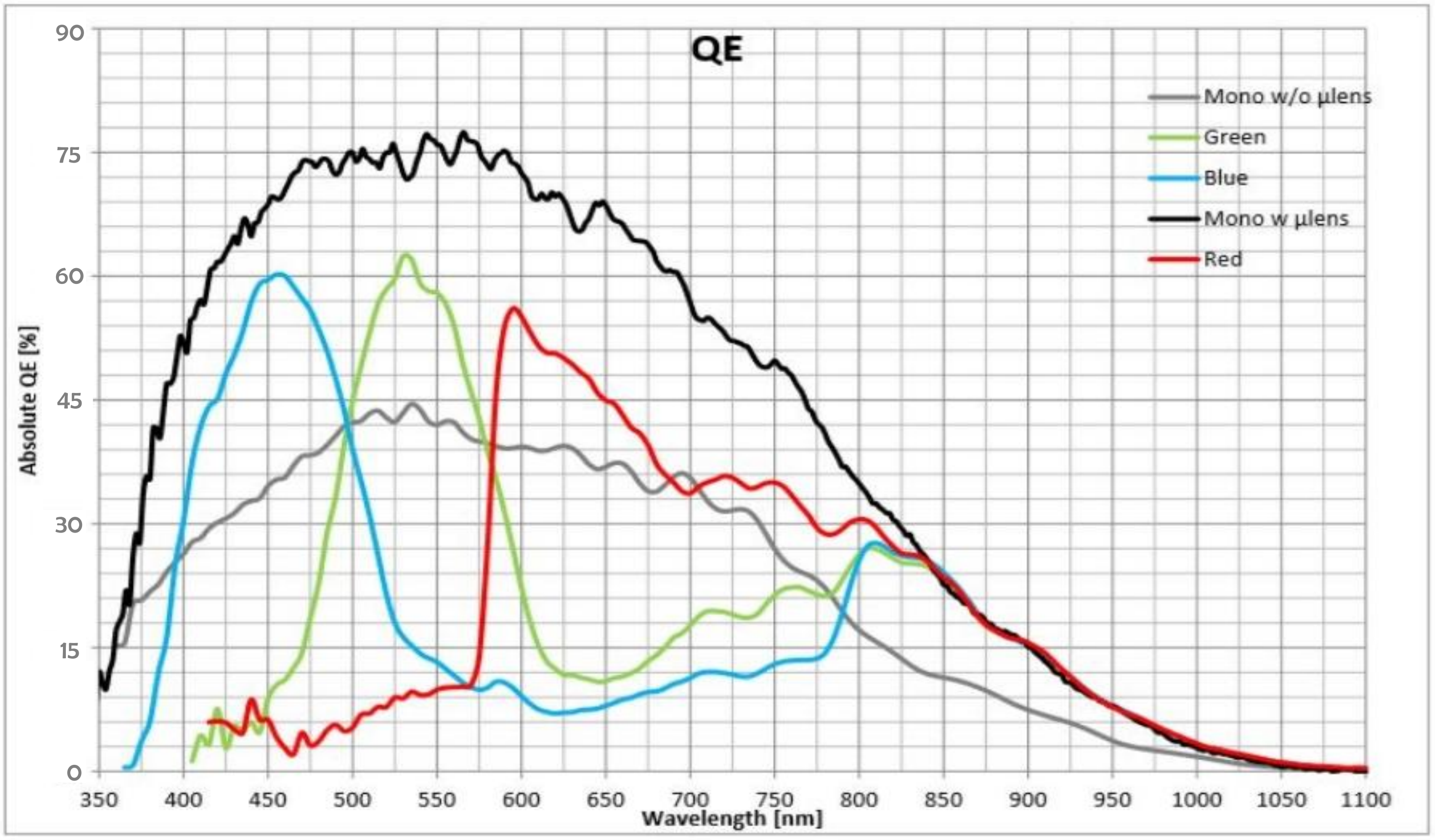
Quantum Efficiency

- Happy coincidence! Si has a spectral photo-response that quite neatly overlaps the human eye:



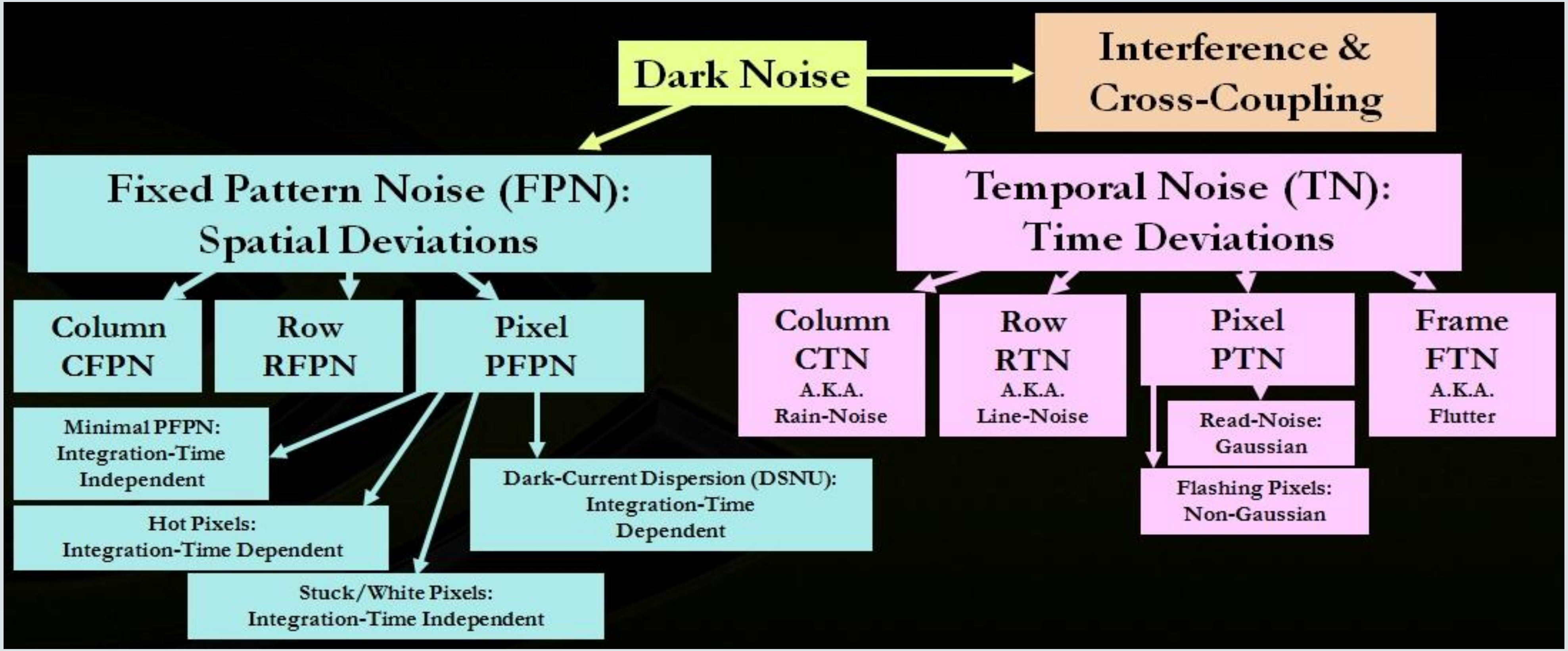
Quantum Efficiency

- Typical quantum efficiency curve from a modern CMOS image sensor
- 4.2μm pixel, FSI, 4T



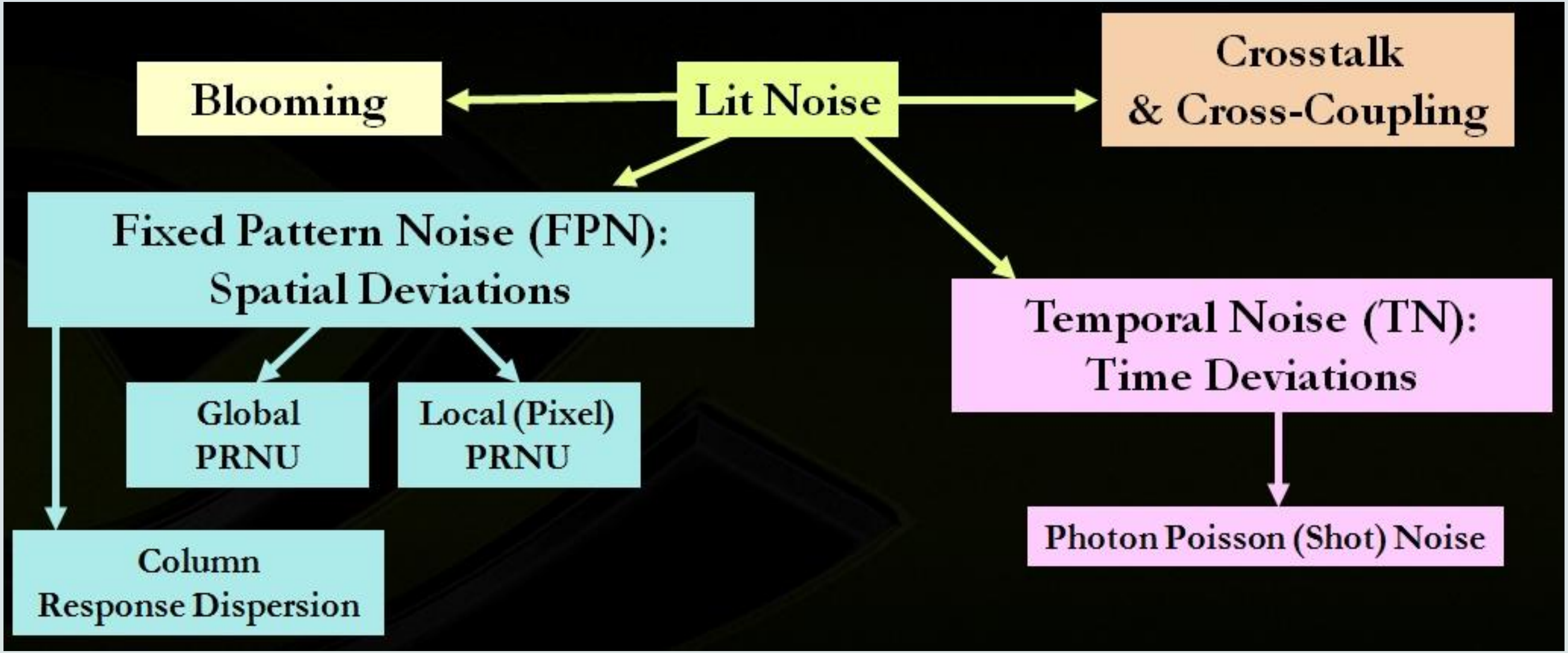
Deviancy in the Dark

- Time/space deviations in the **absence of any photo-signal**
- Highly complex. Different phenomena have **vastly varying consequences**



Lit Deviancy

- Deviations in time and space of the **representation of the photo-signal :**



Lit Noise

Blooming

Crosstalk & Cross-Coupling

Fixed Pattern Noise (FPN): Spatial Deviations

Global PRNU

Local (Pixel) PRNU

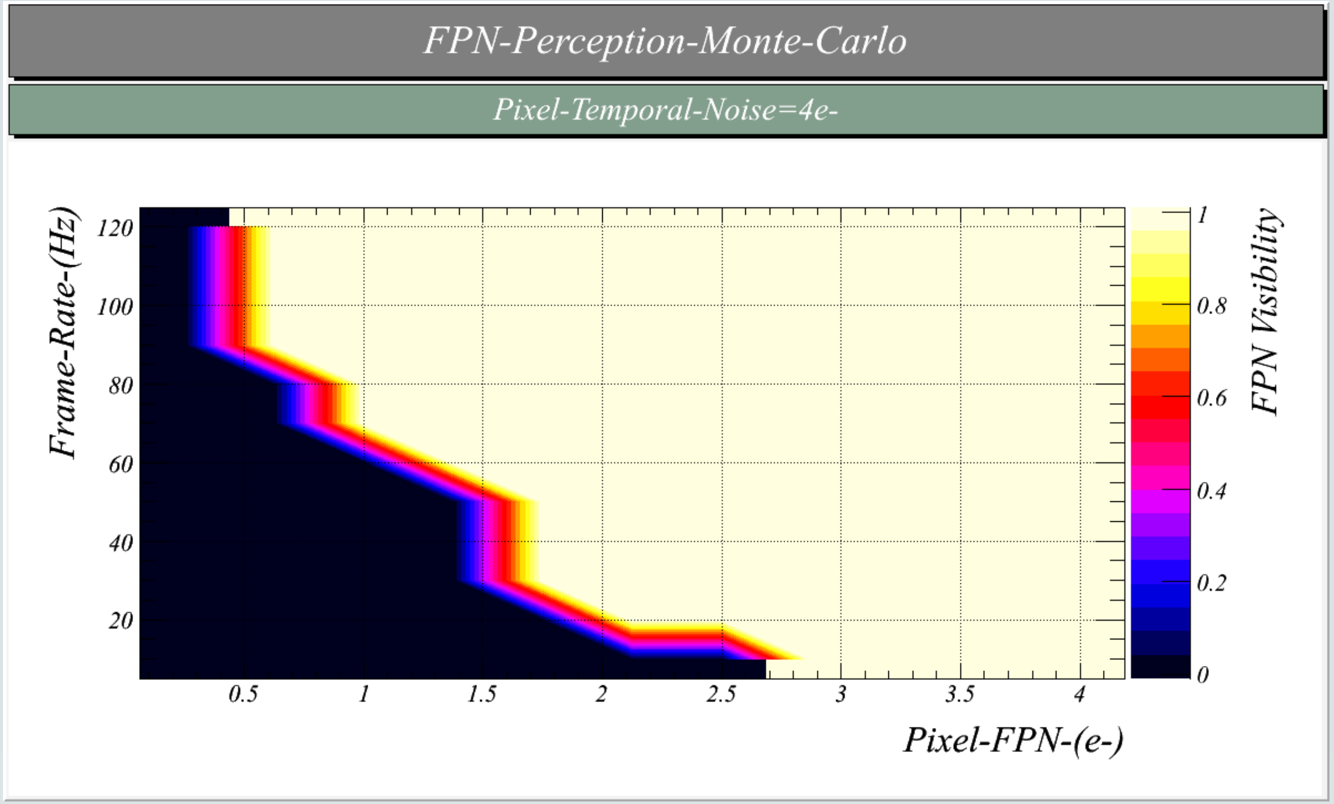
Column Response Dispersion

Temporal Noise (TN): Time Deviations

Photon Poisson (Shot) Noise

Target Performance

- Target performance for artifacts such as pixel FPN etc., determined using **psychophysics experiments**, made possible by MC simulation



Noise: Operational Zones

Total Noise as *f* (**ILLUMINATION**)

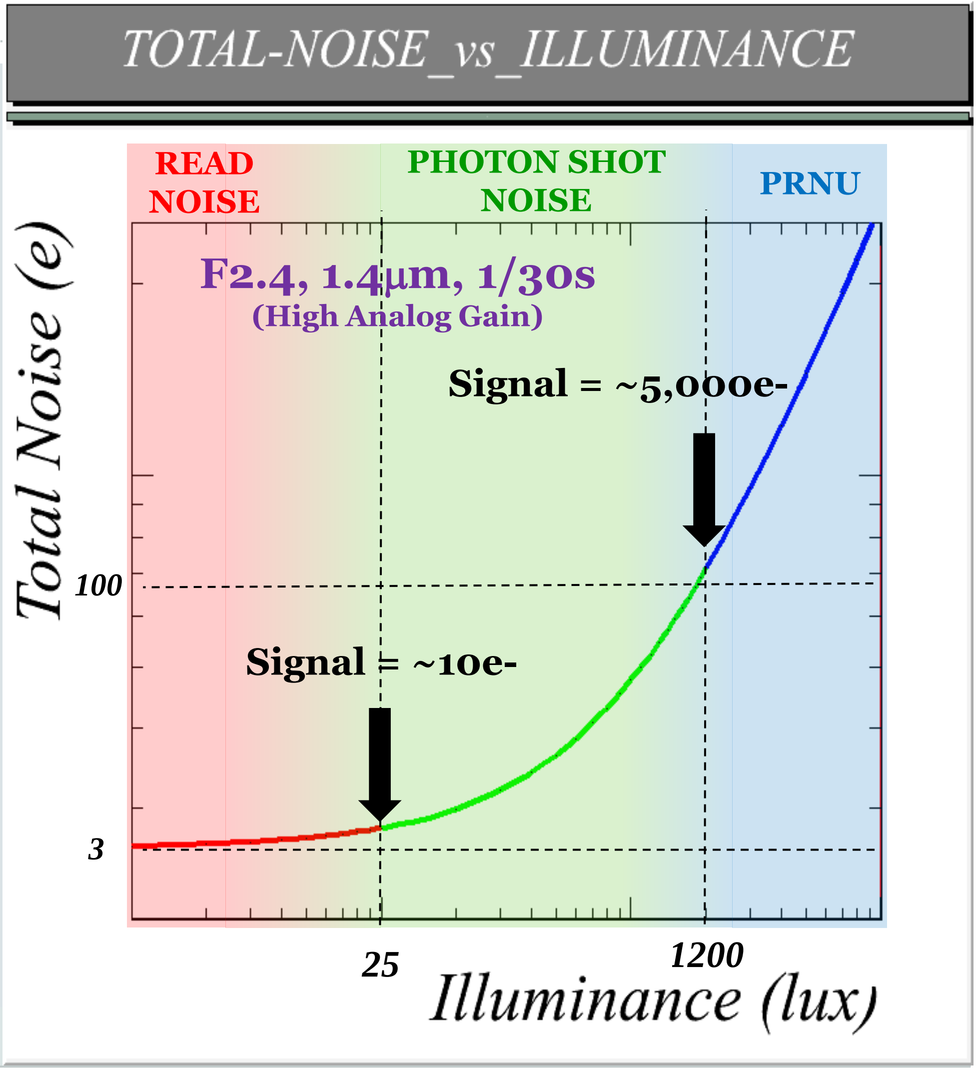
Three distinct zones:

- **Read noise** dominated: ~ Flat
- **Shot noise** dominated: Logarithmic
- **PRNU dominated: Linear region**

$$\sigma_{Total} = \surd[\,\sigma_{Sensor}{}^{2} + N_e + (PRNU_{\%} \times N_e)^2]$$

N_e = signal in e-, *PRNU* = Pixel-Response-Non-Uniformity

- **Shot noise** looks **natural**
- **PRNU** is **ugly**!



