CMOS Imagers and HDTV Cameras

Peter Centen R&D Cameras

THOMSON

THOMSON images & beyond

Agenda

- **Introduction**
- **CMOS imagers**
  - why did it take so long
  - a Self-fulfilling prophesy
- **On the design of Xensium**
  - A CMOS imager for Broadcast applications
- **Evaluation Techniques**
- **Conclusion**

Peter.centen@thomson.net

My World

In cooperation with DALSA we added functionality to the CCD-imager, that was not found in imagers of the competition.

HD-DPM gave an competitive edge

Recently we developed our own CMOS imager

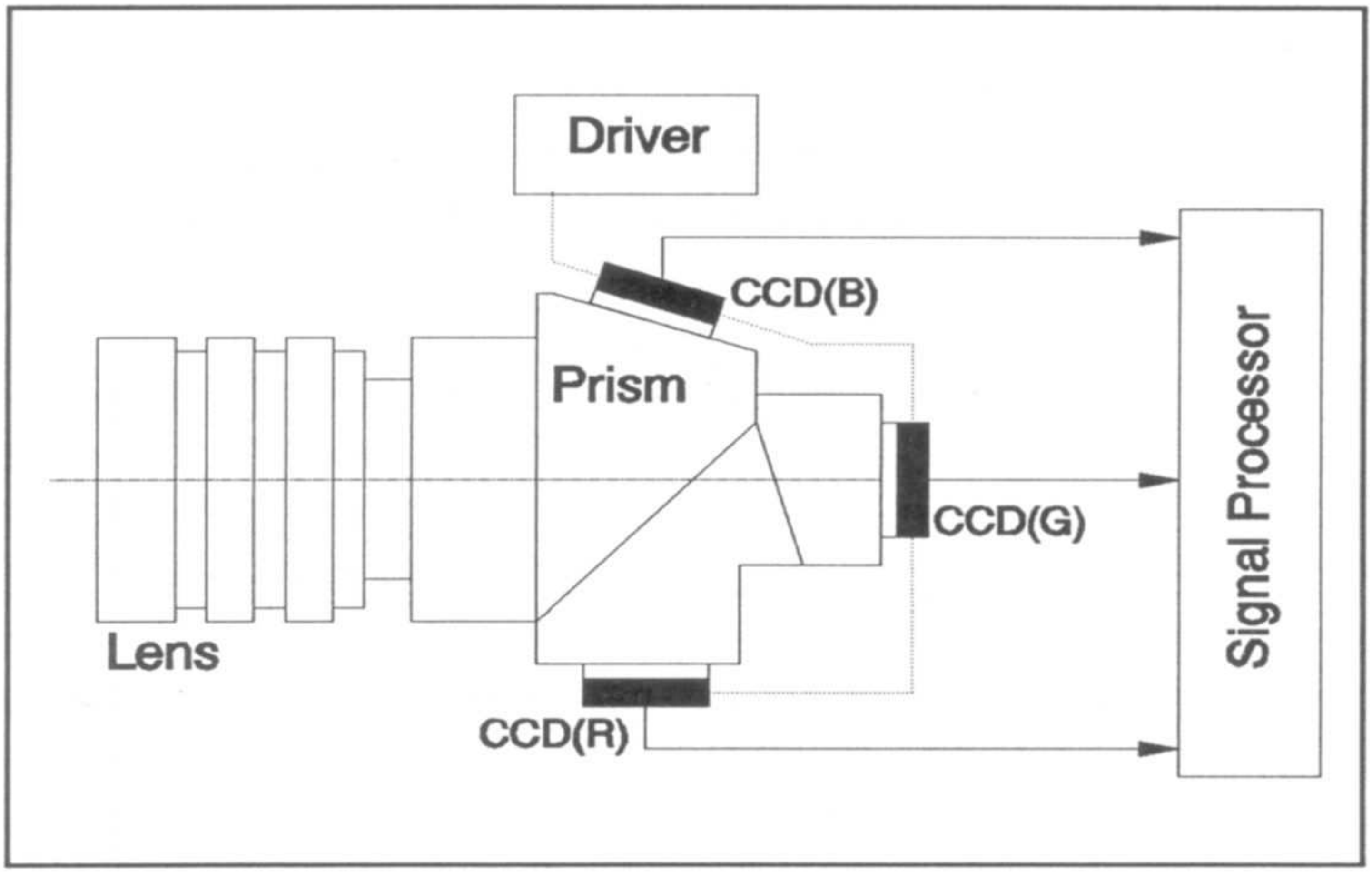
Broadcast

- **The image diagonal is not free to choose**
  - A large installed base of very expensive lenses
    - 2/3“ or 11.0 mm
    - ½” or 8.0 mm
- **A full HDTV imager: 1920x1080**
  - In 2/3” one has 5um pixels and diffraction limit at around f/19 (f/7.6)
  - In ½” one has 3.65um pixels and diff. lim. f/14 (f/5.5)
- **The master clock is 74.25MHz or 74.25/1.001 MHz**
  - 74.25MHz for the p24, p25, p30, i50, i60
  - 74.25/1.001 for the p23.98, p29.97, i59.94
    - p: progressive, i: Interlace, psf: progressive segmented frame
- **MTF**
  - SINE wave at input frequency of eg 27MHz
  - SQUARE wave at eg 27MHz
    - About 1.2 times the sine value……it is a marketing thing