Noise: Operational Zones

Dark Noise as *f* (**EXPOSURE TIME**)

Two zones:

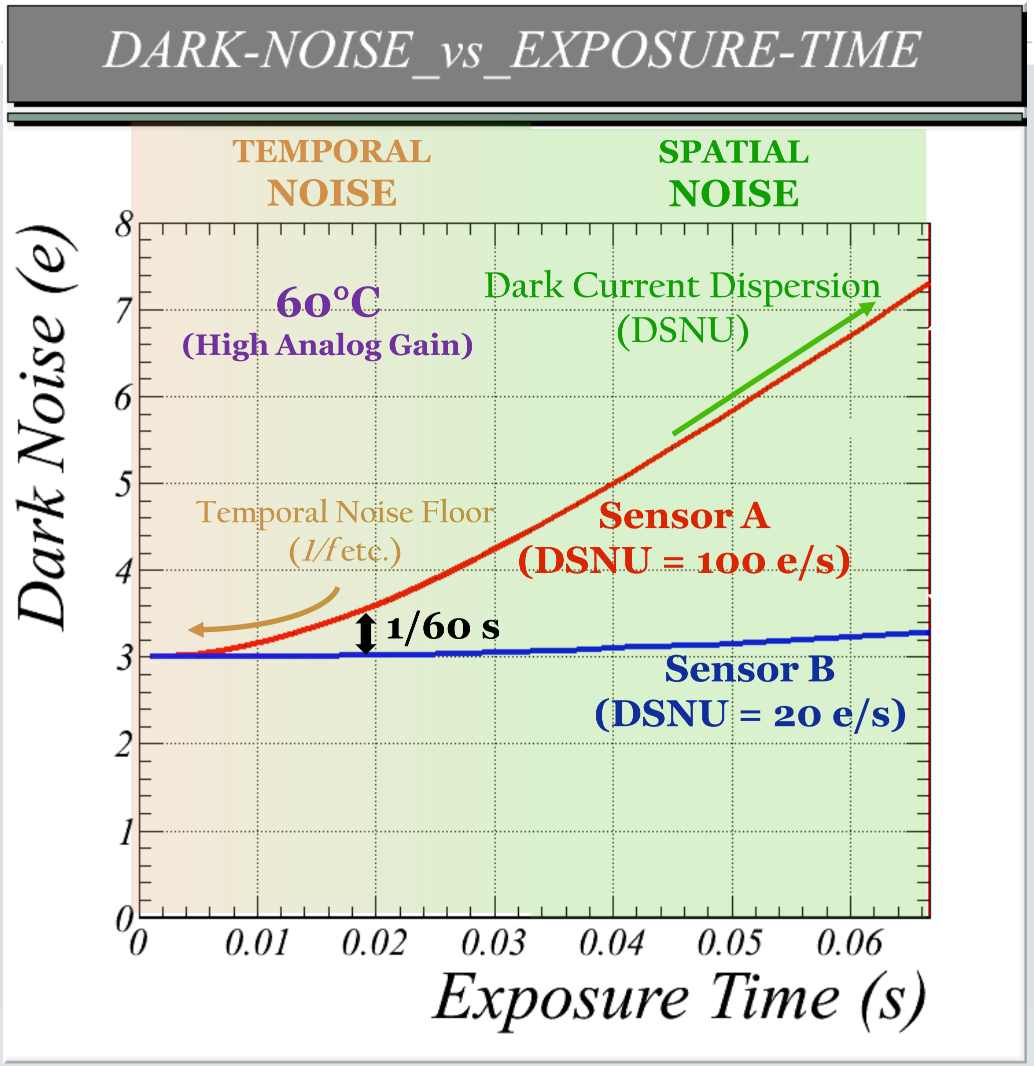
- **Temporal noise** dominated: ~ Flat
- **FPN** dominated: Linear

$$\sigma_{Dark} = \sqrt{[\,\sigma_{Temporal}{}^2 + \sigma_{Spatial}{}^2\,]}$$

$$\sigma_{Spatial} = \sqrt{[\,A^2 + t^2 \times DSNU^2\,]}$$

t = exposure time, *DSNU* = Dark-Signal-Non-Uniformity

- **DSNU** can become very **problematic** for **long exposures**



Noise: Operational Zones

Dark Noise as *f* (**TEMPERATURE**)

Two zones:

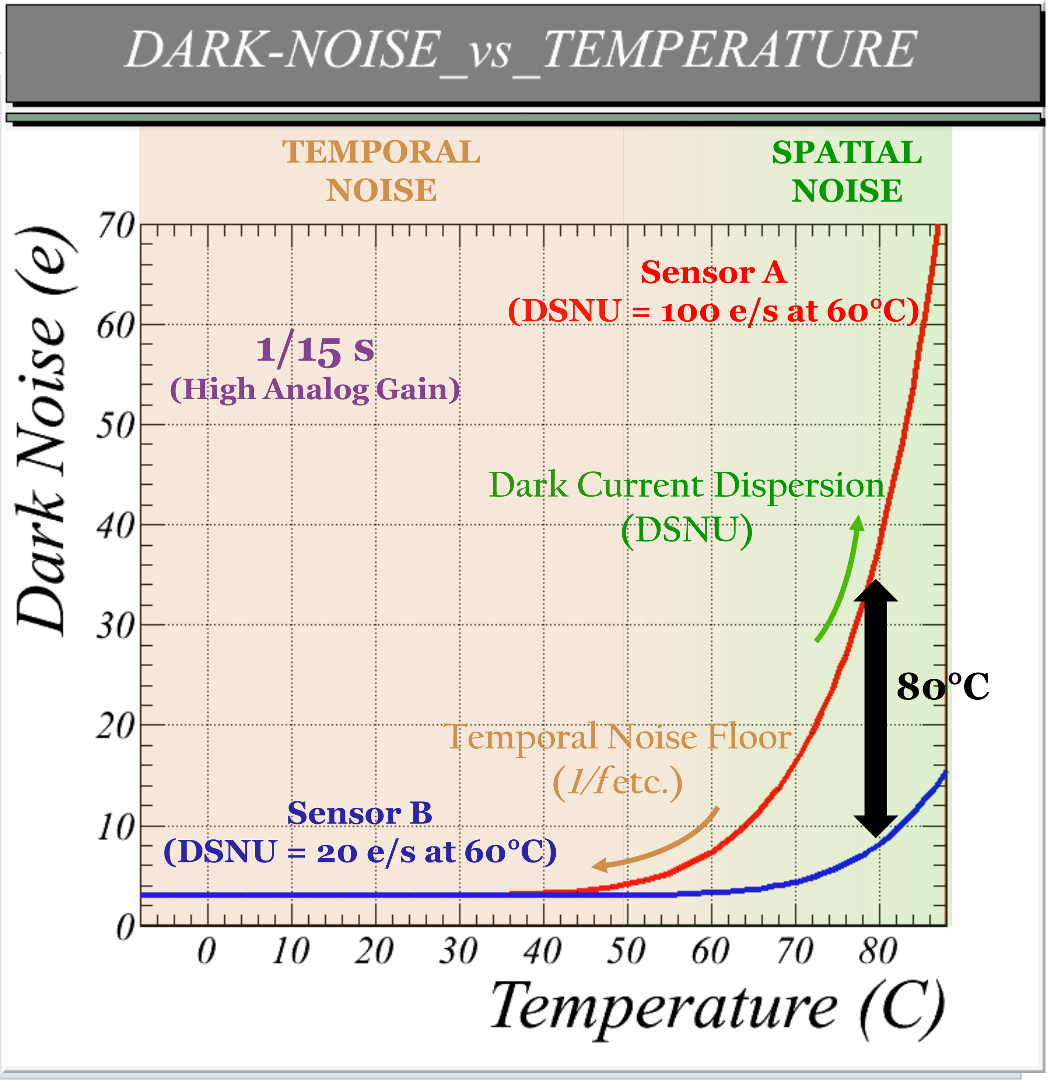
- **Temporal noise** dominated: ~ Flat
- **FPN** dominated: Exponential!

$$\sigma_{Spatial} = \surd[\,A^2 + t^2 \times DSNU_T{}^2]$$

$$DSNU_T = DSNU_{60} \times 2^{[(T-60)/8]}$$

T = temperature (°C), $DSNU_{60}$ = DSNU at 60°C

- **DSNU critical** for elevated **temperatures**!



Noise: Operational Zones

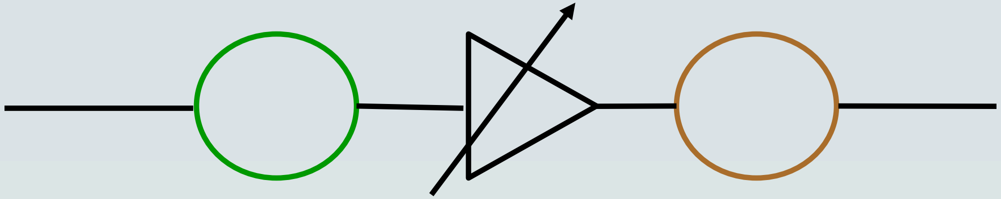
Dark Temporal Noise as *f* (**ANALOG GAIN**)

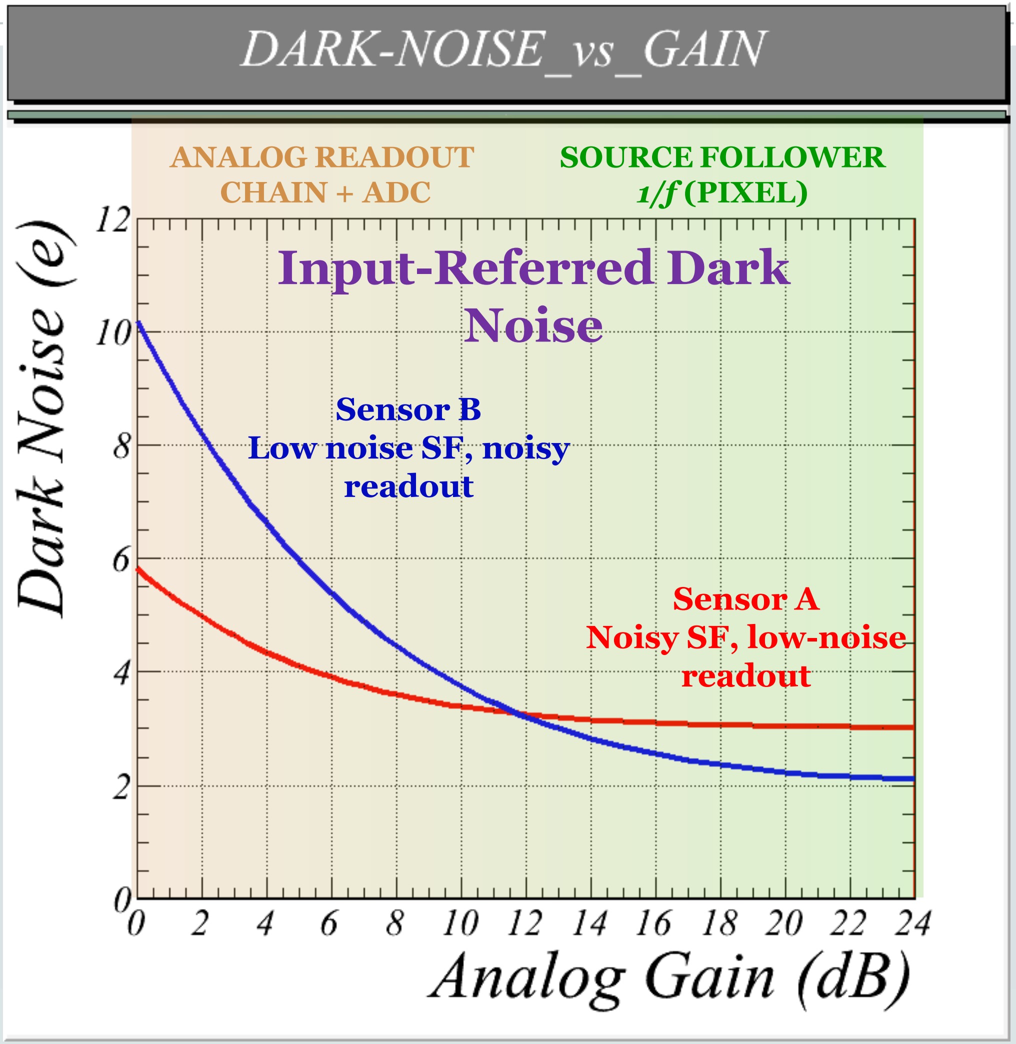
Two zones:

- **Analog chain+ADC** dominated
- **Pixel** dominated (source follower *1/f*)

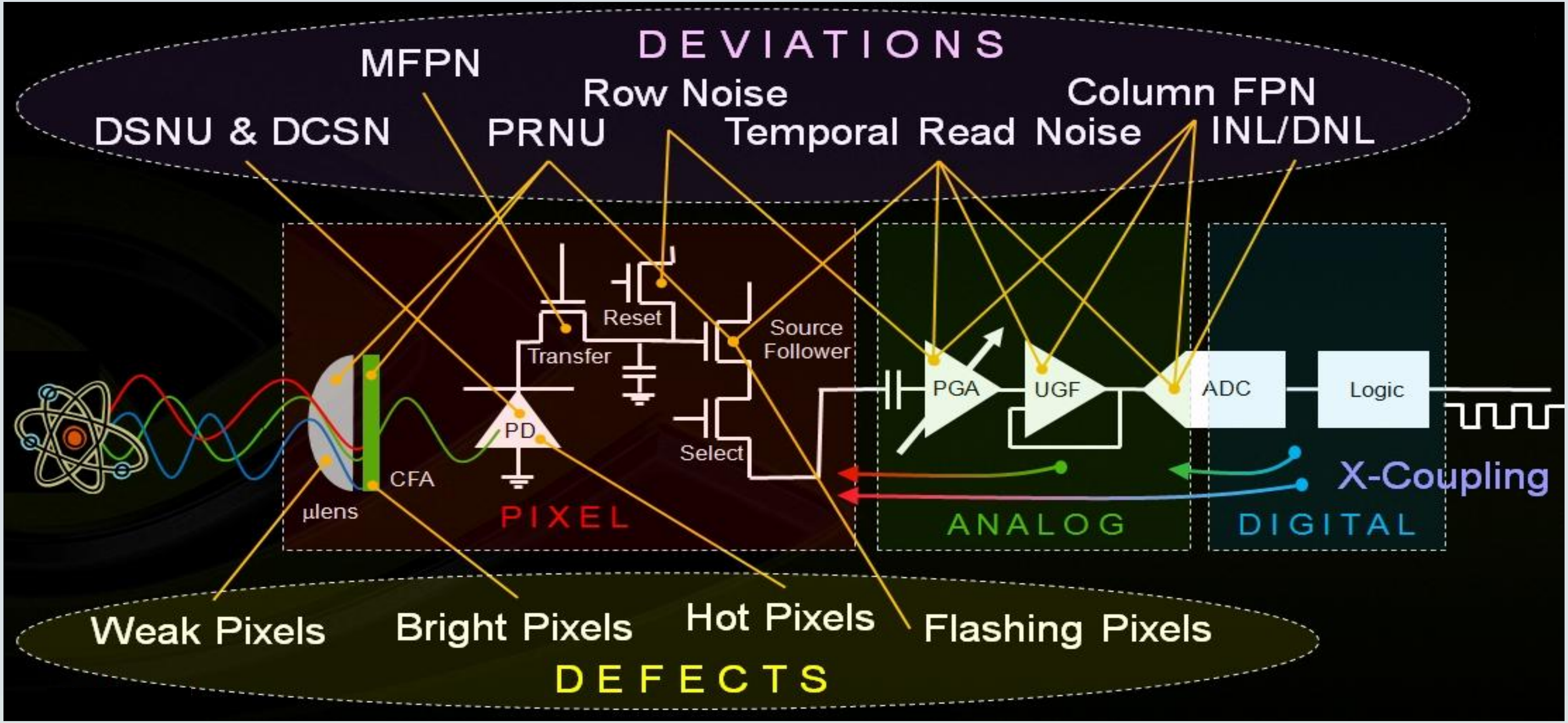
$$\sigma = \sqrt{[\sigma^2_{Pixel}/g_c^2 + \sigma^2_{Chain} \times g_f^2]}$$

g_f = conversion factor in e/DN
g_c= conversion gain in μV/e (=1/C_{fd})