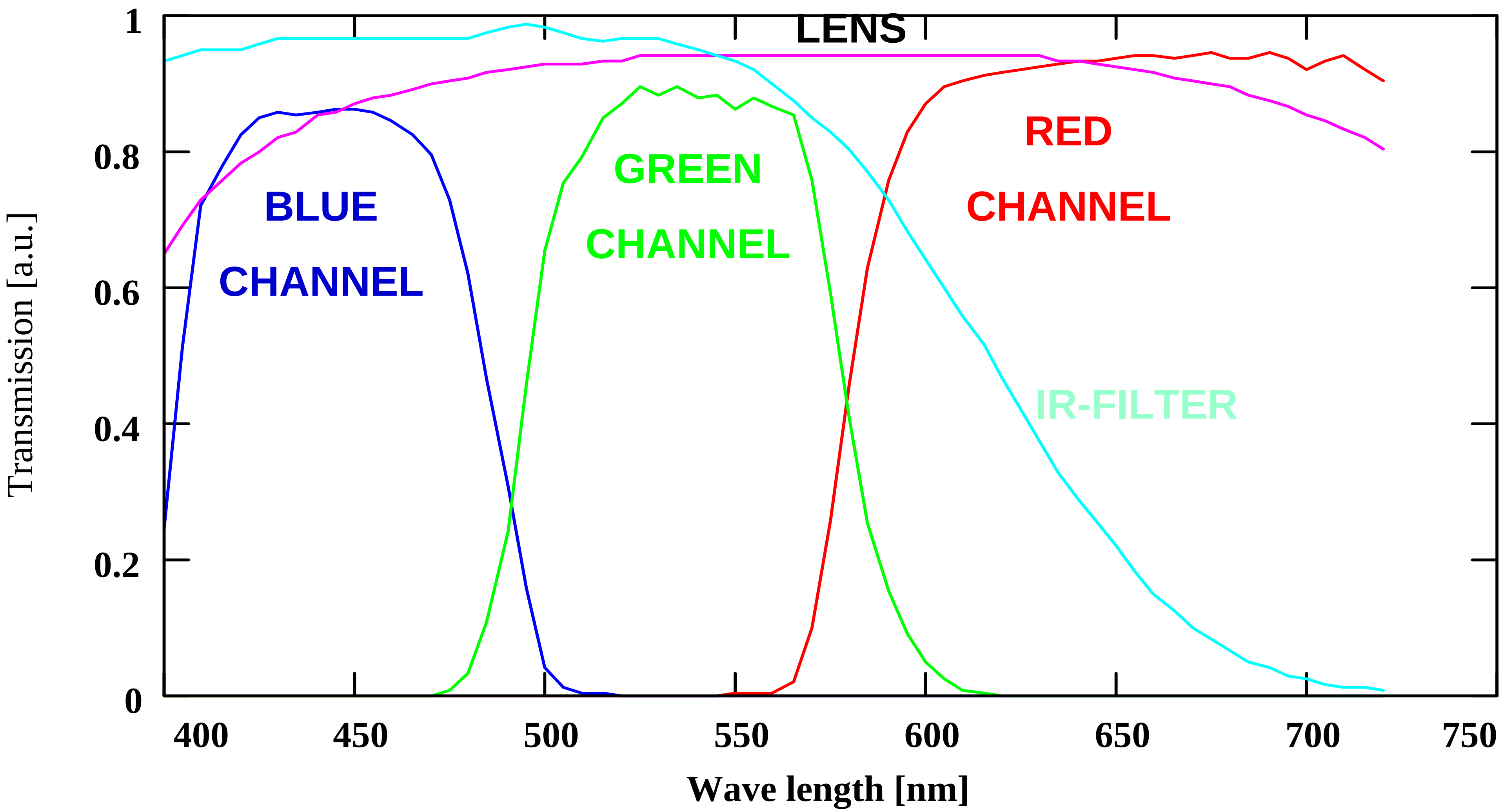
Broadcast

- **SNR in HDTV**
  - Camera settings
    - Linear (gamma off)
    - No contours
    - Matrix off
      - These are artificial setting to have a defined operating point for comparison
  - Noise in 0.2MHz - 30MHz bandwidth in black >-54dB in Y
    - Flat or eye response
  - 0dB
    - Known as the nominal setting
    - This is defined by
      - 2000 lux; 89.9% reflectance; 3200K; **f/8-f/11**
    - The f number denotes the sensitivity

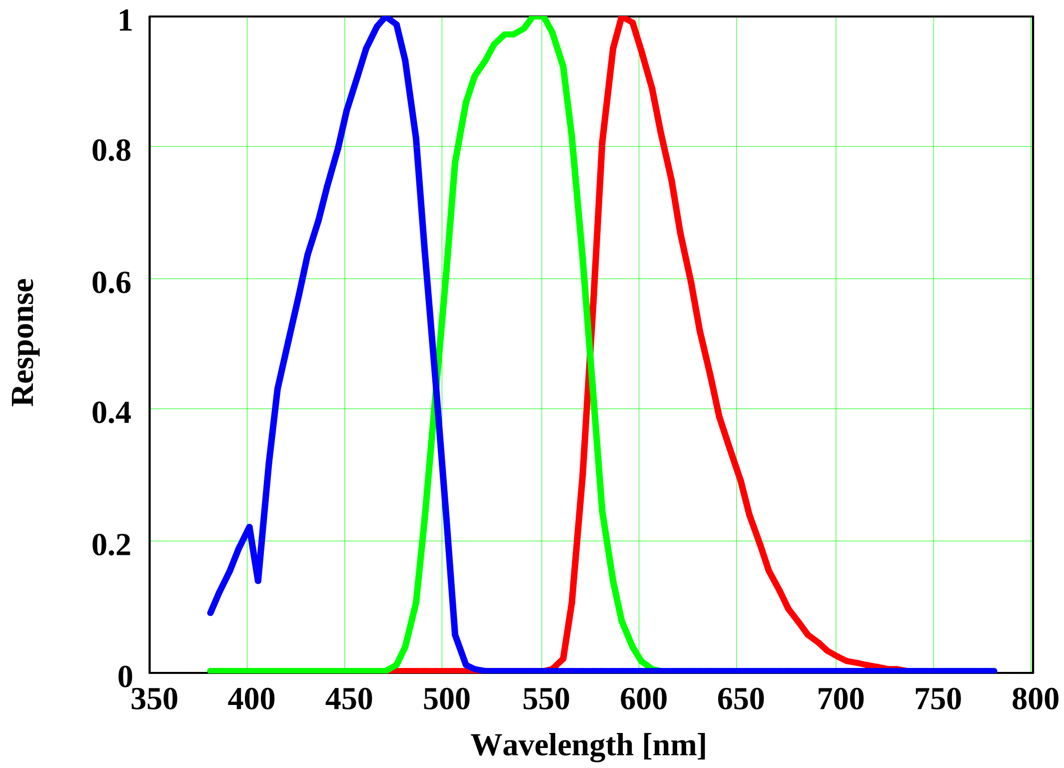
Broadcast: 3 Imager Optical Block



Broadcast: Optical elements



Broadcast: Imager RGB-output



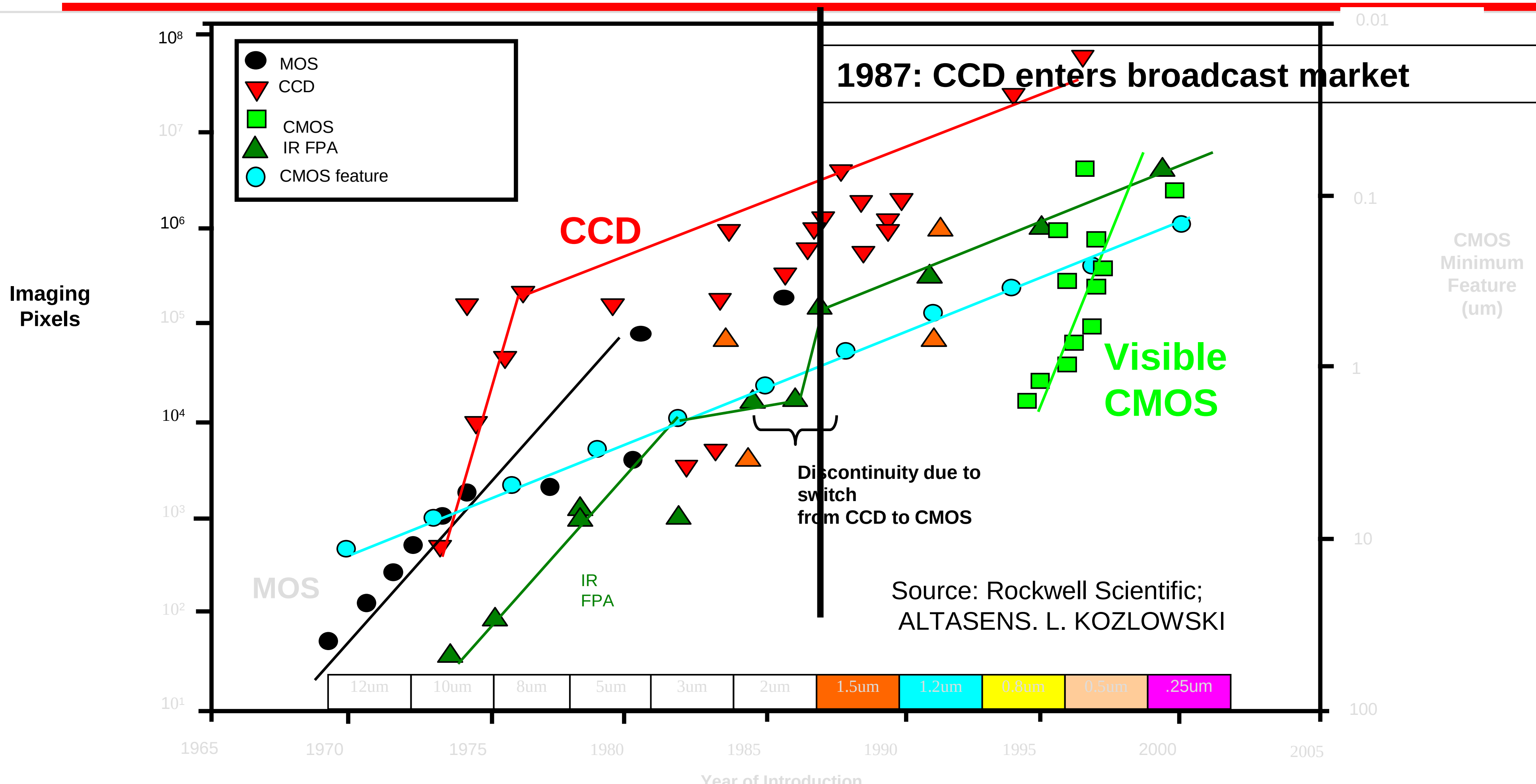
SEN

Broadcast

- Photon flux in a broadcast camera at **2000lux; f/11; 3200K and 89.9%** scene reflection
  - R 8.5k photons/um^2/sec
  - G 7.5k photons/um^2/sec
  - B 2.5k photons/um^2/sec
- **Pixel is 5x5um^2 and 30 frames/sec ; Photons per pixel**
  - R 7.0kph
  - G 6.2kph
  - B 2.0kph
  - Assume overall **QEeff=60%** (QE x Aperture x(1-reflection) x ulens) then
    - Charge packet in Green **NG=3k7e** and for SNY=54 dB noiselevel must be **Nrms<=10e**
  - **FPN<=2e at 35C**
- Qmax=20kel/pixel **(for at least 5x overexposure)**
- **High light handling (blooming, smear, etc)**
  - 16-fstop more light at the imager

CMOS imagers
Why did it take so long?

Feature Size and CMOS Imagers



Notice the early ramp up of CCD imagers (1973) and the delayed ramp up of CMOS imagers (1970 /1995)

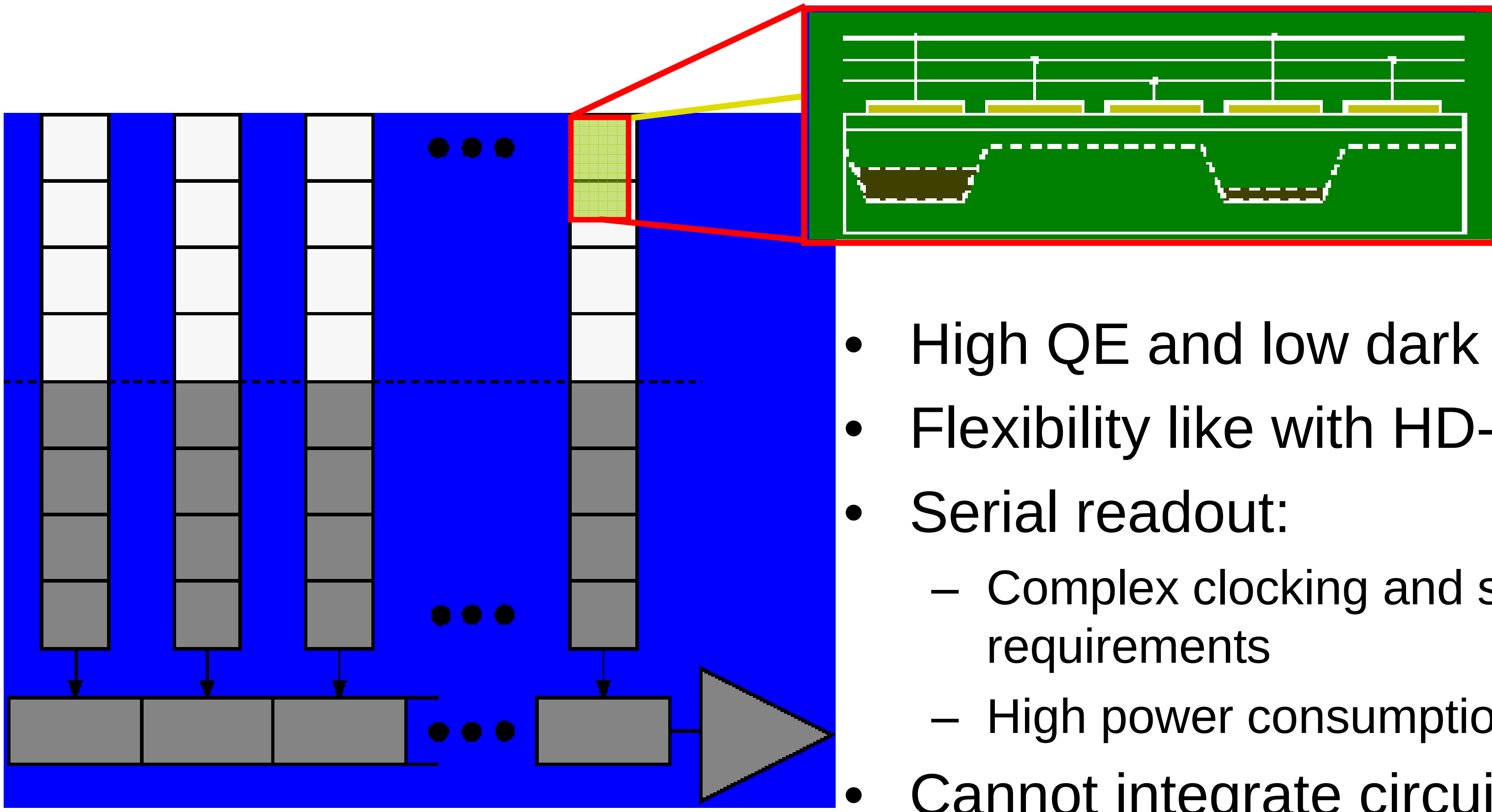
Feature Size and CMOS Imagers

- **MOS** **1967 Wecker&Noble**
- **CCD** **1970 Boyle&Smith**

- **Why did it take so long for CMOS imagers to enter the market, even though they where conceived before the CCD imagers?**
  - The word is **Lithographic Feature Size**
  - In general a CCD-pixel is simpler than a CMOS-pixel, the latter contains more active elements