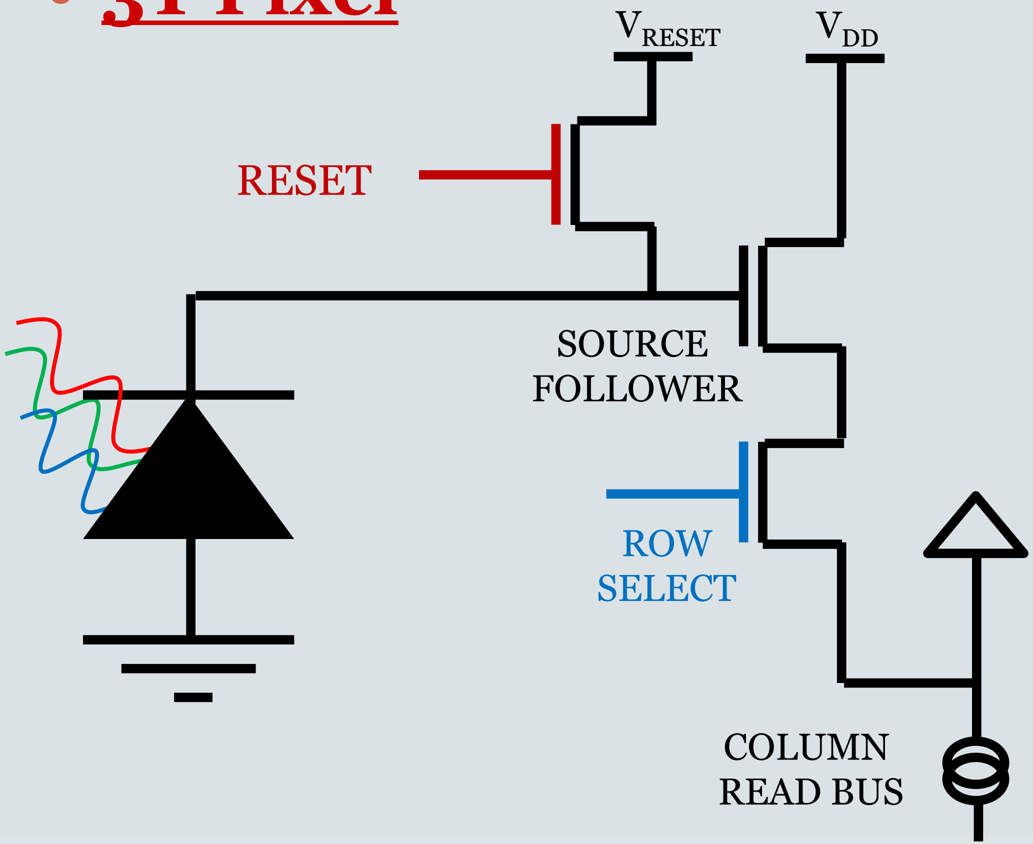


Anatomical Origins of Deviance

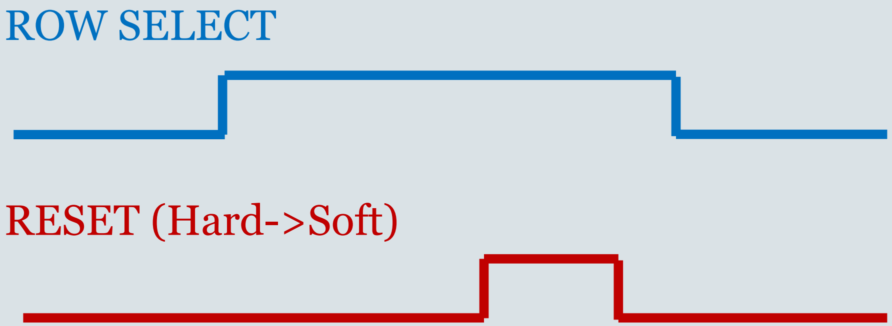


CMOS Sensor: Principles of Operation

- **3T Pixel**



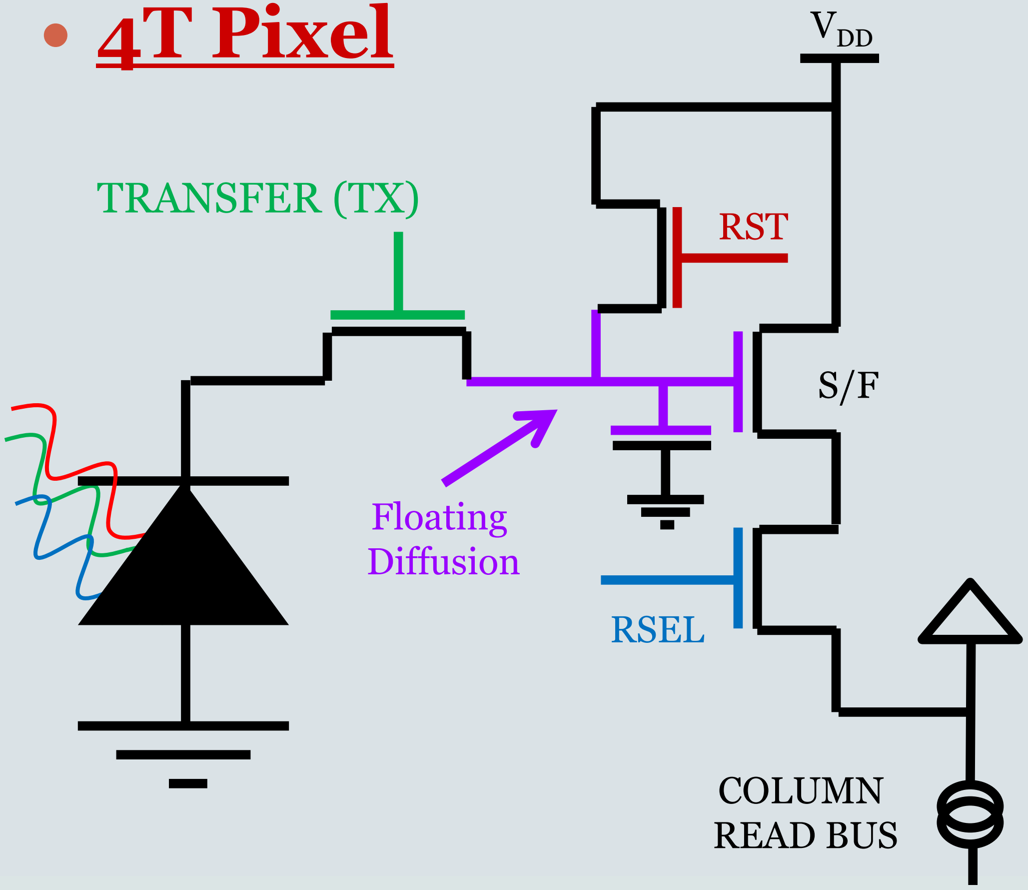
- Usually NMOS (in pixel)
- Read State Machine:
- Visits each row in turn (rolling shutter)



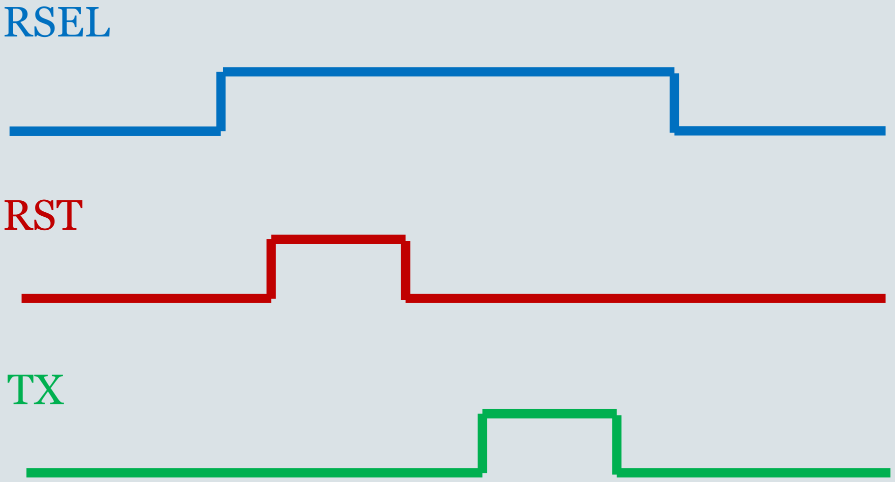
- Facilitates double-sampling (not correlated)

CMOS Sensor: Principles of Operation

- **4T Pixel**



- Addition of **transfer gate**



- Facilitates correlated double-sampling (CDS) at **floating diffusion** node

CMOS: Principles of Operation

- **3T Pixel**

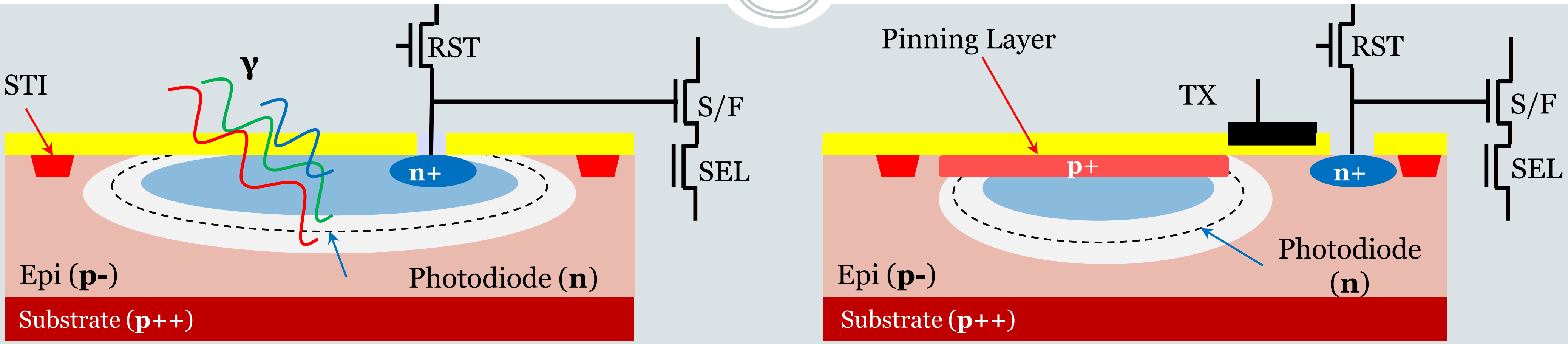
- **Advantages**
  - **Higher fill-factor**: ~negated by addition of microlens and by transistor sharing schemes for 4T (2.5T, 1.75T)
  - **Higher full-well** (charge capacity) >100,000e-: but dynamic range and S/N not necessarily better than 4T

- **Disadvantages**
  - Read noise completely **dominated by kTC noise** at photodiode since **CDS not possible**. **~30e-** (hard-soft)
  - Surface contacted photodiode has **much higher dark current**, therefore DSNU (and subsequently pixel-wise FPN) is much higher

CMOS: Principles of Operation

- **4T Pixel**: Two reset nodes (photodiode and floating diffusion), so potentially two sources of **kTC noise**
- kTC noise at floating diffusion **resolved by CDS**
- kTC noise at photodiode **resolved by pinned photodiode** (buried diffusion): Total depletion. Full well~10-20ke-
- **Buried diffusion greatly reduces dark current**, therefore much better FPN performance
- Read noise **now dominated by *1/f* noise** from the source follower. ~1e-
- Pixel engineering focused on leakage reduction at F/D and *1/f* noise reduction at S/F etc.

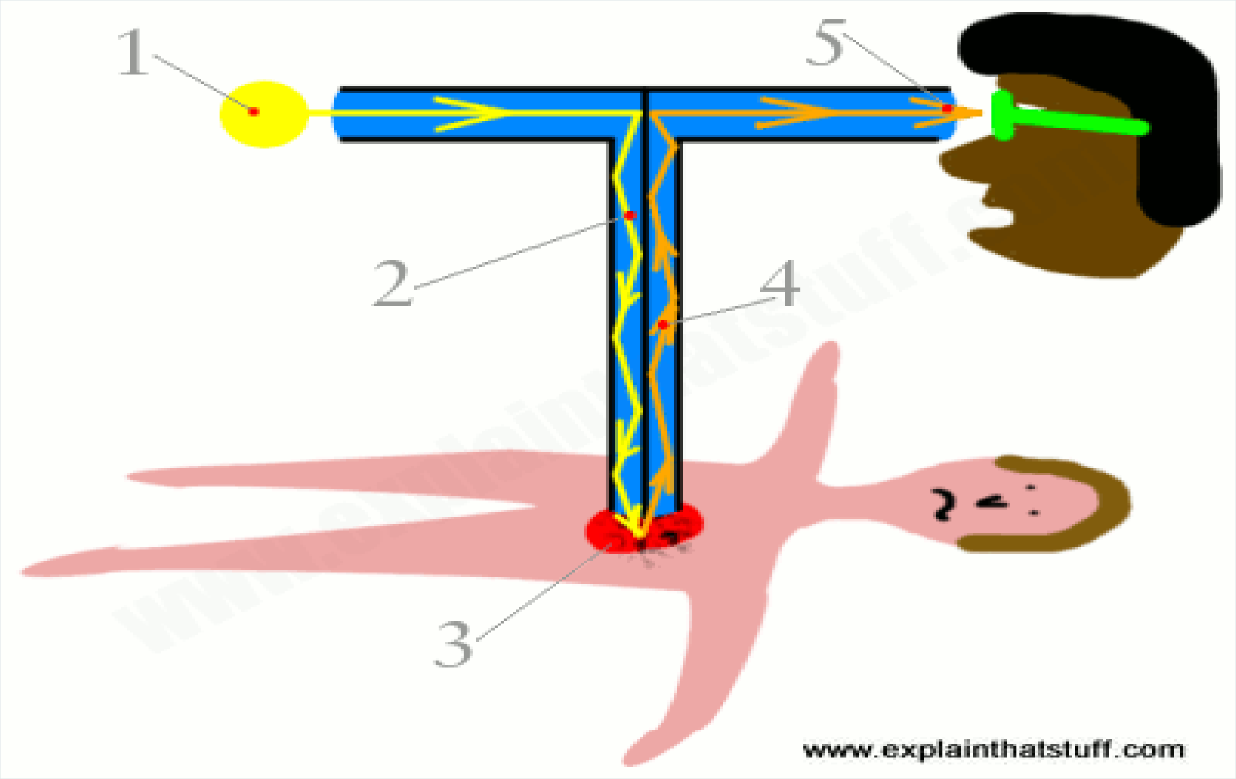
Surface vs. “Pinned” Photodiode



- **Surface photodiode** (3T) dark current:
  - ○ **~2000e-/s** at 60°C (UMC)
- **Pinned photodiode** (4T) dark current:
  - ○ **~0.5e-/s** (Sony, Panasonic, Samsung) at 60°C
  - ○ **~100e-/s** (IBM, TSMC, Tower) at 60°C

Surgical Visualization

- **Laparoscope:** Top-level Schematic:



19th Century Endoscopy

- **Originally** a means to examine via **natural orifices**
- First device: **Lichtleiter** (*Bozzini*, ***1806***)
- Illumination via **candlelight** through mid-1800s
- Introduction of alcohol/turpentine lamp enabled operative endoscopy (*Desormeaux*, ***1853***)
- First practical **esophagoscope** made possible by water-cooled, **galvanized wire illuminant** (*Mikulicz/Leiter*, ***1881***)
- Greater impact from the introduction of **platinum-wire** light source by *Trouve* in ***1873*** (urethra, bladder etc.)
- Application of **microscopy optics** and miniature Edison-style light bulb illuminant: **Huge improvements in image quality**
- 1 death reported from 150 bladder tumor removals reported in (*Nitze /Leiter*, ***final decade***)

20th Century Laparoscopy/Arthroscopy

- Air-based **insufflation** makes **first laparoscopy** procedures a reality. ***1901***: dog, ***1910***: first humans (*Kelling*)
- **First arthroscopy** also around this time with saline (*Nordentoeft*)
- **CO_2 insufflation**: Major development (*Zollikofer*, ***1924***)

- **Image transmission** via fiber bundles was introduced in ***1953*** and improved using the **rod-lens system** by *Hopkins* in ***1959***
- **Light transmission** via optical fibers provided for strong, cold light operation in ***1967***
- **CCD invention** in ***1969*** led, arguably, to the most impactful breakthrough when it was introduced in the first video endoscope in ***1983*** (by *Welch Allen*, then *Olympus* and *Pentax*)
- **Highly incremental evolution** of Laparoscopy and Arthroscopy, eventually becoming mainstream by the ***1990s*** (*Storz, Fujinon et al.)*

CMOS in Surgical Imaging

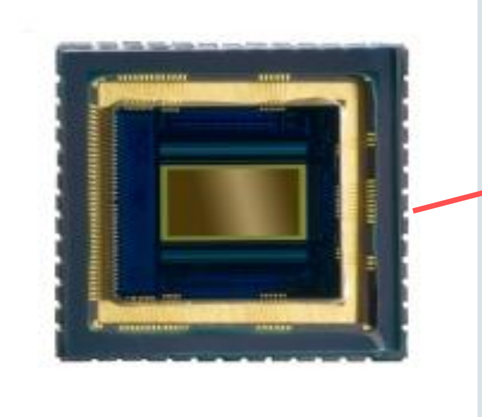
- **CCDs revolutionized surgical visualization**, providing the means for monitor-based color viewing and electronic recording
- Market domination for ~1/4 century, very high quality but very **expensive** and **complex** to operate
- By the mid-’00s, **CMOS** sensors starting to become a **more attractive** alternative.
- **Much cheaper** to procure, **integrated** design, **much lower voltage/power**, RF immune

Olive Medical Corporation

- **Olive Medical Corp.** founded in ***2008*** in Salt Lake City by 4 engineers from *Stryker* (one of the 3 biggest Worldwide players)
- They had worked on Stryker's **3-sensor CCD** systems and risked proving a **single chip CMOS** system could compete on image quality for **<< $**
- Developed their own camera head (*TCK1*) and camera system (*OVB1*) and enjoyed some success, esp. in the developing World
- **Holy grail** for laparoscopy and arthroscopy at that time was for a fully **disposable endoscope**.
- Olive system still relied on established, **very expensive rod-lens endoscopes** which unavoidably require sterilization and frequent repair operations

Three-Chip Killer!

- TCK1 Camera head based on **AltaSens 3372** CMOS sensor, designed by *Blanquart*, *Meddeler*, *Richardson* et al.
- **1920X1080** (full HD), 4T, color (*Bayer*)



Single-Use Endoscopy

- **Acquaintanceship** of Olive Medical and AltaSens Inc.
- *Laurent Blanquart* and myself **joined Olive in 2010** with *Gerrit Meddeler* working as a consultant

- Brought with us **CMOS image sensor design capability**, unique for a medical device company. Also high-end imaging knowledge and experience
- Leveraged our capabilities and know-how to develop a solution to the "holy grail" and create a **truly disposable** lapara/arthro-scope solution ($6000 → $30)
- **Impossible to achieve** a color, high definition quality system **with any off-the shelf sensor** at that cost

Disposable HD Surgical Endoscopy: Approach

KEYS

- **Light-deficient** environment

  → **Total control** of illumination

- **Eliminate** expensive **rod-lens** assembly (several k$)
- **Create custom image sensor design**, small enough to fit on the tip of a 4mm scope, with a cheap (plastic) lens assembly (few $)

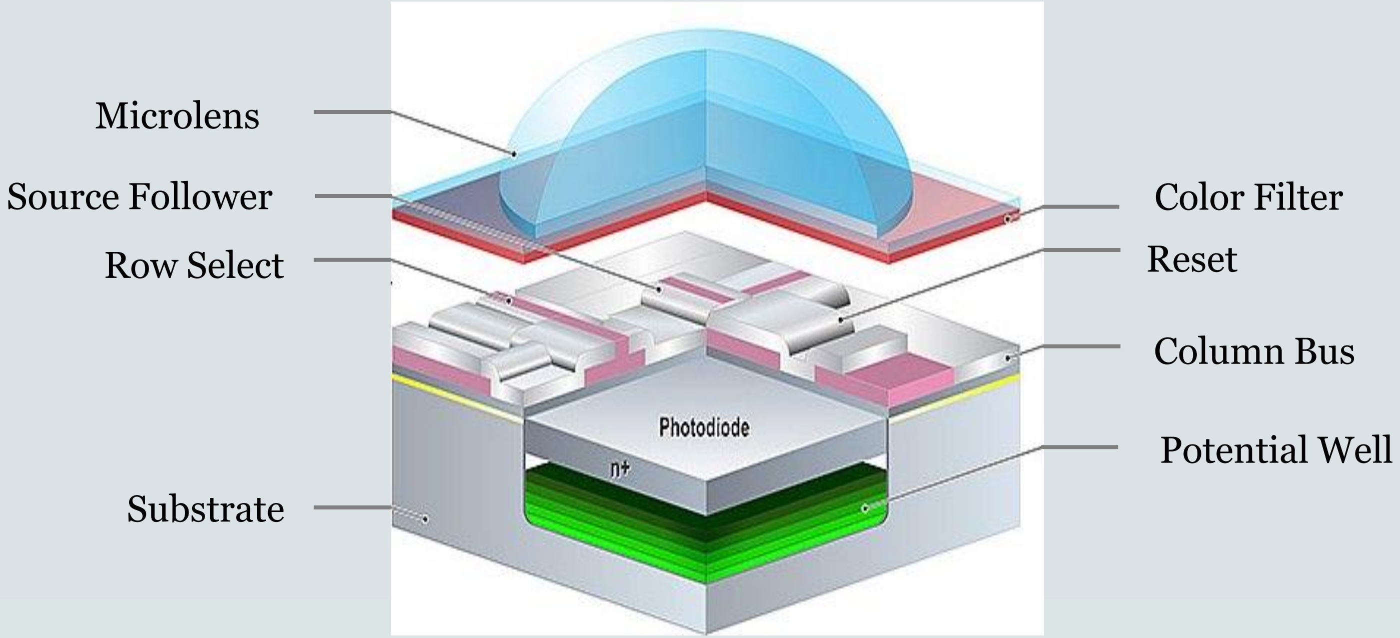
  → Figure out how to get **HD-equivalent resolution** with smaller pixel count (and reasonably big pixels to meet the dynamic range and quality demands)

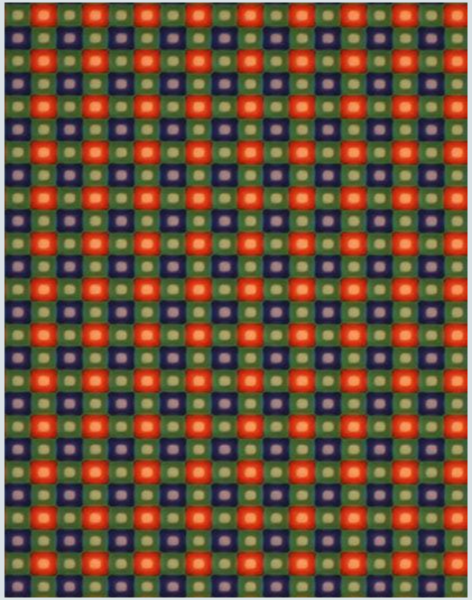
  → **Reduce the pad count** to an absolute minimum

- Develop a **strong relationship** with an R&D-friendly **foundry!**

Sensor: Optical Front End

- Modern image sensors have organic **microlenses** above each pixel to alleviate fill factor (FSI: typically 40%)
- Color sensors used in single-chip cameras also have color filter arrays (CFA), arranged in the ***Bayer* pattern**. RGB info. is recovered for each pixel digitally in the image signal processer (ISP): **Demosaic**





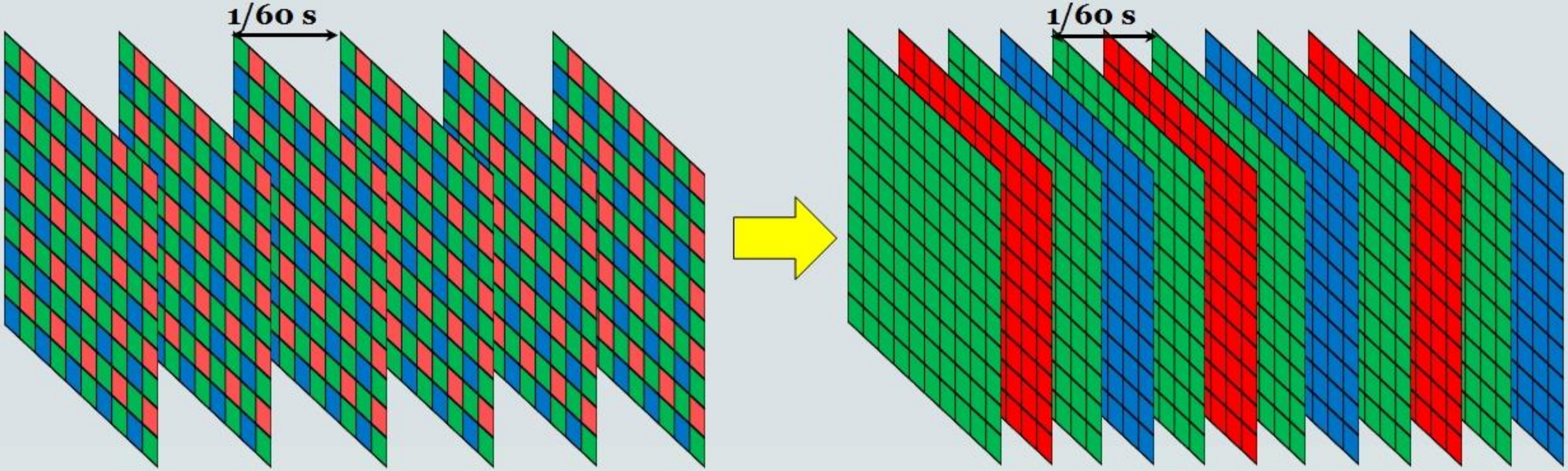
Single-Use HD Arthroscope: Approach

- Had to **target** a **spatial resolution** that could defensibly be called **HD**
- Two popular HD progressive formats: **1080P** and **720P**
- Color discrimination based on Bayer pattern sacrifices some spatial resolution (factor 1/√2), but cameras based on a **single color sensor** with **1280×720** pixels are **marketed as HD**
- Therefore we **targeted** the MTF of a **720P Bayer** sensor-based camera

- But! **Desire/need** for relatively **large pixels** (~3µm) and space constraints (2.4mm □) would inevitably mean **fewer than 720 rows**
  - **How to get HD equivalent resolution?**

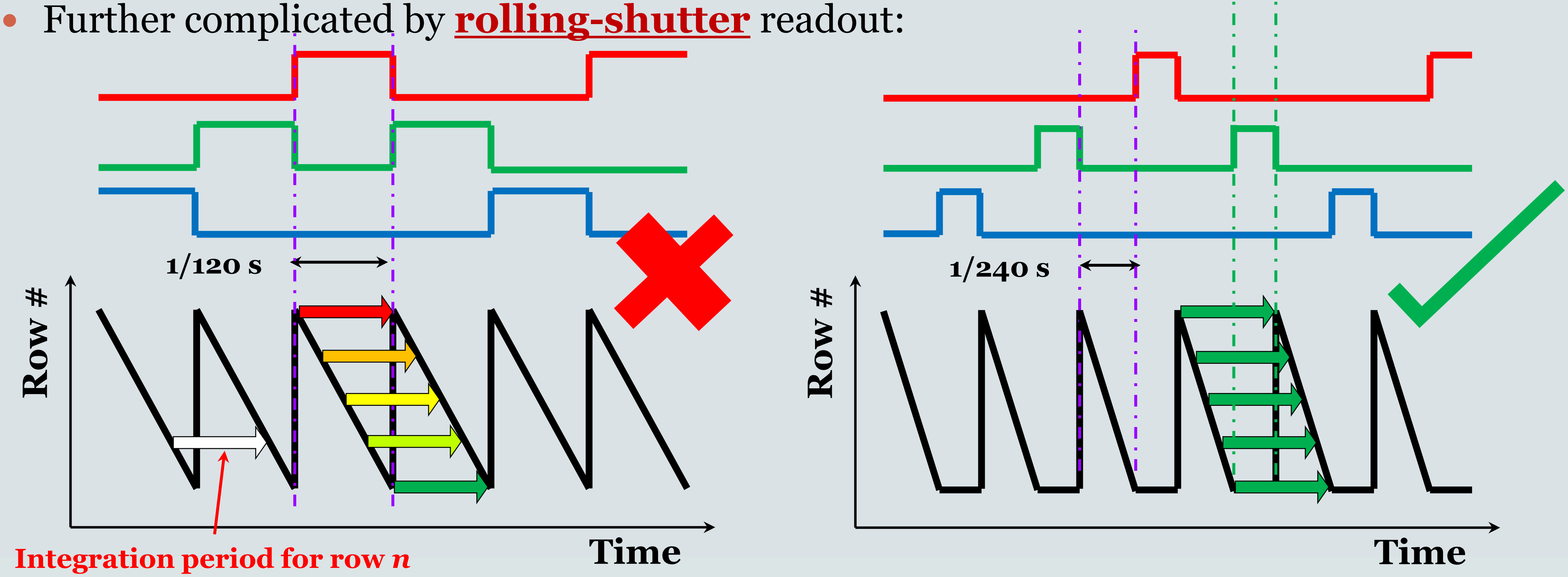
Single-Use HD Arthroscope: Approach

- First step was to **dispense with the Bayer pattern** and go with monochrome sensor
- Since we control the illumination, realized we could **derive the color information temporally** instead of spatially
- That meant illuminating different frames with different color components of light, i.e. **monochromatic pulsing**



Single-Use HD Arthroscope: Approach

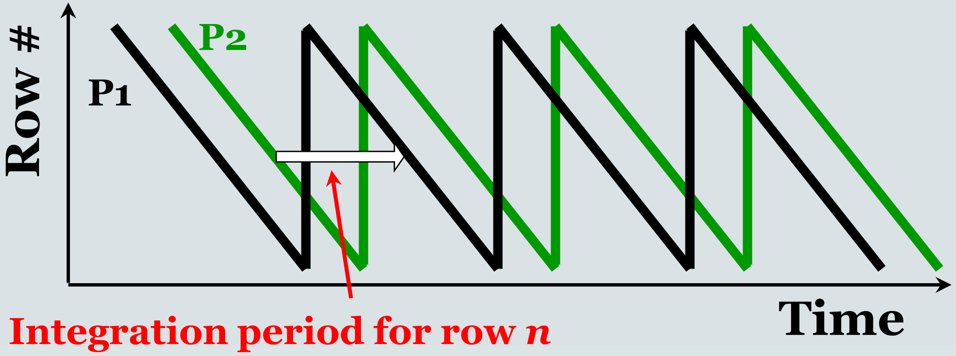
- **Conventional** illuminants are **continuous** and **broad-spectrum** (Xe)
- New approach would **require fast pulsing** capability
- Further complicated by **rolling-shutter** readout:

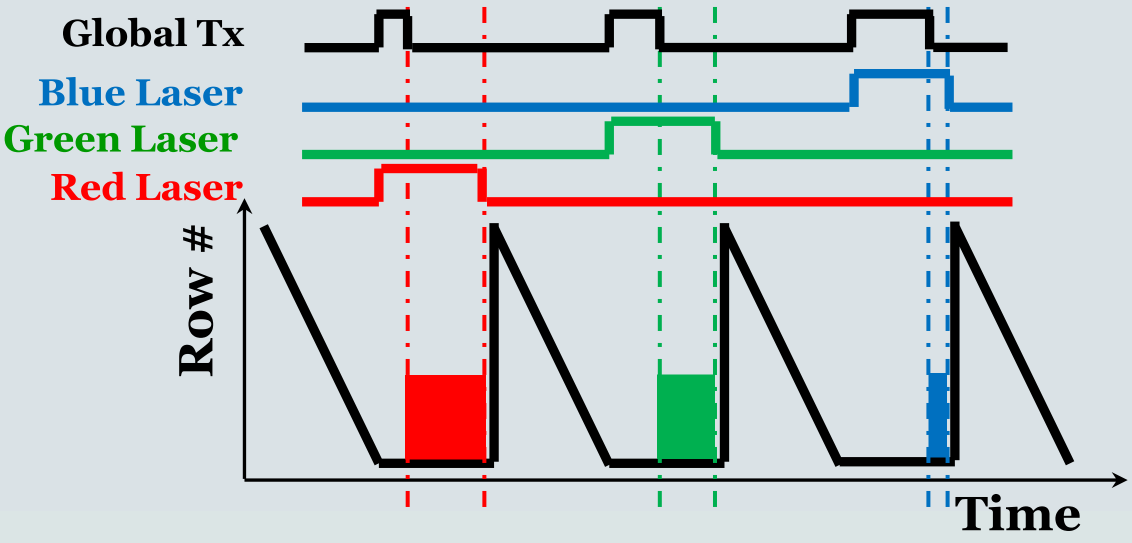


Single-Use HD Arthroscope: Approach

- Pulsed illumination → **LEDs** or **Lasers**
- **Limited available time** to pulse & only one component at a time pushed us toward lasers (**collimated** → efficient transfer of energy through fibers)
- However, **no prior experience**, so developed a relationship with *Necsel Inc*. to prototype a laser illumination system
- Also needed an **alternative approach to auto-exposure**! Used **global Tx** operation to dictate the effective beginning of the integration period

Conventional Auto-Exposure
2 Vertical Pointers



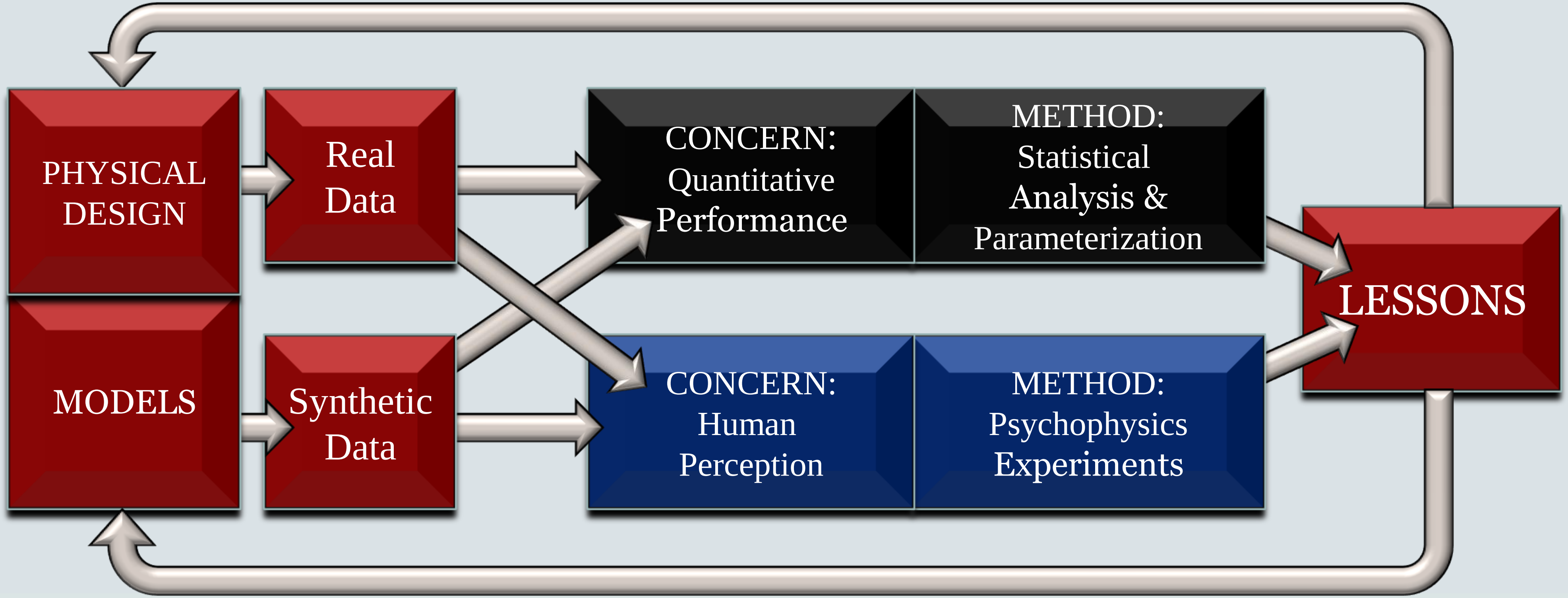


Single-Use HD Arthroscope: Approach

- **Final** displayed **image is 1080P** so wanted simple scaling factor; simulated 360 and 540 row count. Settled on **405×405** =1080 * 3/8
- Striving for 2.4mm chip edge required **several innovations**, e.g.
- **Pad count reduced to absolute minimum** (**10**): (*US 2014/0275783A1*)
  - **Single bi-directional data port**; 1Gbps sub-LVDS out / 2-pin I2C in
  - Image data ping-pong between 2 ADCs (DDR)
  - **No clock out**, special serial data encoding & CDR at receiving FPGA
  - **Consolidation of** analog and digital **supplies** (DC-DC up-converter)
  - **Encoding of register readback into image** (readback mode)
- **Minimization of digital logic** (*US 2013/052423*)
  - Normal iSoC sensor datapath processes such as Blackclamp moved to FPGA (“Front-End ISP”)

Modeling and Evaluation

- **Integrated approach** to **modeling** and **evaluation**
- **Tight** feedback loop: **Design→Evaluation→Design**



PHYSICAL DESIGN

MODELS

Real Data

Synthetic Data

CONCERN: Quantitative Performance

METHOD: Statistical Analysis & Parameterization

CONCERN: Human Perception

METHOD: Psychophysics Experiments

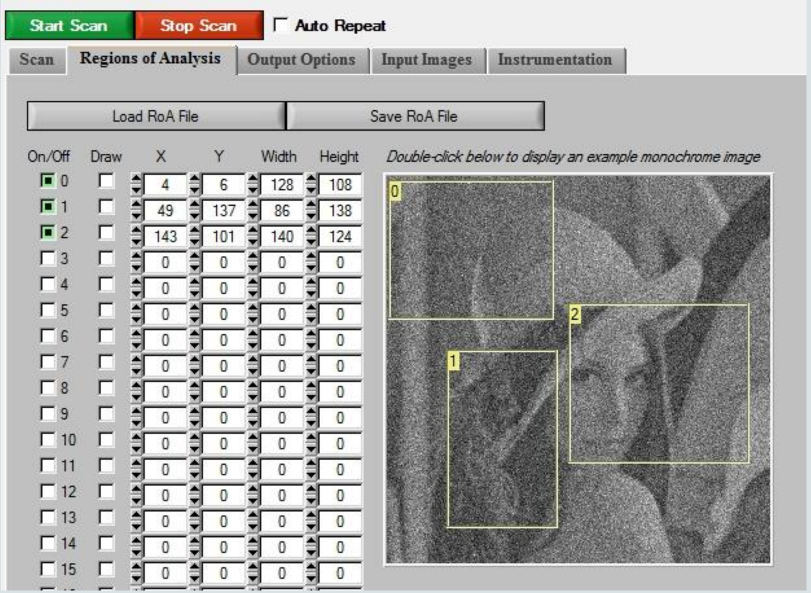
LESSONS

Sensor and Camera Evaluation: ARES

- Two large C/C++ applications: **ARES** and **ARTEMIS**
- **ARES**: **A**pplication for **R**&D of **E**ndoscopic **S**ystems
- Automated scanning and image data analysis
- Used for **characterization** and **parametric tuning** of e.g. pixel biases for optimal FPN, temporal noise and lag
- Automatic **deconvolution of** all 13 **noise spatial and temporal components** (per Bayer channel, ADC etc.)
- Fully tunable **defective pixel identification** and counting
- Uses **XML files** to dictate physical system protocol, GUI layout, settings and scan conditions:
- This facilitates easy reproduction of old scans
- Online, **real-time plotting** of data (histograms, projections, maps)
- Various output formats for digestion by specific offline analysis scripts

ARES

- Region of Interest selection and online plots:



On/Off	Draw	X	Y	Width	Height
☒ 0	☐	4	6	128	108
☒ 1	☐	49	137	86	138
☒ 2	☐	143	101	140	124
☐ 3	☐	0	0	0	0
☐ 4	☐	0	0	0	0
☐ 5	☐	0	0	0	0
☐ 6	☐	0	0	0	0
☐ 7	☐	0	0	0	0
☐ 8	☐	0	0	0	0
☐ 9	☐	0	0	0	0
☐ 10	☐	0	0	0	0
☐ 11	☐	0	0	0	0
☐ 12	☐	0	0	0	0
☐ 13	☐	0	0	0	0
☐ 14	☐	0	0	0	0
☐ 15	☐	0	0	0	0

Double-click below to display an example monochrome image

Current Stage: 0 0 Time Remaining: 0 : 00 : 00

All Pixels Region of Analysis 0 Raster Order: Horizontal Vertical

MEAN SIGNAL Range Mode Peak to Peak From 31.36 To 38.64

Mean 34.56 Sigma 0.69 Fitted Mean 34.51 Fitted Sigma 0.69 Lowest 32.20 Highest 37.80