Peter.centen@thomson.net

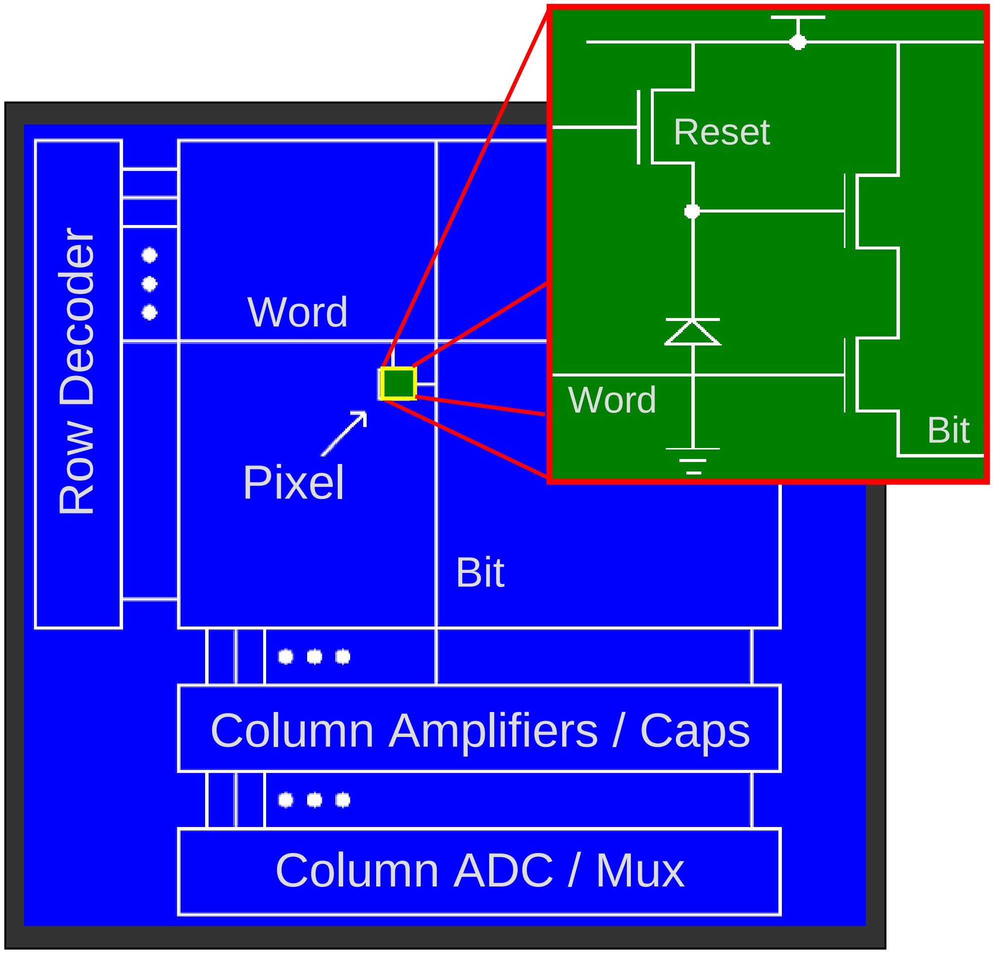
Feature Size and CMOS Imagers



- High QE and low dark current
- Flexibility like with HD-DPM
- Serial readout:
  - Complex clocking and supply requirements
  - High power consumption
- Cannot integrate circuitry on chip

IEDM 2002 Gamal

Feature Size and CMOS Imagers

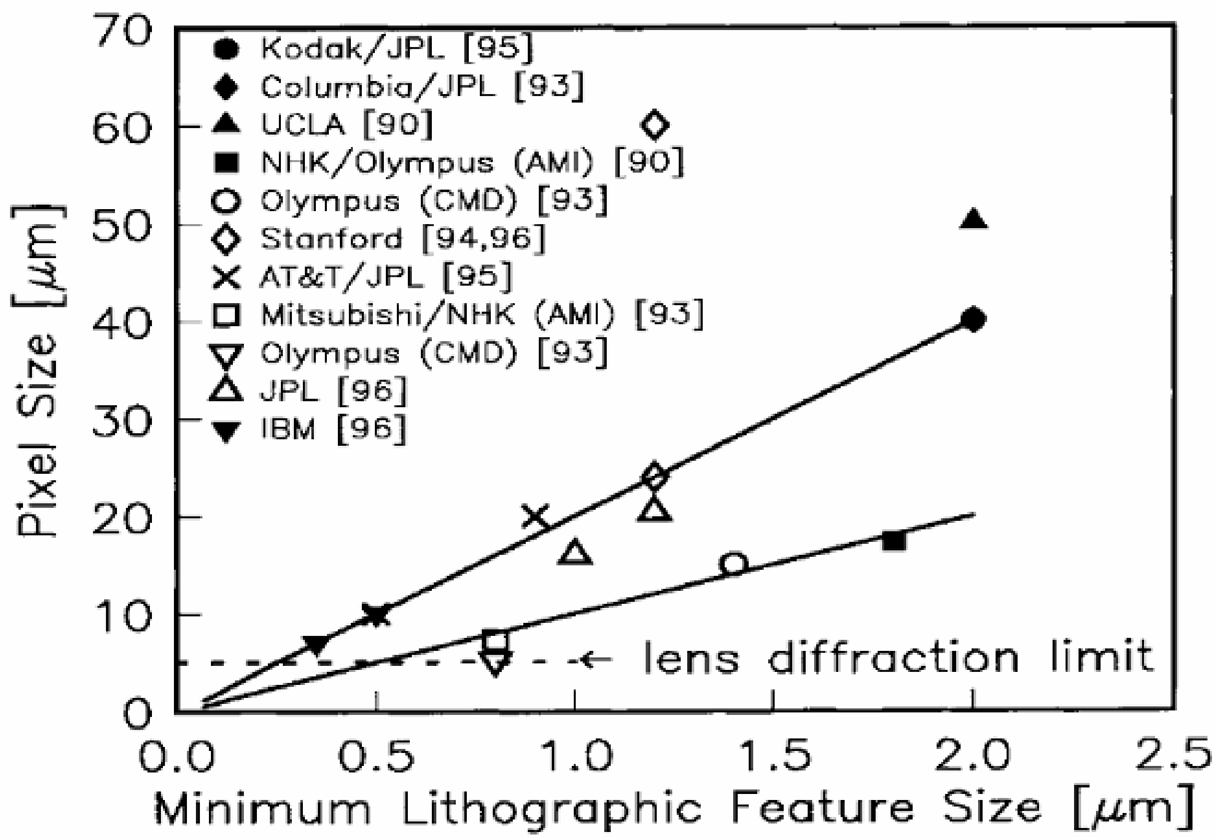


IEDM 2002 Gamal

- **Memory-like readout:**
  - Enables high speed operation
  - Low power consumption
  - Region of interest
- **Integration**