NOISE Range Mode Peak to Peak From -0.46 To 3.51

Mean 1.06 Sigma 0.37 Fitted Mean 0.97 Fitted Sigma 0.37 Lowest 0.00 Highest 3.05

Current Stage: 0 0 Time Remaining: 0 : 00 : 00

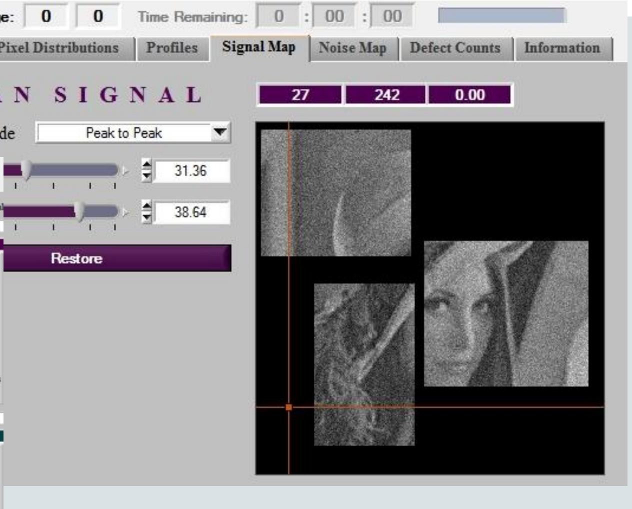
All Pixels Region of Analysis 0

COLUMNS Range Mode Peak to Peak From 33.33 To 35.66

Mean 34.56 Sigma 0.42 Fitted Mean 34.56 Fitted Sigma 0.47 Lowest 33.60 Highest 35.39

ROWS Range Mode Peak to Peak From 34.35 To 34.79

Mean 34.56 Sigma 0.08 Fitted Mean 34.56 Fitted Sigma 0.09 Lowest 34.40 Highest 34.74



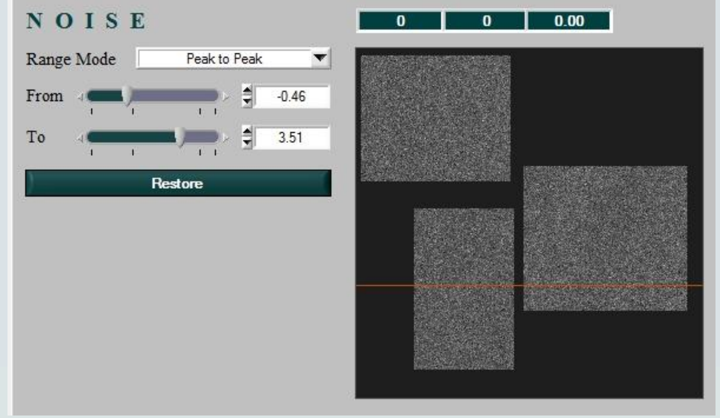
Current Stage: 0 0 Time Remaining: 0 : 00 : 00

MEAN SIGNAL 27 242 0.00

Range Mode Peak to Peak

31.36

38.64



Time Remaining: 0 : 00 : 00

NOISE 0 0 0.00

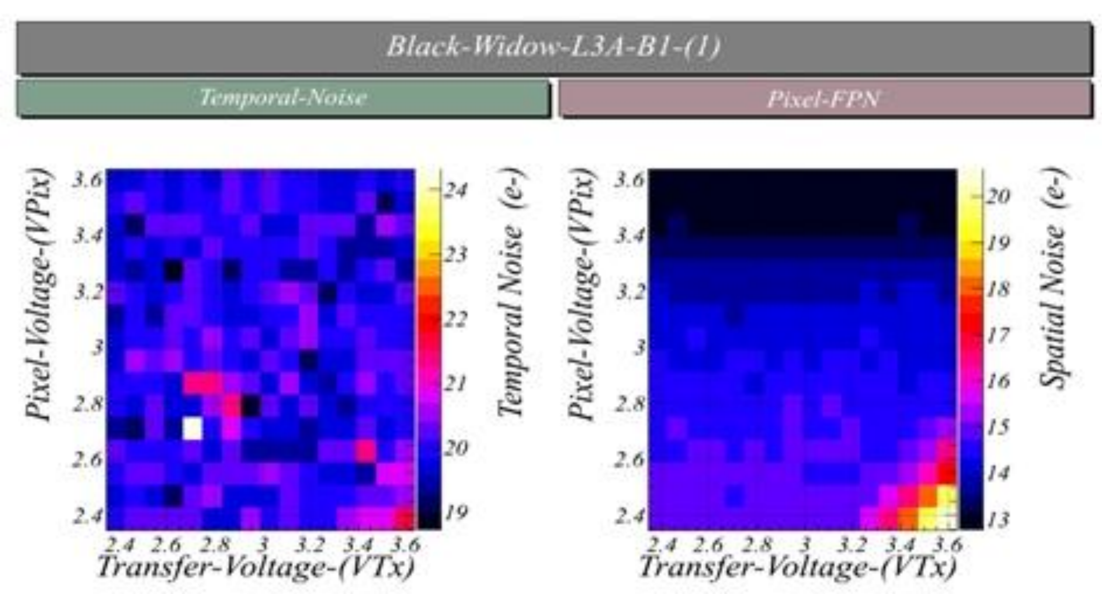
Range Mode Peak to Peak

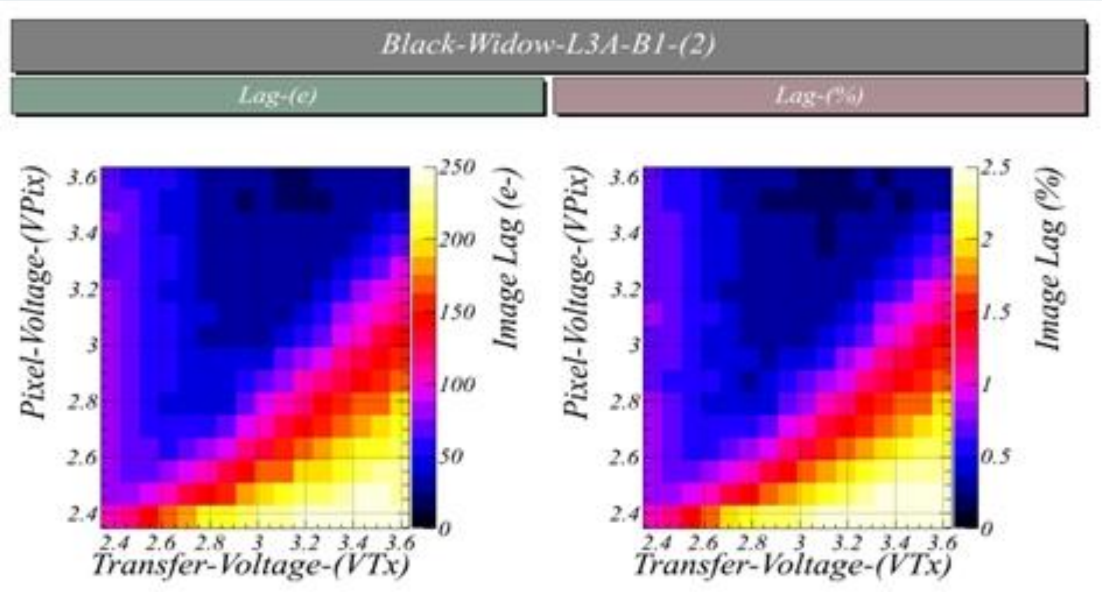
From -0.46

To 3.51

ARES

- **Sensor tuning** examples
- **2D scanning capability** used to build up **maps of e.g. noise and image lag** versus pixel voltages



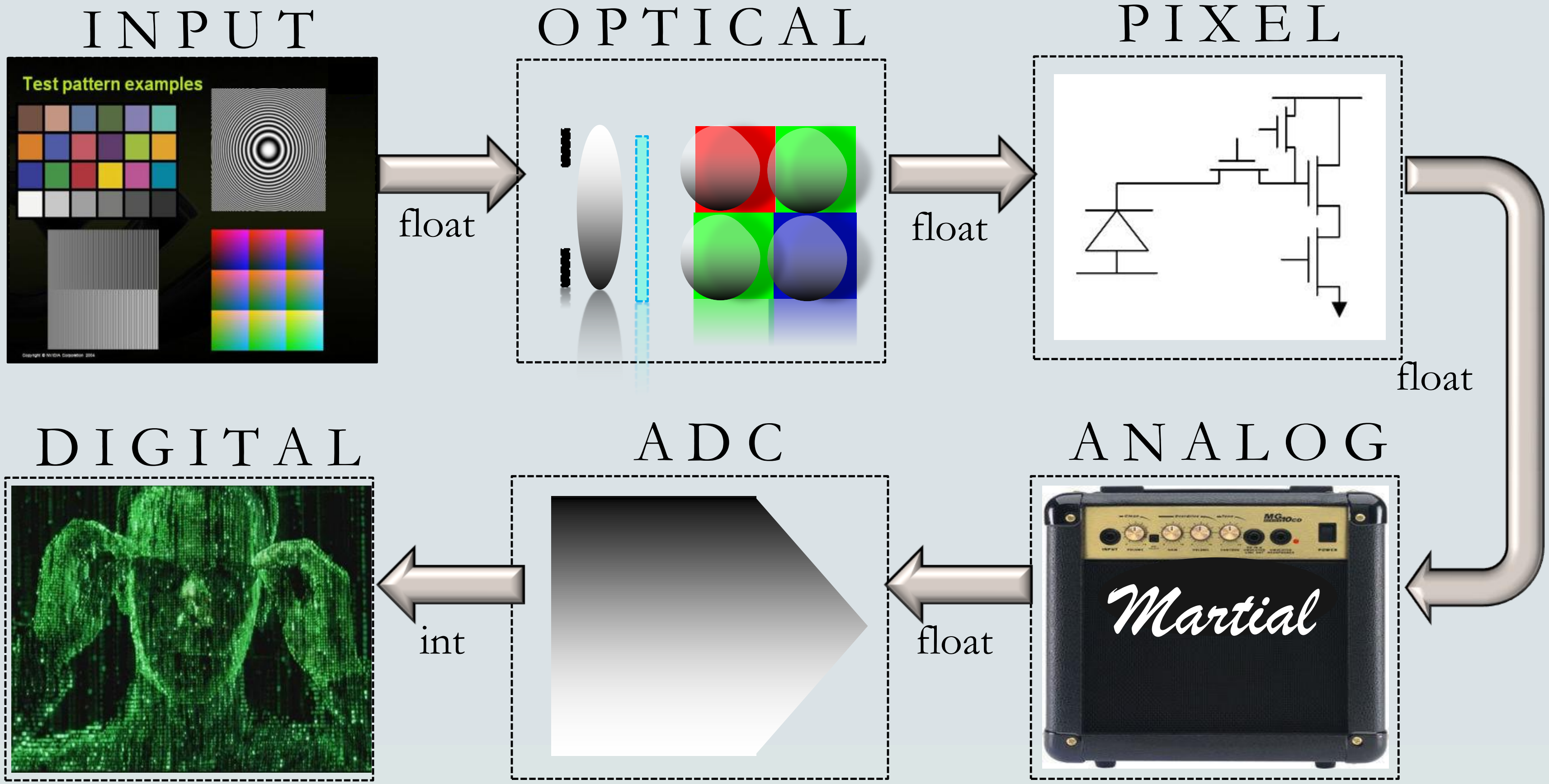


Full Camera C-Model: ARTEMIS

- **ARTEMIS: A**ppa**R**a**T**us for **EM**ulating **I**maging **S**ystems
- **Phenomenological C-model** of full camera chain
- **Optics** + **Sensor** + **ISP**
- Used to
  - **Simulate** different **sensor design** options
  - **Develop** and evaluate **ISP architectures**
  - **Create** and test image **processing algorithms**
  - **Test ARES**
- May take **real** images **or** create **synthetic** image **data**
- **Monte Carlo noise generation** drawn from realistic PDFs
- Facilitates **bit-correct C-Model** representations → RTL

ARTEMIS: SENSOR MODULE

- Sensor Model:



INPUT

float

OPTICAL

float

PIXEL

float

ANALOG

float

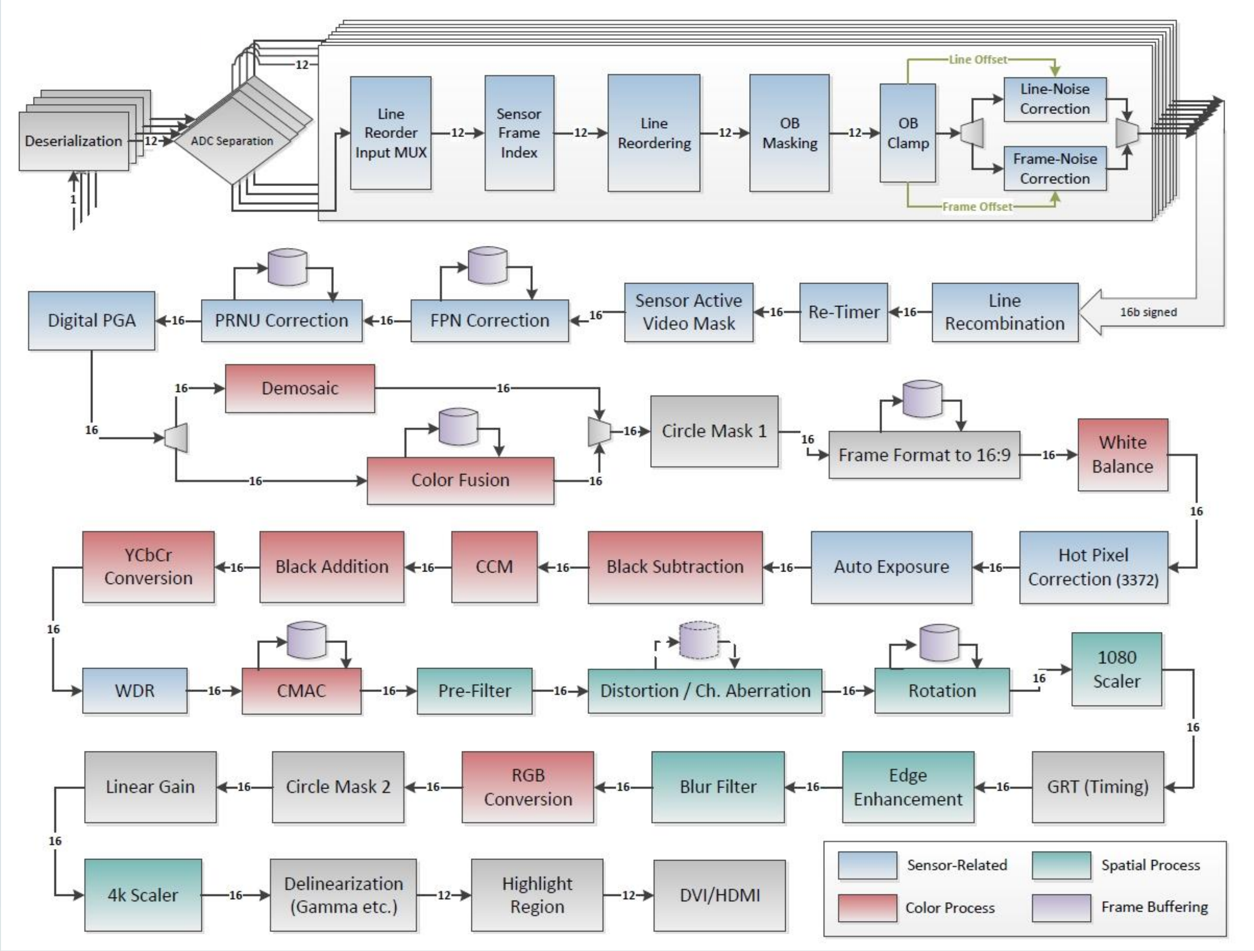
ADC

int

DIGITAL

ARTEMIS: IMAGE SIGNAL PROCESSING (ISP)

- ARTEMIS **ISP Model**:
- Top 2 rows: Low level **sensor corrections** (normally iSoC resident)
- Red blocks are **color processes**
- Green: **spatial/filtering processes**



ARTEMIS: MONTE CARLO PROCESSES

- **Data, *v***, from a given pixel (for column c, row r and frame f)

$$v_{c,r,f} = d_{c,r,f} + p_{c,r,f}$$

- **Dark offset, *d***:

$$d_{c,r,f} = o + C_c^s + C_{c,f}^t + R_r^s + R_{r,f}^t + P_{c,r}^s + P_{c,r,f}^t$$

- **Photosignal, *p***:

$$p_{c,r,f} = (q_{c,r} + \delta_{c,r,f}) \cdot G \cdot C_c^g \cdot R_r^g \cdot P_{c,r}^g$$

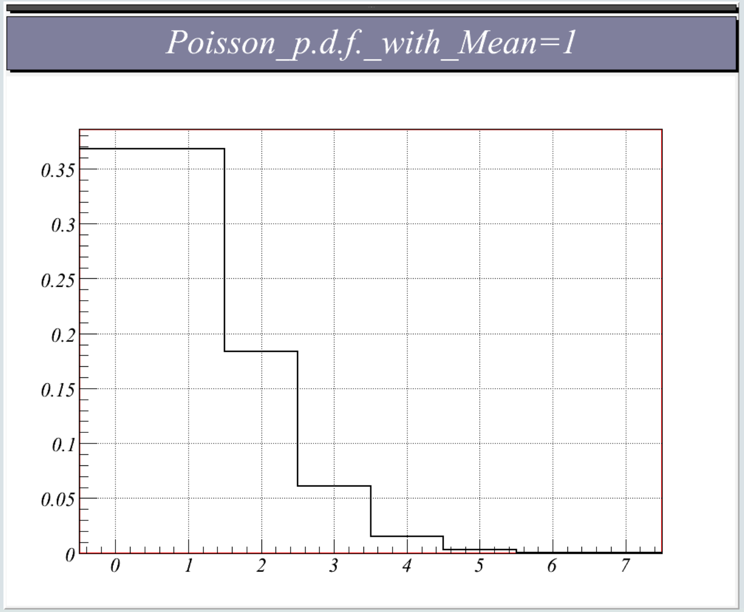
- Distilled expression containing important components:

$$v_{c,r,f} = o + \left(C_c^s + P_{c,r}^s\right) + \left(R_{r,f}^t + P_{c,r,f}^t\right) + G \cdot C_c^g \cdot P_{c,r}^g \cdot (q_{c,r} + \delta_{c,r,f})$$

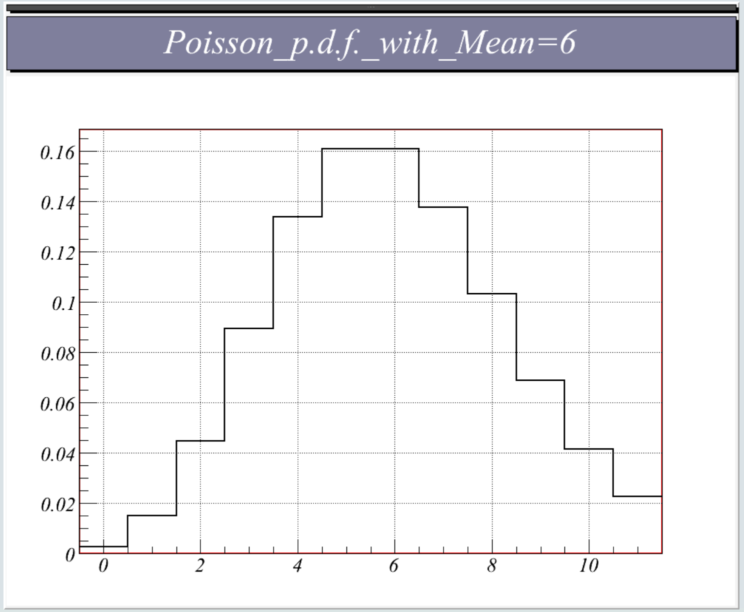
ARTEMIS: MONTE CARLO PDFs

- Example **PDFs:**
- **Photon shot noise, δ** (Poisson)

Photocharge, q = **1e-**



Photocharge, q = **6e-**

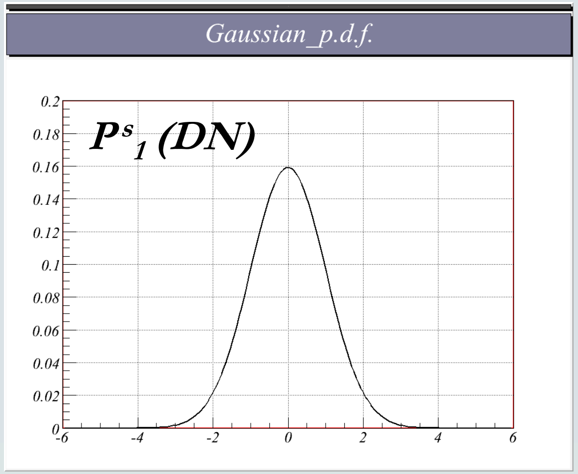


ARTEMIS: MONTE CARLO PDFs

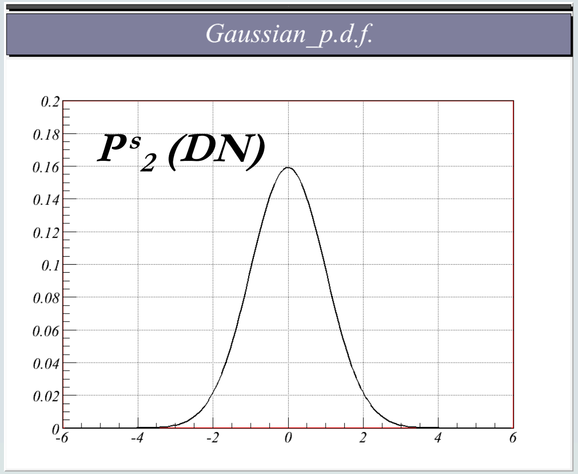
- Example **PDFs:**
- **Pixel offset dispersion, P^S (FPN):** (Gaussian + Gaussian + Exponential)

$$P^s = P^s{}_1 + P^s{}_2 + P^s{}_3$$

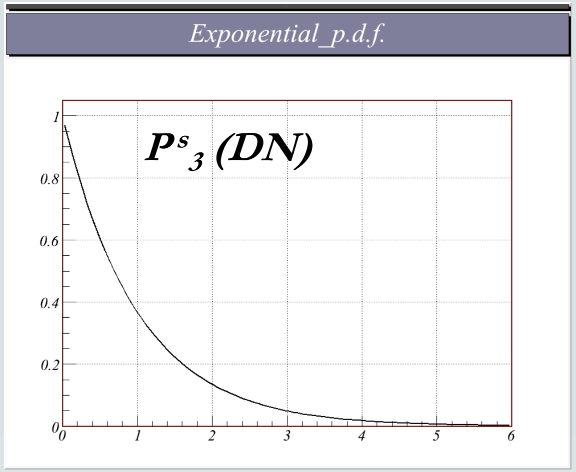
“Minimal” pixel FPN



DSNU



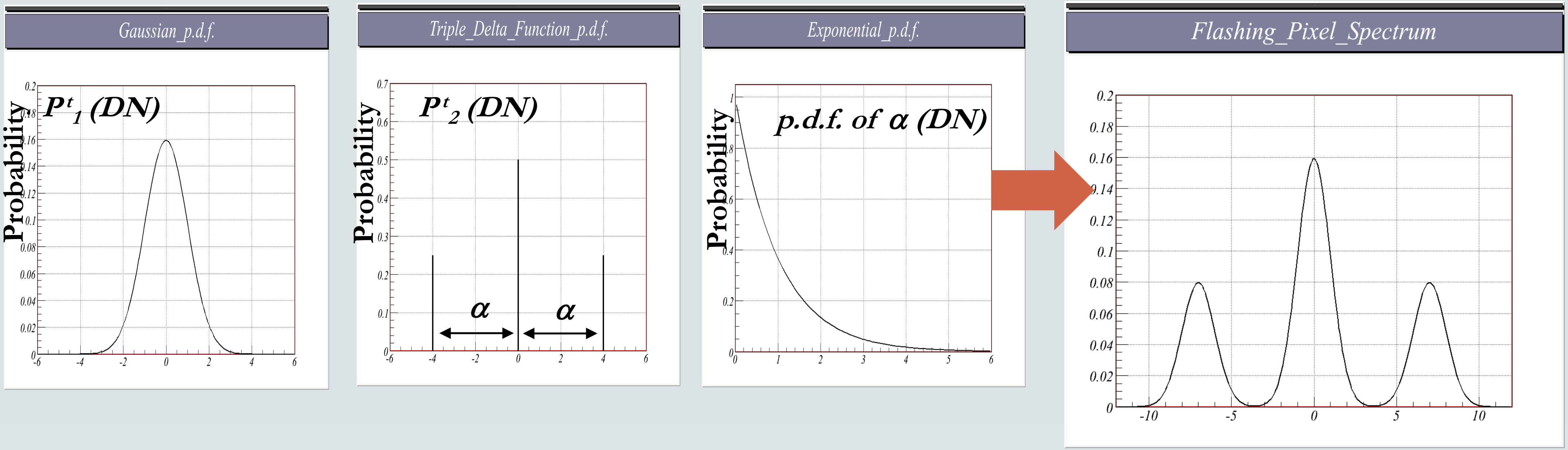
DSNU (dark current tail)



ARTEMIS: MONTE CARLO PDFs

- Example **PDFs:**
- **Random Telegraph Signal (RTS)** AKA “Flashing Pixels”

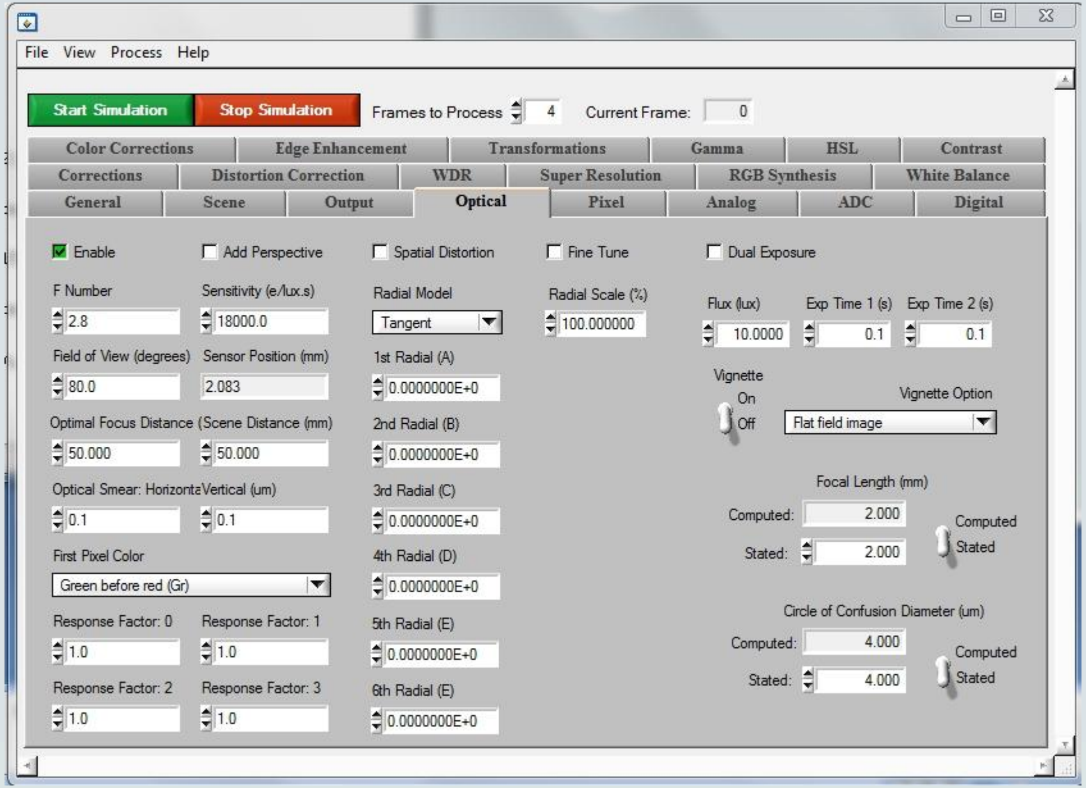
Pixel temporal noise　　Bistable trap　　Modulation amplitude, α



ARTEMIS: GUI

Artemis: GUI

“**Optical**” tab



Frames to Process 4

Current Frame: 0

☑ Enable
☐ Add Perspective
☐ Spatial Distortion
☐ Fine Tune
☐ Dual Exposure

F Number 2.8
Sensitivity (e/lux.s) 18000.0
Field of View (degrees) 80.0
Sensor Position (mm) 2.083
Optimal Focus Distance (Scene Distance (mm) 50.000 50.000
Optical Smear: HorizontaVertical (um) 0.1 0.1
First Pixel Color Green before red (Gr)
Response Factor: 0 1.0
Response Factor: 1 1.0
Response Factor: 2 1.0
Response Factor: 3 1.0

Radial Model Tangent
1st Radial (A) 0.0000000E+0
2nd Radial (B) 0.0000000E+0
3rd Radial (C) 0.0000000E+0
4th Radial (D) 0.0000000E+0
5th Radial (E) 0.0000000E+0
6th Radial (E) 0.0000000E+0

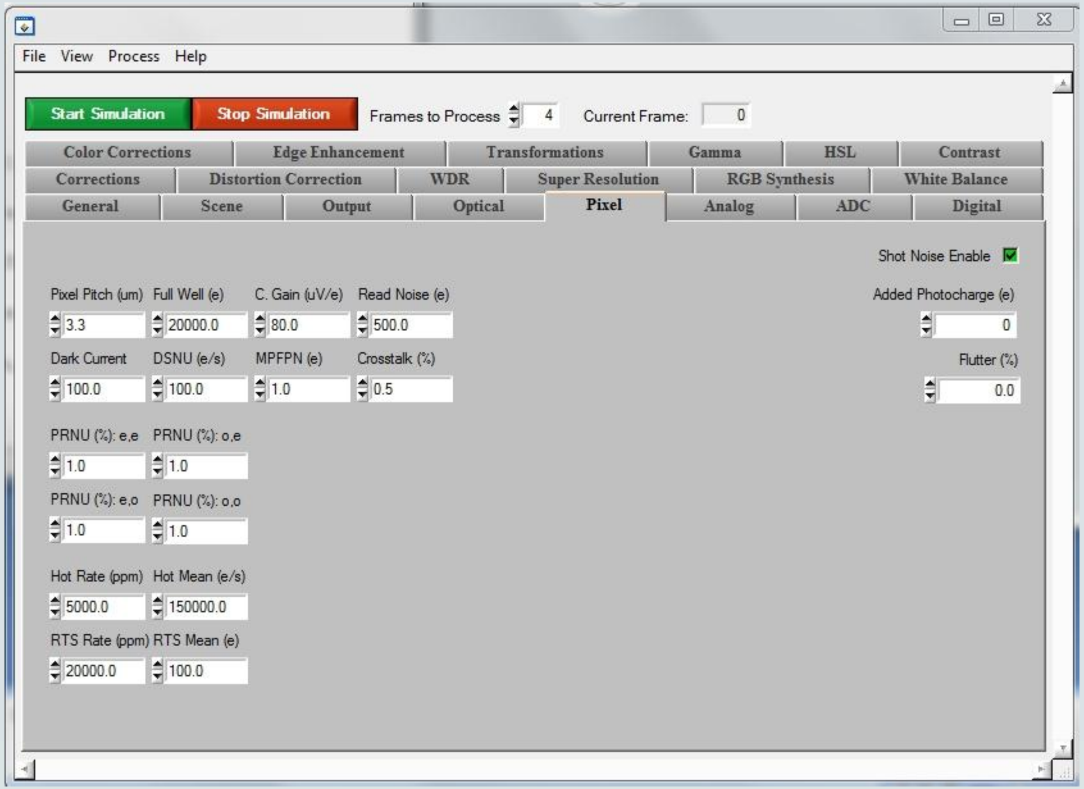
Radial Scale (%) 100.000000

Flux (lux) 10.0000
Exp Time 1 (s) 0.1
Exp Time 2 (s) 0.1
Vignette On Off
Vignette Option Flat field image

Focal Length (mm)
Computed: 2.000
Stated: 2.000
Computed Stated

Circle of Confusion Diameter (um)
Computed: 4.000
Stated: 4.000
Computed Stated

“**Pixel**” tab



Frames to Process 4

Current Frame: 0

Shot Noise Enable ☑

Pixel Pitch (um) 3.3
Full Well (e) 20000.0
C. Gain (uV/e) 80.0
Read Noise (e) 500.0
Dark Current 100.0
DSNU (e/s) 100.0
MPFPN (e) 1.0
Crosstalk (%) 0.5
PRNU (%): e,e 1.0
PRNU (%): o,e 1.0
PRNU (%): e,o 1.0
PRNU (%): o,o 1.0
Hot Rate (ppm) 5000.0
Hot Mean (e/s) 150000.0
RTS Rate (ppm) 20000.0
RTS Mean (e) 100.0

Added Photocharge (e) 0
Flutter (%) 0.0

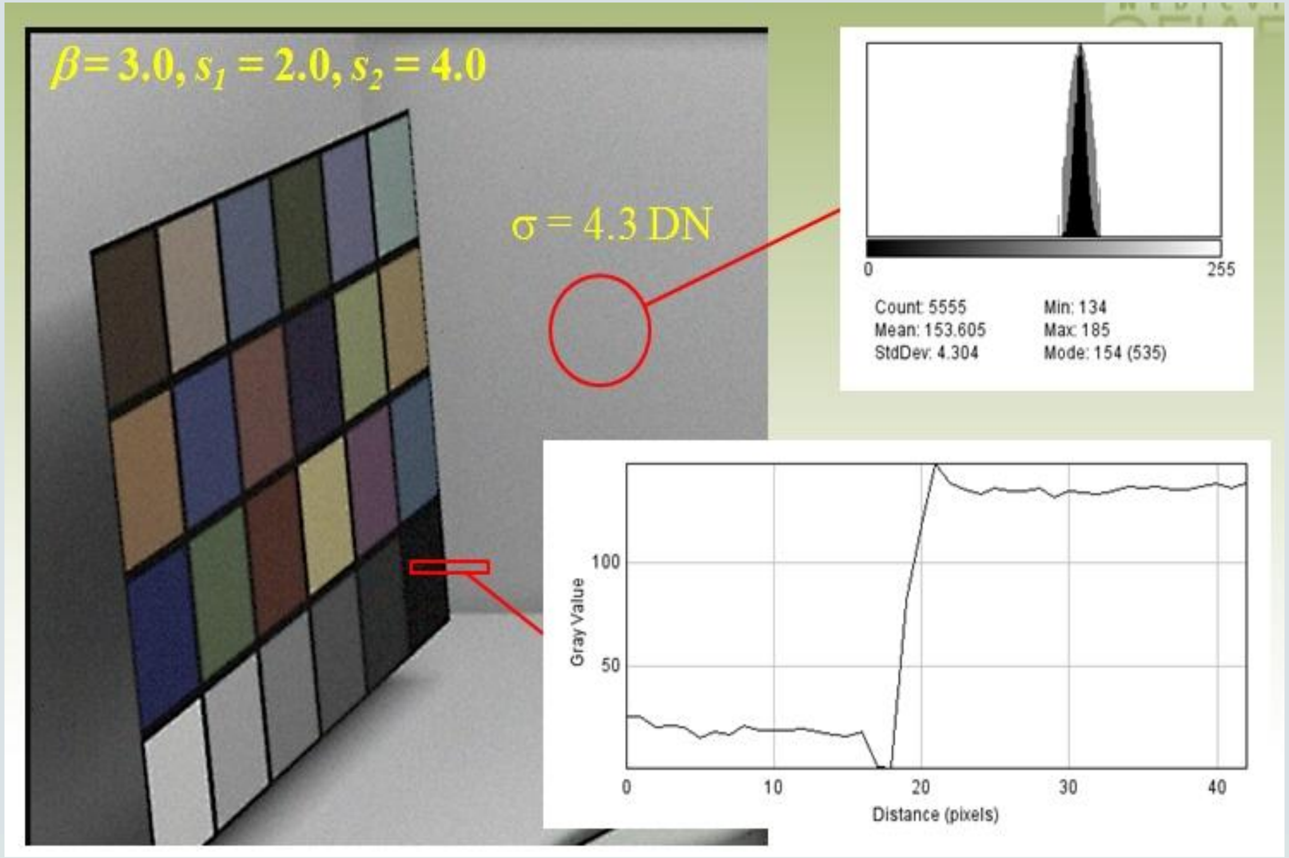
ARTEMIS

Artemis use case:

Development of

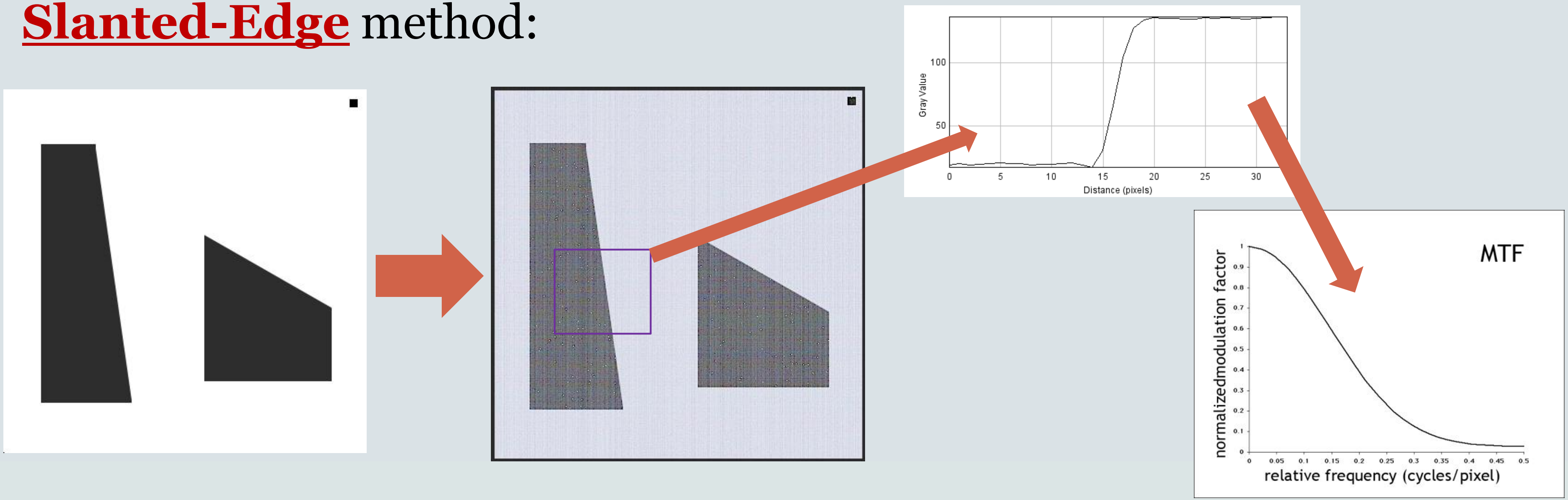
Noise-aware edge-enhancement algortihm

(US 2014 0267653A1)