Feature Size and CMOS Imagers

Pixel size is about Feature_Size*20.................still valid



IEEE ED Vol 43, DEC 1996, Hon-Sum Wong

Feature Size and CMOS Imagers

- **The average pixel size in a SDTV (PAL, NTSC) imager**
  - SDTV: **10um** ; **7.5 um**; **5 um**
- **The average pixel size in HDTV**
  - 720p: **7.5 um**; **5.0 um**; **4.0 um**
  - 1080P: **5 um**; **3.6 um**; **2.7 um**
    - ***2/3-inch***; ***½-inch***; ***1/3-inch***

➢Using the safe rule of thumb between Feature Size and Minimum Pixel dimension of a factor 20 (Wong)

- One needs a **litho of <0.5um** for **SDTV** imagers
- And <0.25um for **HDTV** Imagers

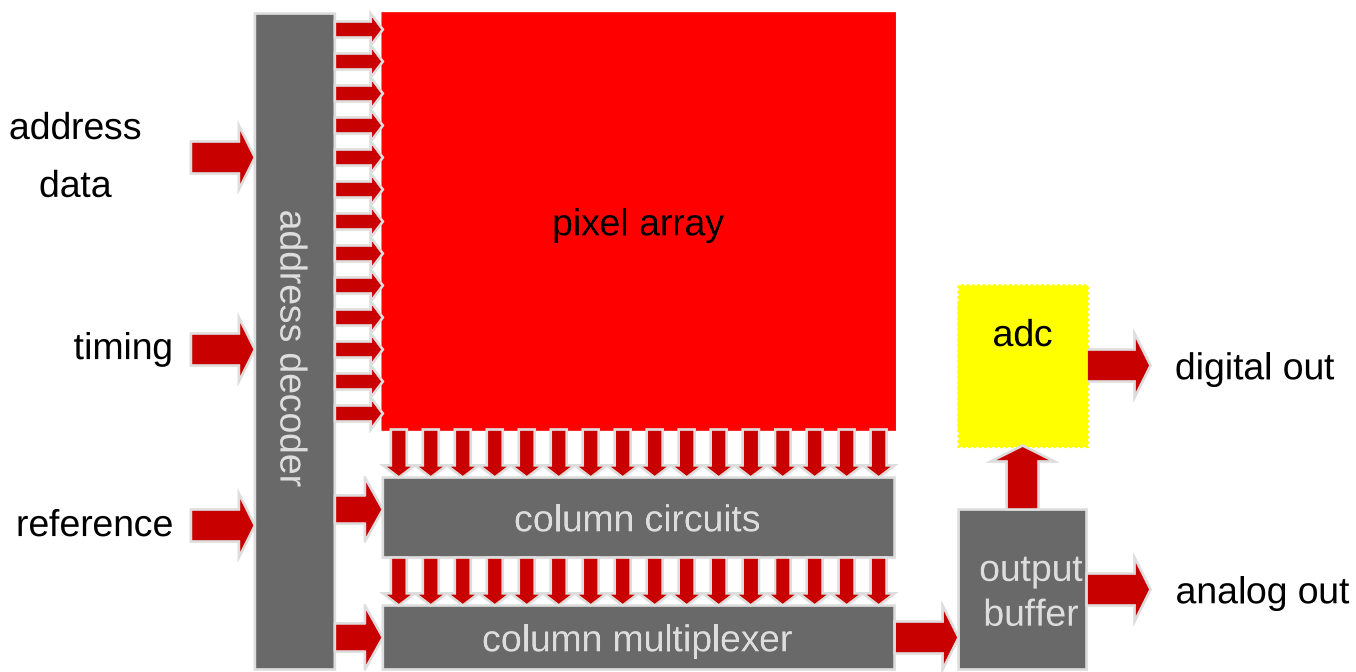
➢**CMOS imagers to become feasible in Broadcast**

CCD and CMOS Imagers

- **Both have**
  - **PIXELs** where photons are converted into electron-hole pairs (*usually only electrons are used and the holes are drained to substrate)*
    - In **CMOS** the charge is converted in a **VOLTAGE** in the pixel
    - In a **CCD** the charge stays in the **CHARGE** domain until it reaches the single output where it is converted in a voltage
  - an analog (CCD) or a digital (CMOS) output
- **Addition of pixel information**
  - for CCDs in the CHARGE domain=> SNR≈#
  - for CMOS in the VOLTAGE or CURRENT domain=> SNR≈√#
- Scanning
    - CCDs takes a snapshot/global shutter
    - CMOS has a rolling shutter and scans like a tube camera, maybe snapshot becomes available in the near future when the leakage is solved

Feature Size and CMOS Imagers

Basic Structure of a CMOS Image Sensor



Peter.centen@thomson.net

A Self fulfilling Prophesy

A Self fulfilling Prophesy

- **PERCEPTION**
  - CMOS imagers are cheap and have low quality
  - Is the perception correct
    - Yes………..but not complete
- **The sentence could also read**
  - CMOS imagers are expensive and have high quality
- **Basically when you don’t apply all the skills and technology available then CMOS is kept cheap and at low quality**
  - it is a mass market problem

Peter.centen@thomson.net

A Self fulfilling Prophesy

- **Parameters that matter**
  - Temporal **Noise** or readnoise
  - **Sensitivity** (QE and Fillfactor)
    - Together with readnoise it defines SNR
  - **Overexposure** margin (Qmax, Vsat)
    - Together with the readnoise it defines dynamic range
  - **Darkcurrent** or leakage current per pixel
  - **Fixed Pattern Noise in dark** or offset differences per pixel
  - **Fixed Pattern Noise in exposed images** or gain differences per pixel

A Self fulfilling Prophesy

- **CCDs have a long history and as such solved many of the performance related parameters**
  - **Sensitivity**
    - uLens
  - **Noise**
    - real CDS
  - **Darkcurrent, FPN and LAG**
    - P+toplayer

  - THESE solutions can be applied too in CMOS imagers but that needs additional masks and technology steps and hence is more **expensive**

The design of Xensium

Acknowledgement

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- *Thomson Research and Innovation, Villingen, G*