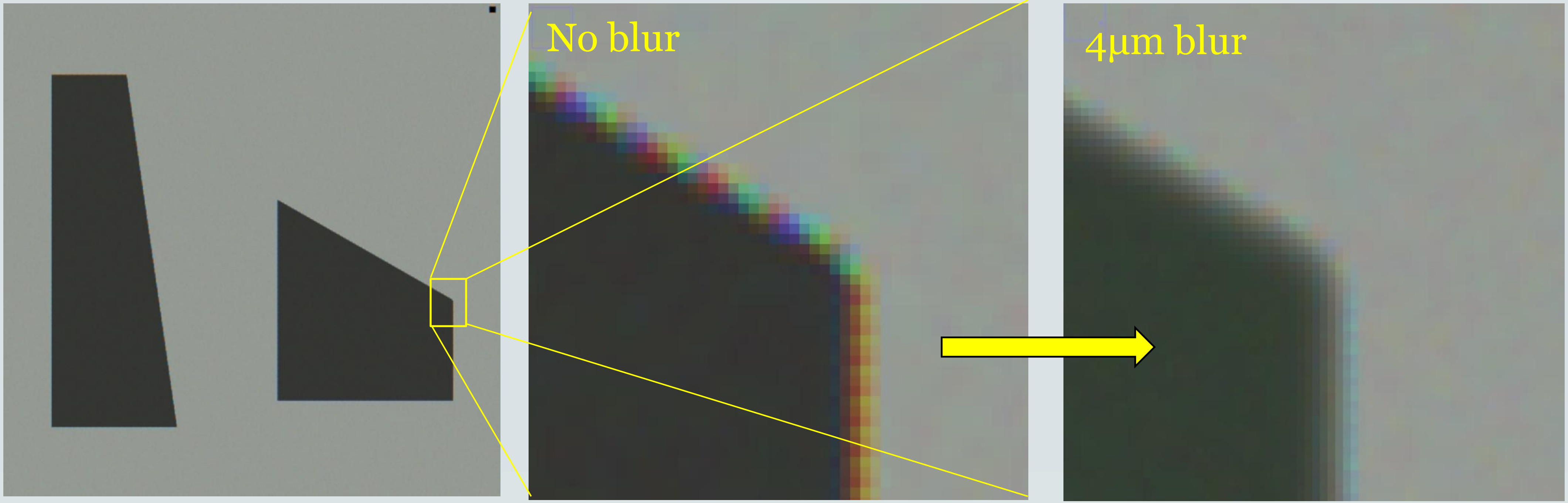
ARTEMIS

- **Artemis** used to simulate proposed arthroscope approach
- Key result: overall **spatial resolution** of system, (HD or not)
- **MTF:** Fourier transform of system response to a step function
- **Slanted-Edge** method:



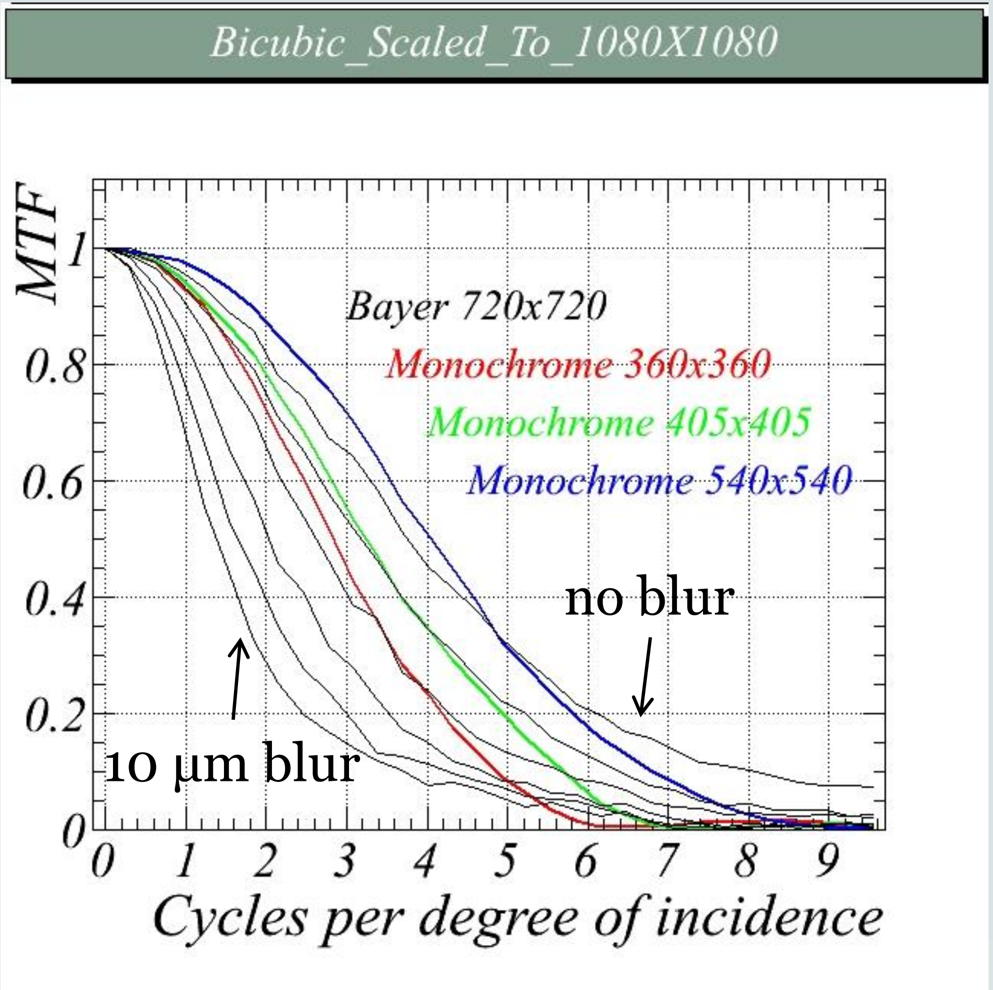
MTF: RESULTS

- **Bayer**-based sensors have **colored sampling artifacts**
- Addressed by **spatially low-passing**
- This is done digitally if the lens assembly is “too good” for the sensor



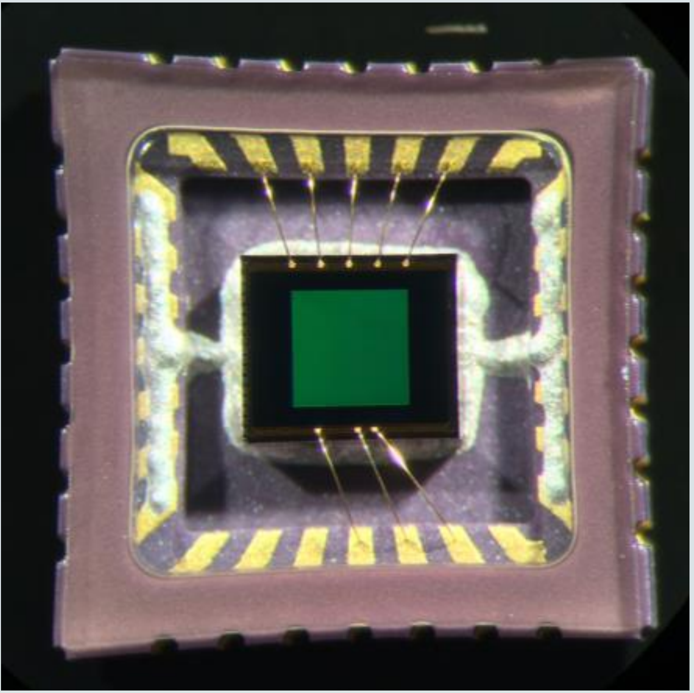
MTF: RESULTS

- 405×405 array **comparable to 720-Bayer** with 2 μm of Gaussian blur
- Optimal blur determined to be 2.8 μm
- Solution therefore **quantitatively competitive with** single-sensor, color **HD** system!



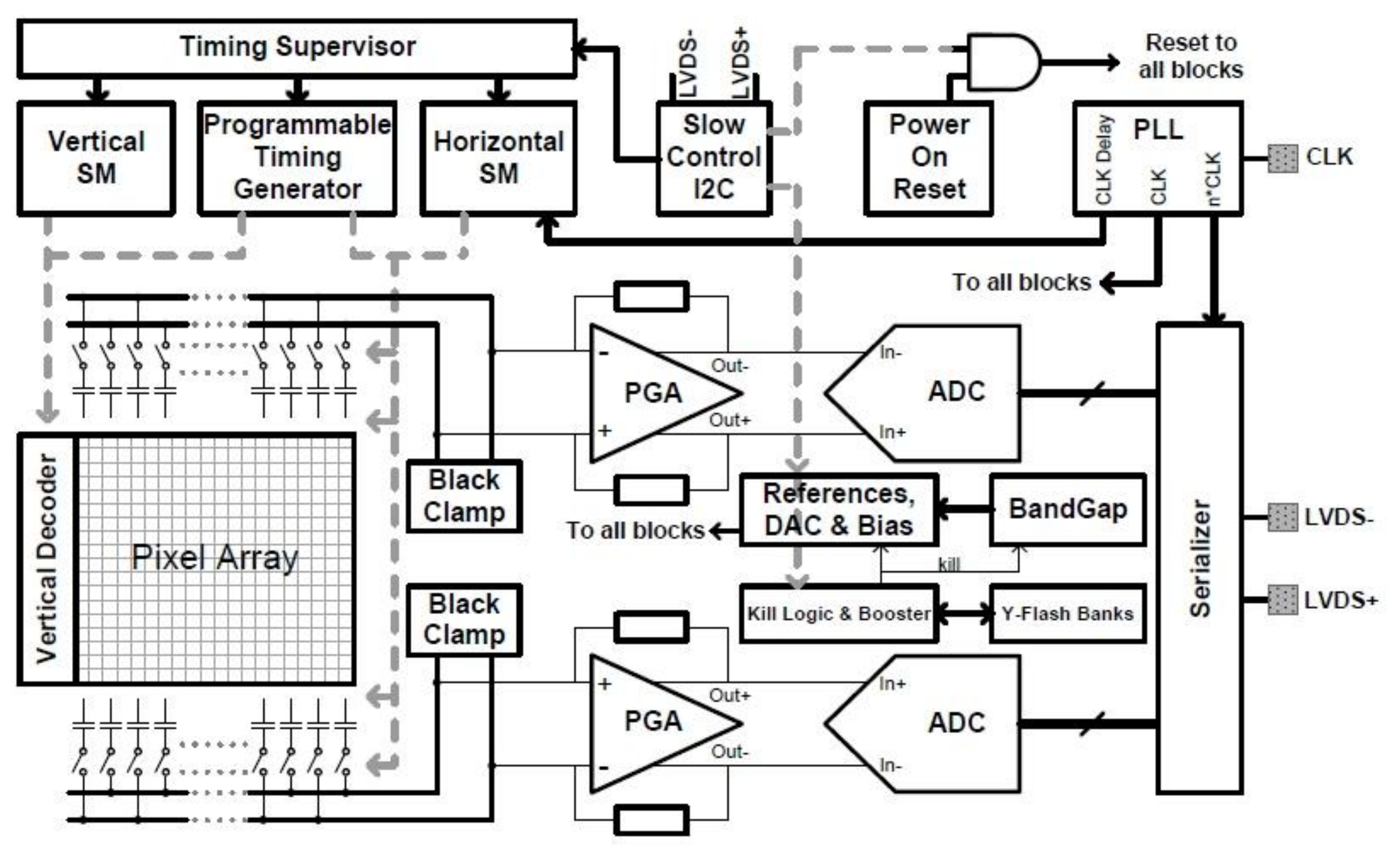
Black Widow: Overview

- Tower-Jazz **180 nm** CIS Epi technology (8”). 1.8V/3.3V.
- Square array: **424×405**, **3.3µm** 4T pixel, 2:1 horizontal sharing (“2.5T”)
- **Two Tx buses** serving pixels in a chessboard pattern (for WDR)
- **Monochrome** (no CFA)
- **2.05 × 2.4 mm** area
- **10 pads** total
- 1 × horizontal and 4 × vertical state machines
- Programmed via two-pin **I²C**
- 2 × PGA-ADC (OTA+11-bit pipeline, ≤45MHz each)
- → 1 serial dataport (1 Gbps)



Black Widow: Architecture

- Block Diagram



Black Widow: Characterization

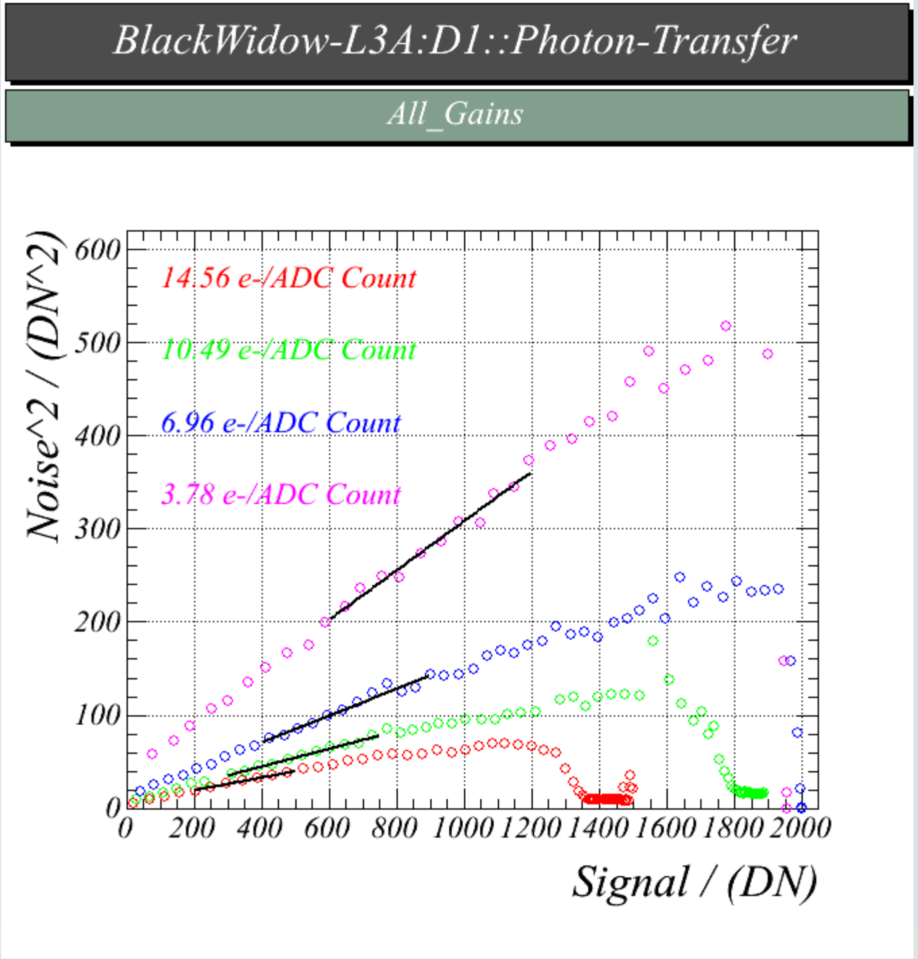
- First stage in characterization is **calibration (DN → e-)**
- Exploit the fact that photon arrival rates are **Poissonian**
- Poisson distribution:

$$\frac{\mu^{k}e^{-\mu}}{k!}$$

- **Variance = mean** (in base number units)

Photon Transfer

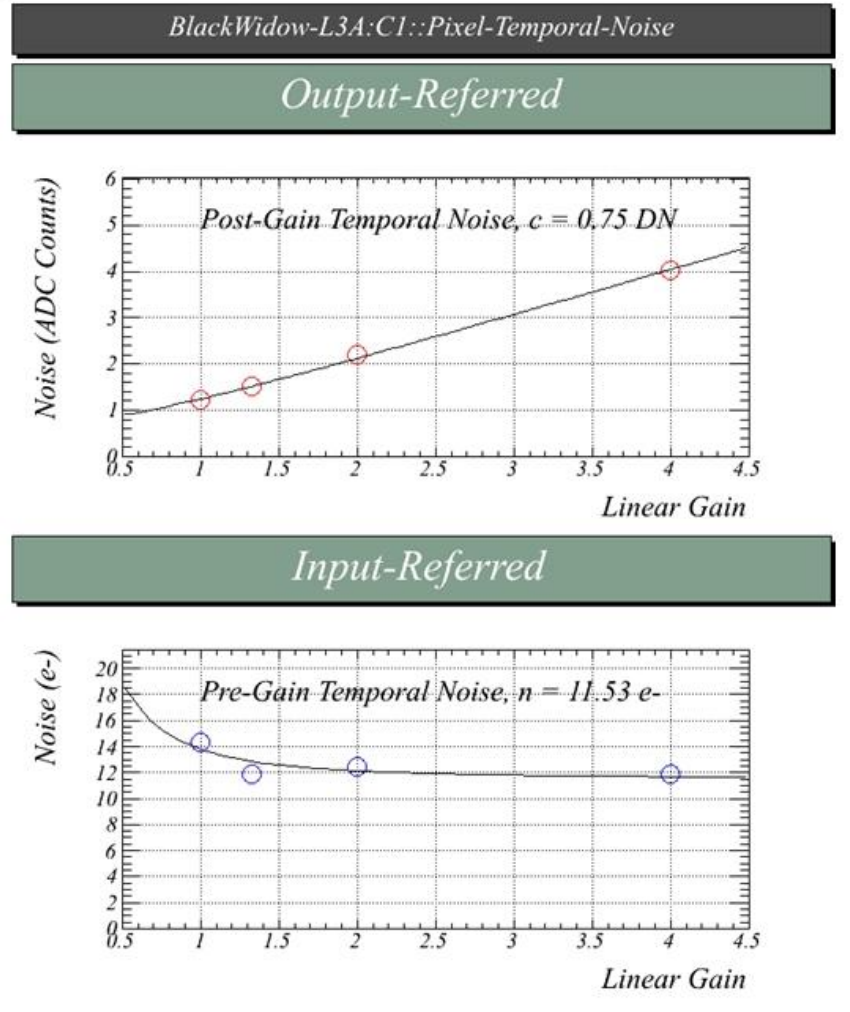
- Plot noise² vs. signal in digital number (DN)
- Gradient is 1/K, where K = conversion from e- to DN
- **Conversion gain** derived to be **61 μV/e-**
- **Pixel capacity** (full well) also revealed to be 17ke-