  Signal Acquisition & Processing

  C. Thébault, W. Endress, R. Zwing

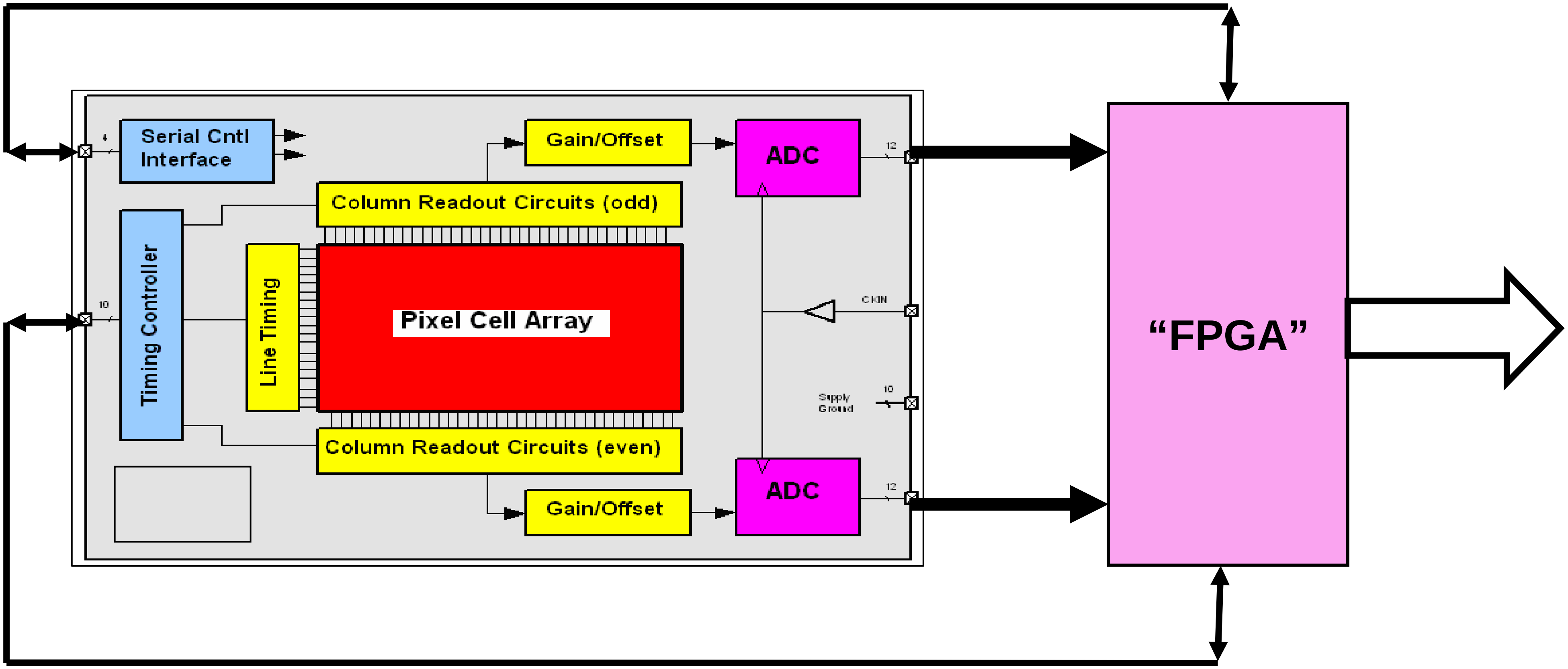
Design Approach

- **Broadcast is a low volume high performance market**
  - In Q1 2005 nobody in the CMOS field was interested in a dedicated development nor had a design available!
- **Special challenges for a CMOS-imager in broadcast applications**
  - 1920(H)x1080(V) :5**µ**mx5**µ**m pixels and 11mm image diagonal
  - Multimode :Interlaced (eg. 1080i60), progressive (**eg. 1080p30**)
  - QE and Noise :2000 lux, 3200 K, 90%, f/8-f/11, SNR=54 dB in Y
  - Dark current :FPN, shot noise
  - Qmax :over exposure margin >400%
  - Lag :None
  - ‘Blooming’ :must handle 16-fstop overexposure
  - Pixel-to-pixel :PRNU<1%
  - column-to-column:<0.06%
  - 3-imagers synchronized for use in R,G and B simultaneously
  - And many other imaging related topics both optical and electrical

Design Approach

- **An imager is an ANALOG device**
  - Keep the imager as simple as possible and make use of of-the-shelf components like FPGA, memory, processing blocks
  - Allow for a simple state machine and ADC's on-chip
  - Flexibility in readout and in frame rate
  - Choose a camera architecture: video processing and imager, that eases CMOS image sensor design
  - Use a 3T-pixel in 0.18μm process
    - do real CDS off-chip
    - use hard reset, no soft reset because of inherent lag problems
    - many other advantages

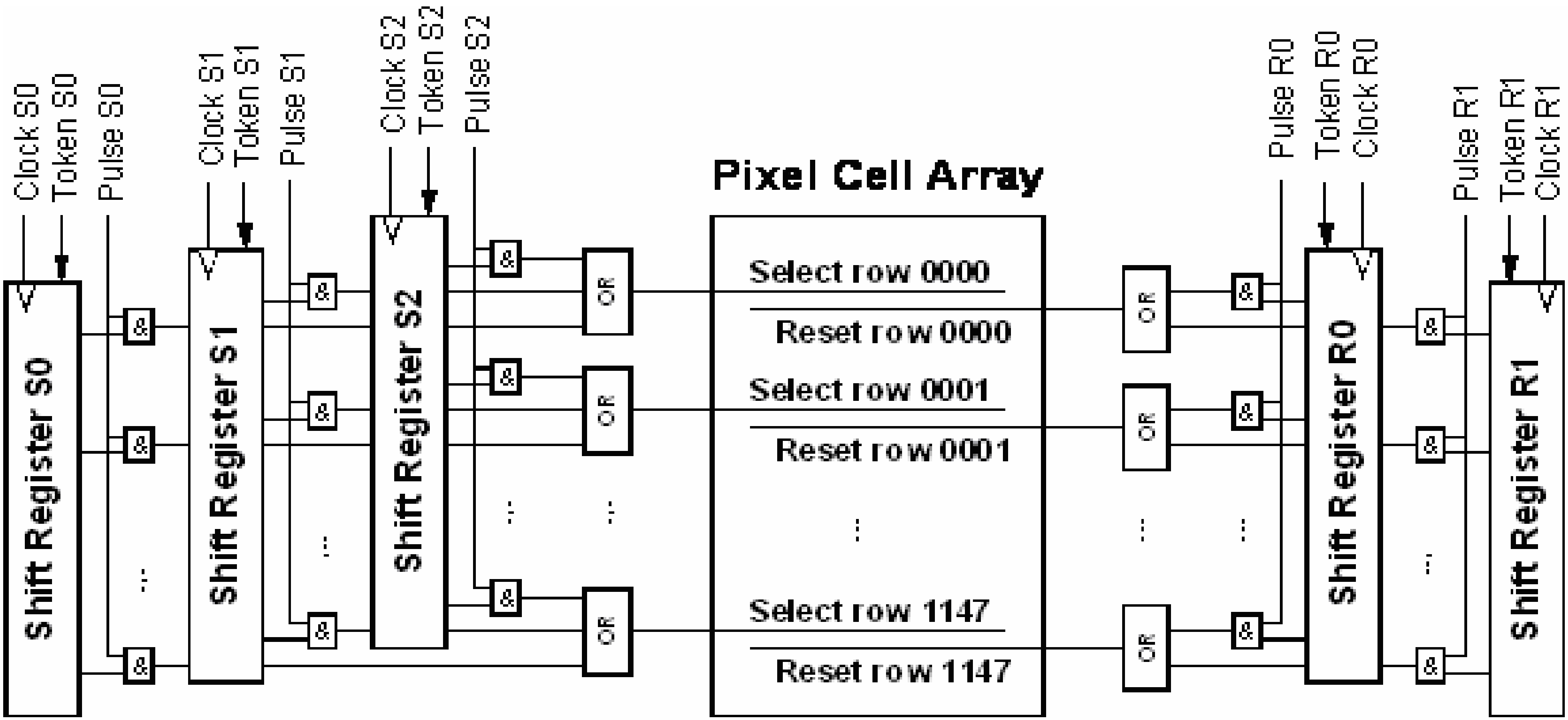
Chip Block Diagram



Black Reference Pixels	**Active Pixels**
-80 black reference columns	-1978 active columns (1920)
-40 black reference rows	-1108 active rows (1080)

Shift Registers

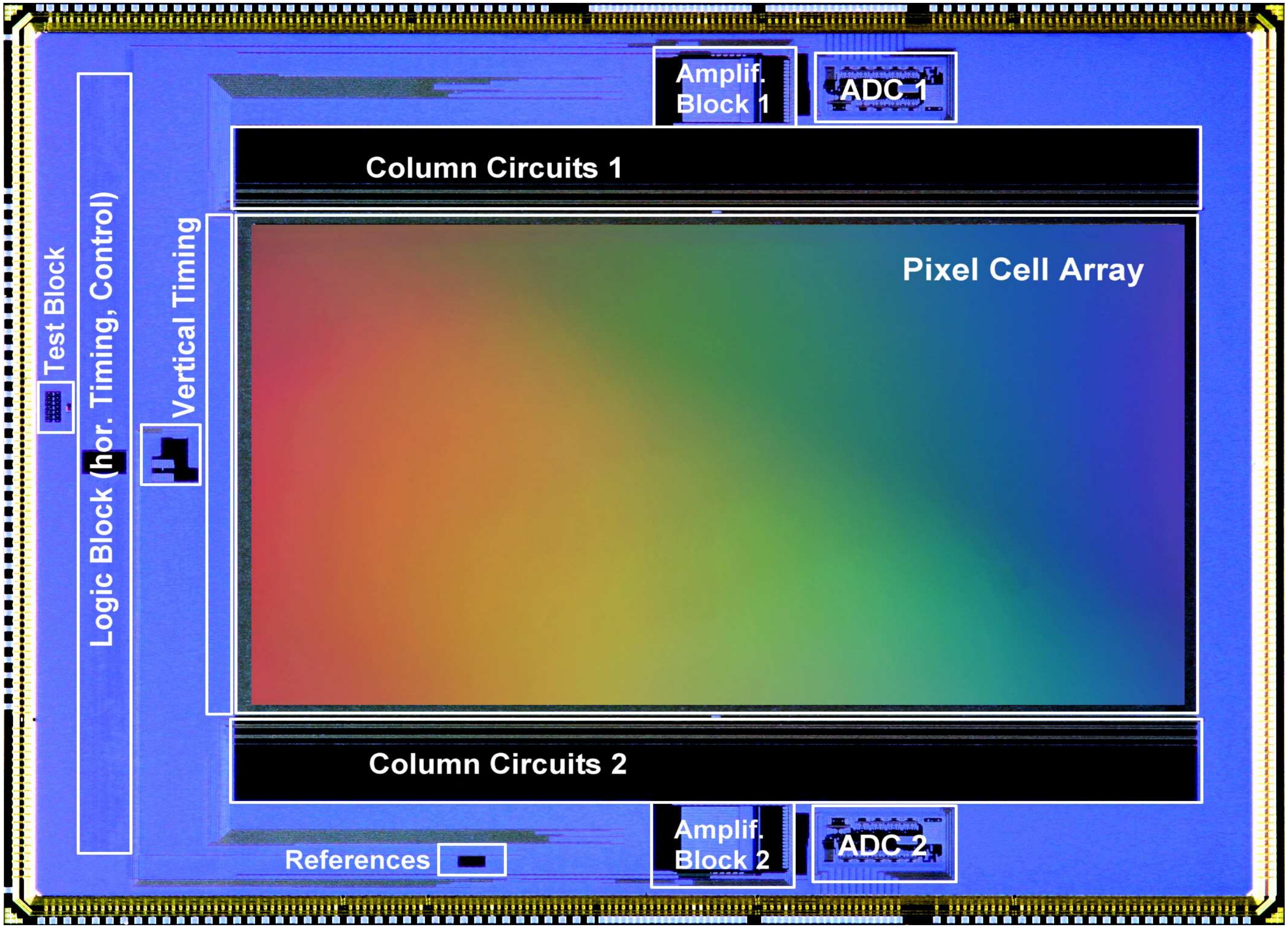
Multiple select and reset shift registers for flexible scanning



Flexible Scanning

- At 2/3 inch image diagonal
  - 1920(H) x 1080p(V)
  - 1920(H) x 1080i(V) with Frame or Field mode
  - 1920(H) x 540p(V) with 1080p or 540p aperture
- At different image diagonals (ROI)
  - 1280(H) x 1440i(V)
  - 1280(H) x 720p(V)
  - 1724(H) x 485p(V)
  - 1724(H) x 485i(V)
- Raw frame rates for the 3 main modes
  - 1080p90 or 1080i180 or 720p180 (=>1080p120)
  - Maximum clock frequency ADCs: 2x112 MHz (=> 2x148 MHz)