Read Noise

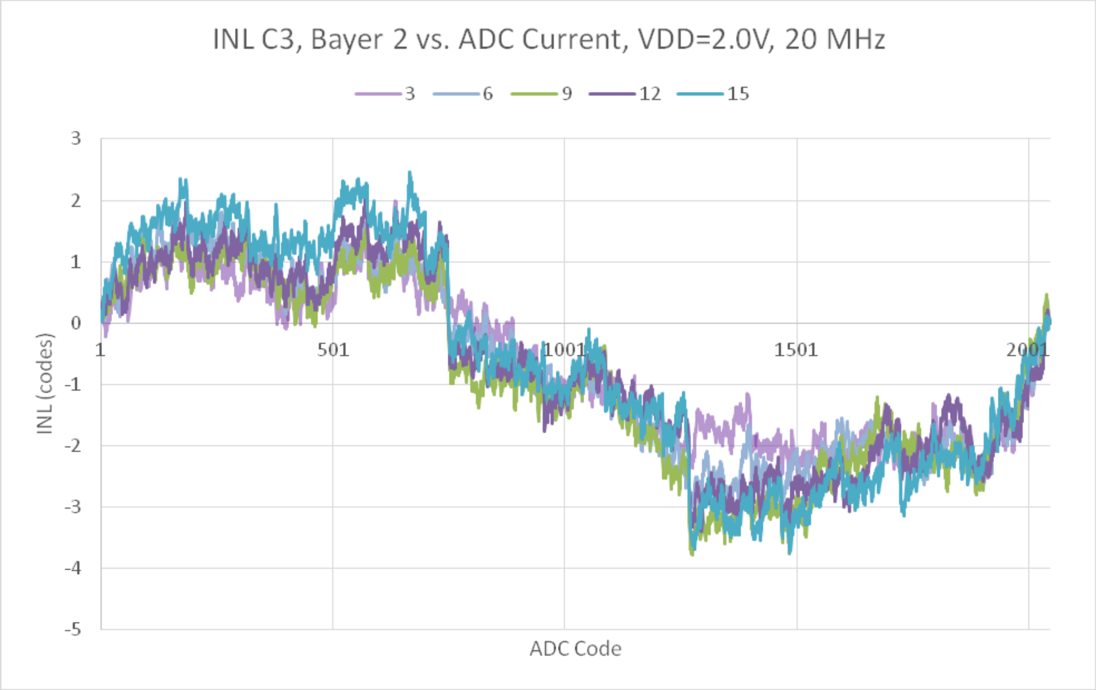
- **Input-referred** temporal noise at high gain = **11.5 e-**

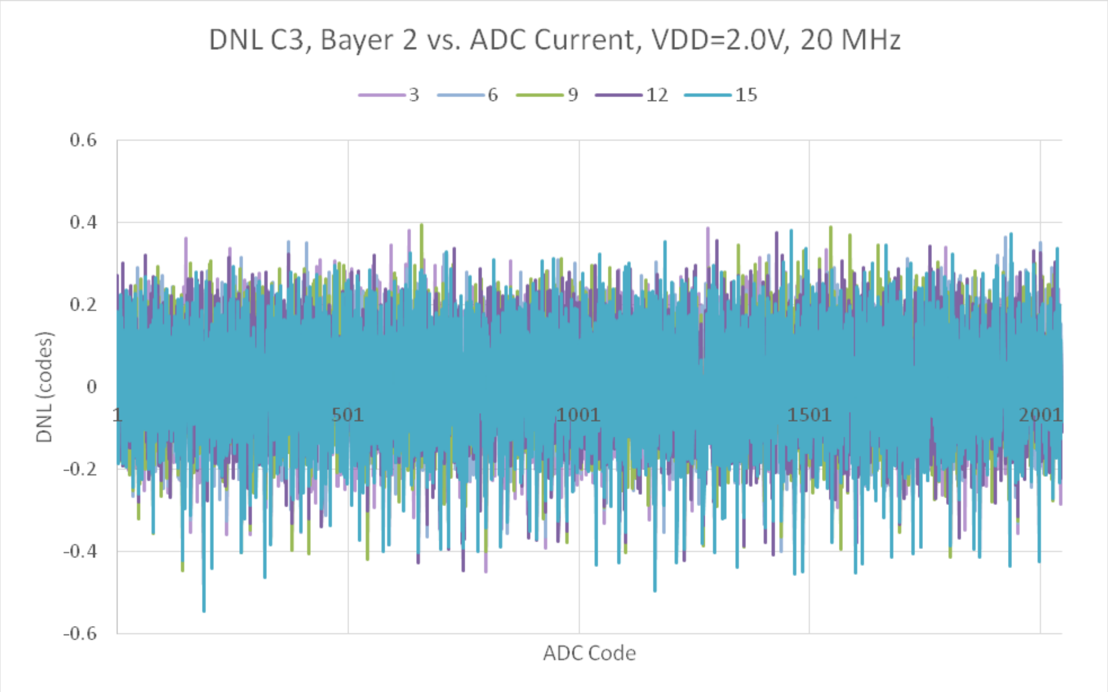
- **Output referred** noise at low gain = **0.75 DN**



ADC INL/DNL

- **INL: +2.0 / -2.7 DN**
- **DNL: +0.37 / -0.42 DN**





Intellectual Property

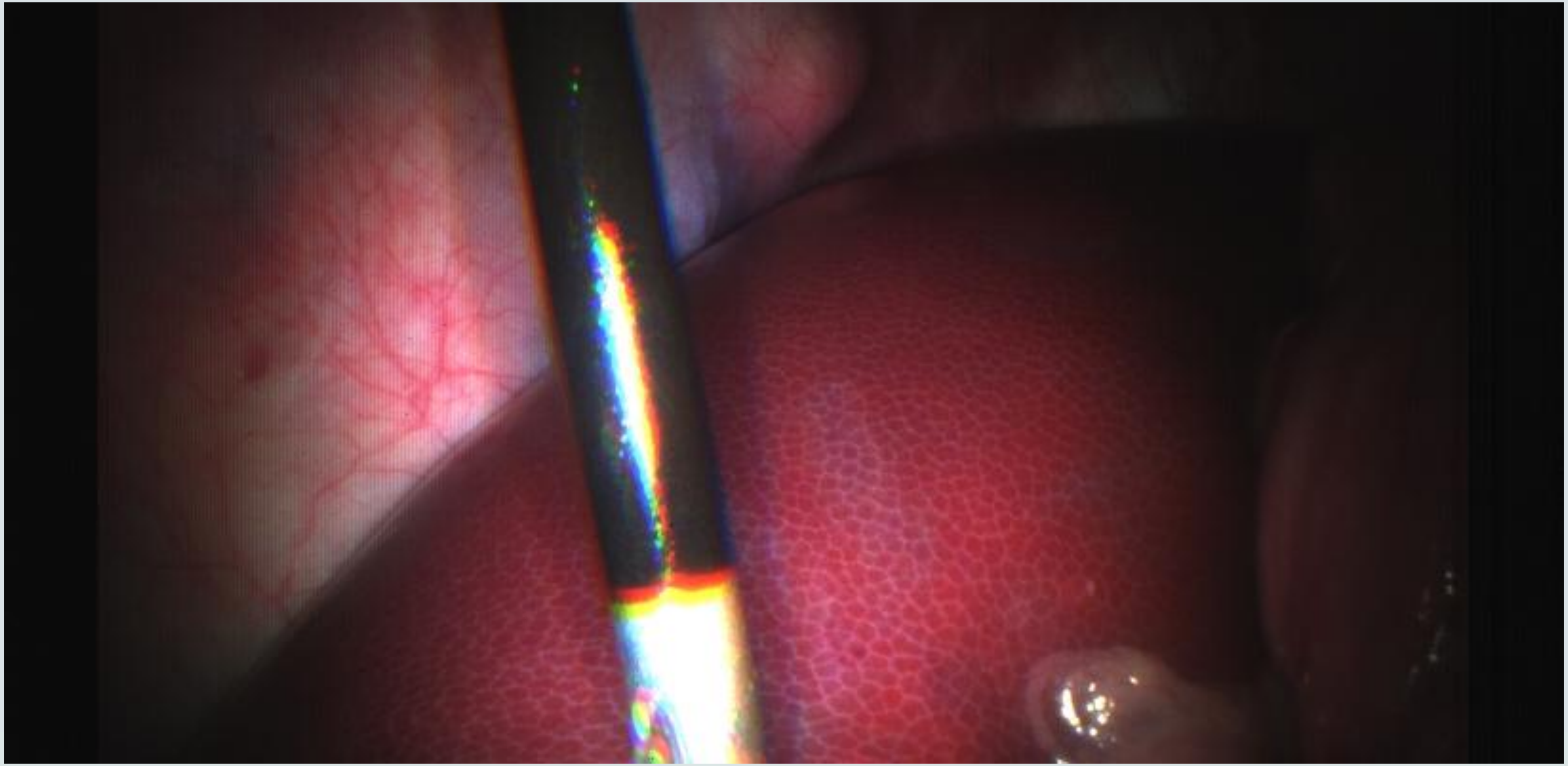
- Overall system solution yielded 18 patents

1. Continuous Video in a Light Deficient Environment
2. Camera System with Minimal Area Monolithic CMOS Image Sensor
3. Wide Dynamic Range using Monochromatic Sensor
4. Super Resolution and Color Motion Artifact Correction in Pulsed Color Imaging Systems
5. Comprehensive FPN Cancellation
6. Noise Aware Edge Enhancement
7. Image Sensor Synchronization without Input Clock and Data Transmission Clock
8. White Balance and FPN Frame Calibration using Distal Cap
9. YCbCr Pulsed Illumination Scheme in a Light Deficient Environment
10. Minimize Image Sensor I/O and Conductor Counts in Endoscope Applications
11. Controlling the Integral Light Energy of a Laser Pulse
12. Mechanical Image Rotation for Rigidly Coupled Image Sensor and Endoscope
13. Safety Protocol for a Scope in a Light Controlled Environment
14. Switching Between Disposable Endoscopes During Use
15. Removing Speckle from a Scene Lit by a Laser Light Source
16. Viewing Trocar with Integrated Prism for Use with Angled Endoscope
17. Image Rotation using Software for Endoscopic Applications
18. Videostroboscopy of Vocal Chords with CMOS Sensors

Example Movie

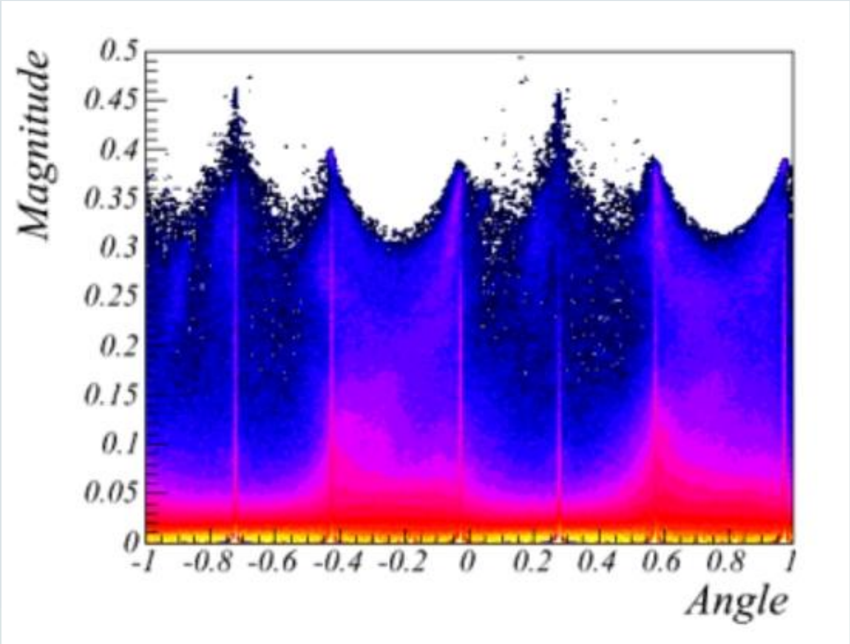
CMAC: Color Motion Artifact Correction

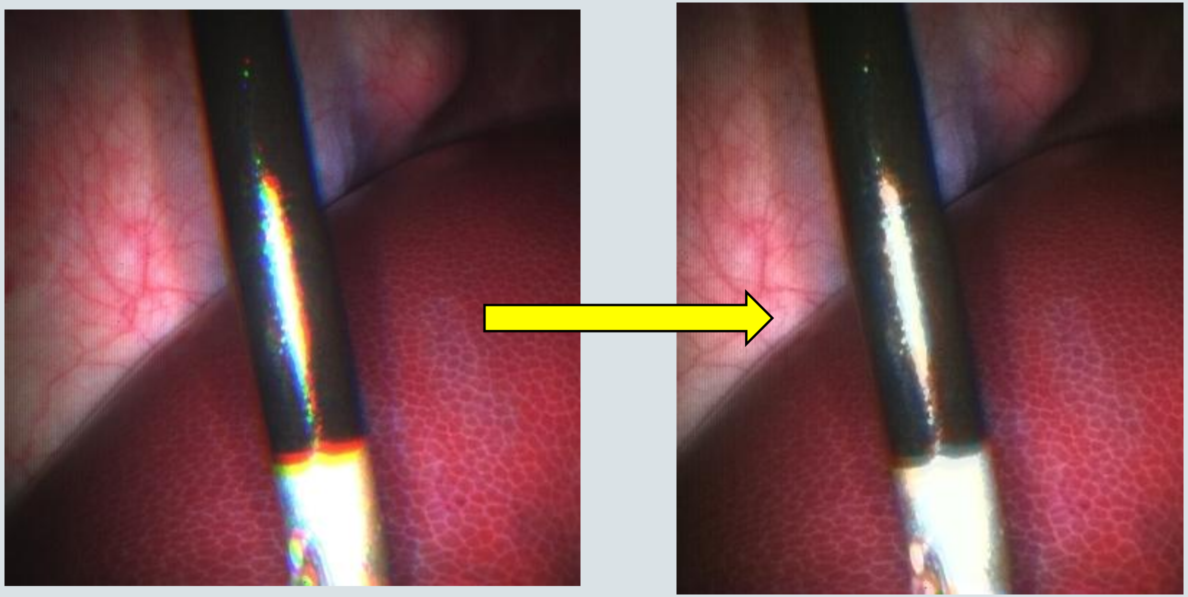
- Color motion artifacts due to color components displaced in time



CMAC: Color Motion Artifact Correction

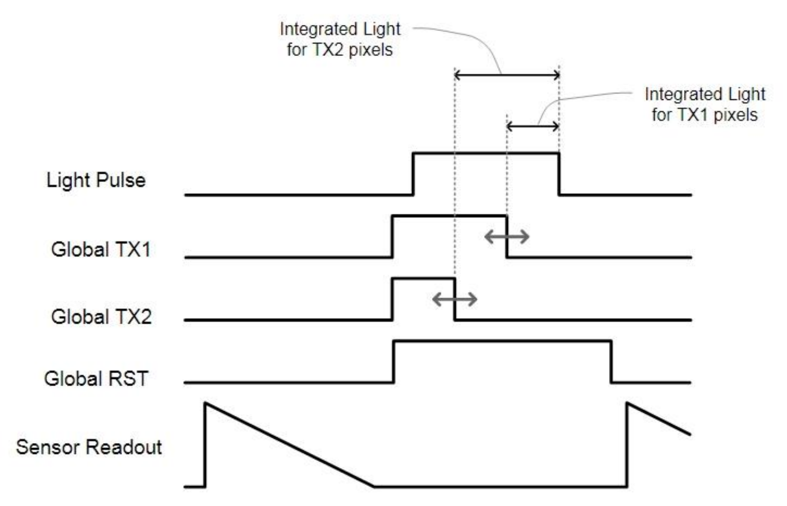
- Observed that **color errors** have a **signature** when plotted as chrominance-red shift vs. chrominance-blue shift
- **Tagged pixels** may thus be restored to **correct chroma**

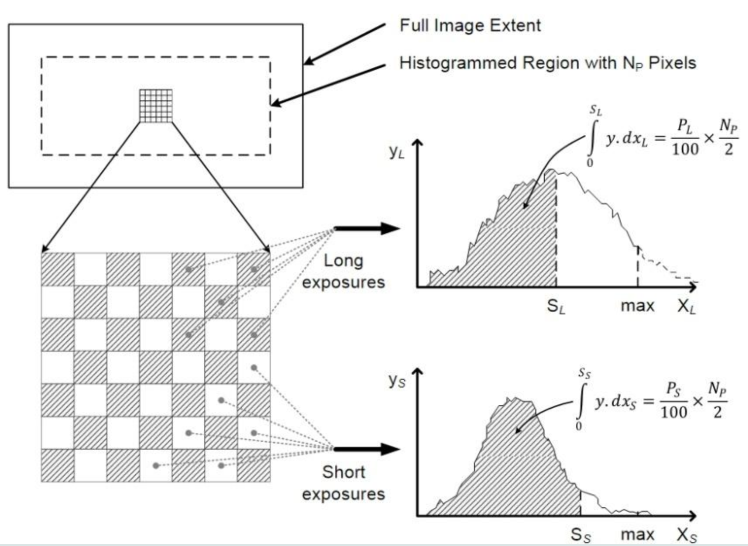


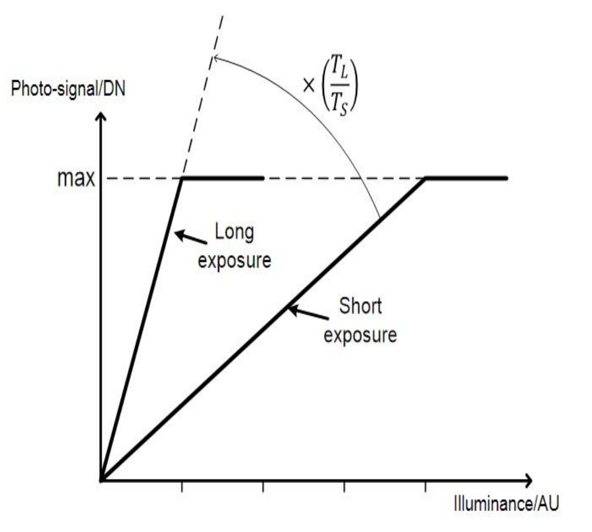


Wide Dynamic Range

- **Two flavors of pixel** arranged in chessboard pattern with independent Tx buses
- Provides for **two exposures in the same image**
- **Ratio** of exposures **=** dynamic range **extension**, e.g. ×4 = +12dB







YCbCr Light Pulsing

- Realized that full control of pulsed laser light allowed for **luma-chroma space illumination**
- For **Luma**: Just use ratios of red, green and blue established in the YCbCr standard for HD
- **Chroma** components have negative coefficients, therefore make linear sums of luma and chroma, tuning the amount of luma to make –ve coefficients =0 or positive
- **Subtract** appropriate quantity of **luma from "chroma"** frames in ISP
- **Better** perceived **spatial resolution** and **less** egregious **CMAC**

Parallel and Future Directions

- **4K** imaging
- **Hyperspectral**; NIR: Special epi & filters etc.
- **III-V 3D Stacking** e.g. InGaAs (1.5 µm), UV, TSV…
- **65 nm**
- Wafer thinning / **Back-Side Illumination** (BSI)
- Pixel Light-Guide engineering
- **Stereo** vision
- **Robotic surgery**
- **Quantum dots**
- **Depth perception**: TOF, Structured Light
- **Computer vision** methods