Chip Micrograph



Peter.centen@thomson.net

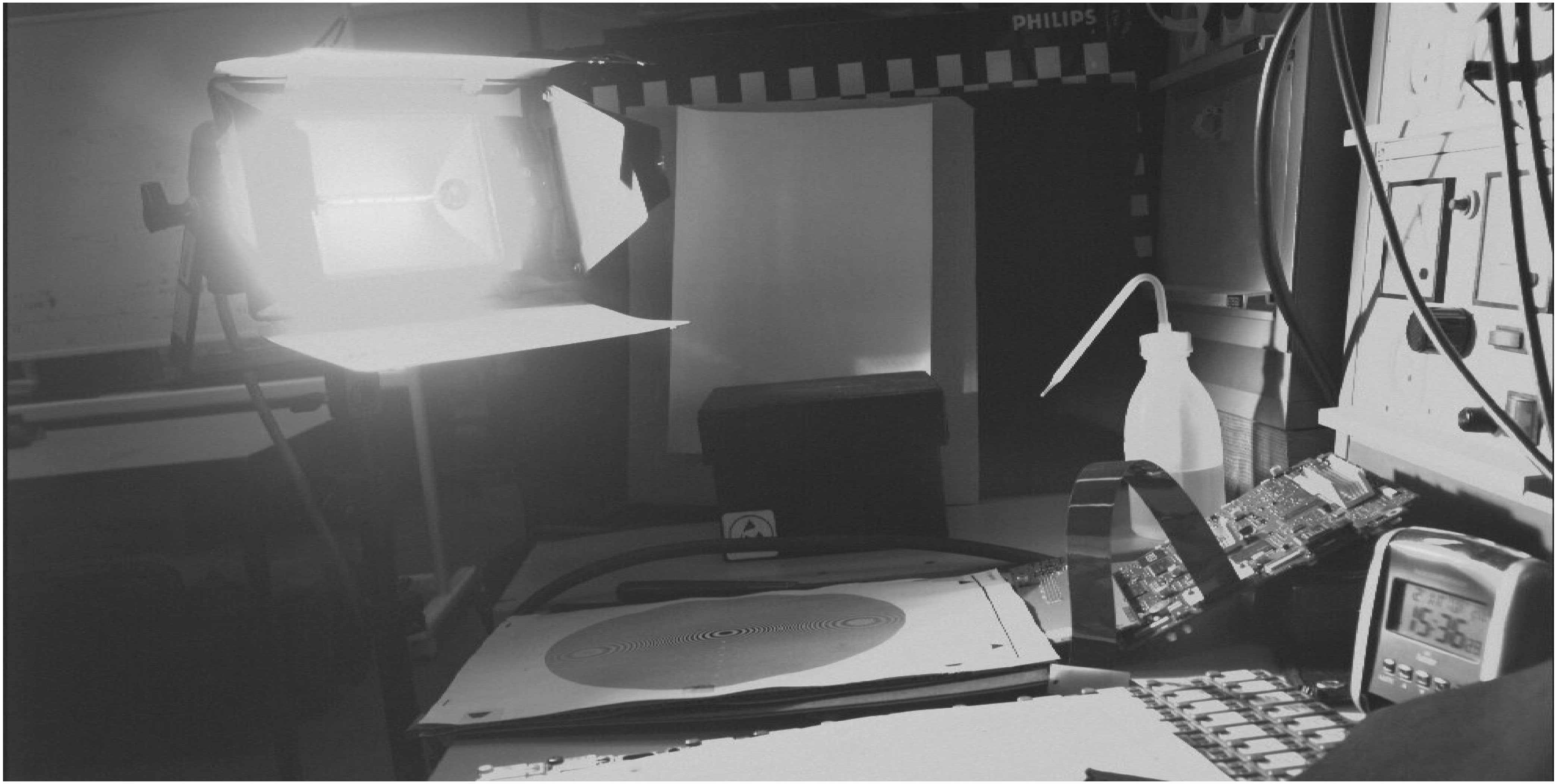
Chip Micrograph

@Michael Schreiber

High-DR modes

- under investigation
- Time sub sampling, 3 samples of the pixel voltage
  - First sample at black
  - Second sample at eg ¼ of the nominal integration time
  - Third sample at the end nominal integration time
- Vertical sub sampling
  - Even rows have pixels with a nominal integration time
  - Odd rows have pixels with eg ¼ of the nominal integration time
- Horizontal sub sampling
  - Even columns have pixels with a nominal integration time
  - Odd columns have pixels with eg ¼ of the nominal integration interval
- Pixel with knee function
  - **Lineair part and knee part**

Experiment: High-DR Image



Peter.centen@thomson.net

Table of characteristics

Pixel size, transistor count	5µm x 5µm; 3T
Number of pixels including opt. black	2048(H) x 1148(V)
Pixel fill factor (without micro-lens)	56%
Analog to digital conversion	2 ADCs of 12bit
Scanning rate demonstrated (2x148MHz)	1080i240 or 1080p120
Conversion gain FD	80µV/e^-
Idark @ 60^{o}C	0.4nA/cm^2
Temporal noise, pixel only, 27^{o}C	4e^-
Temporal noise, all contributors, 27^{o}C	11.5e^-
Sensitivity in green (color splitter)	32ke^-/lux-sec
Maximum reachable dynamic range	116dB in interlaced mode 122dB in progressive mode
Linear saturation level	>15ke^-
Power dissipation	550mW@1080i120

Evaluation Techniques

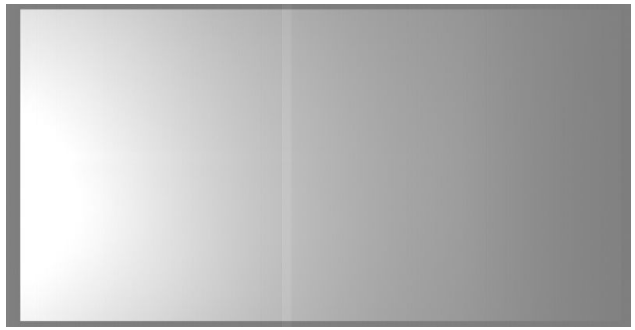
Evaluation Techniques

- **The design of a CMOS imager is not straight forward**
  - Parameters claimed are usually only partly true
- **Traditional camera/imager measurement techniques take to much time or offer less information**

- **Shotnoise transferfunction**
- **2-Dimensional histogram**

Shotnoise tranfercurve

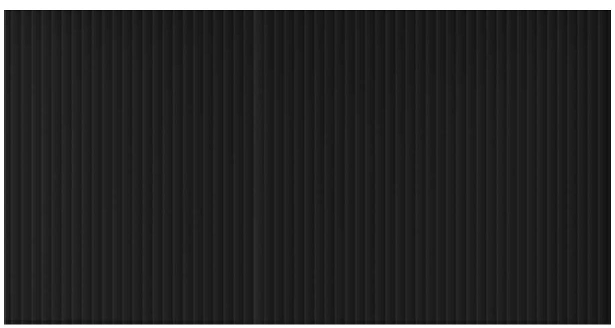
Only 3 pictures needed

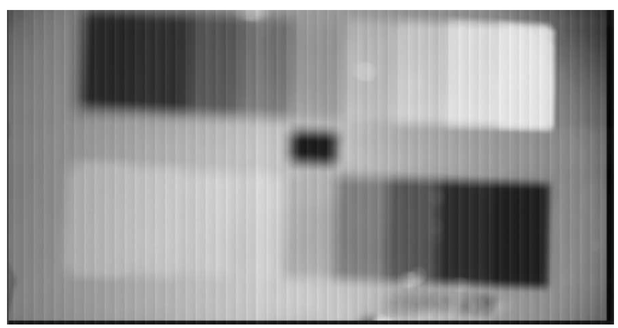


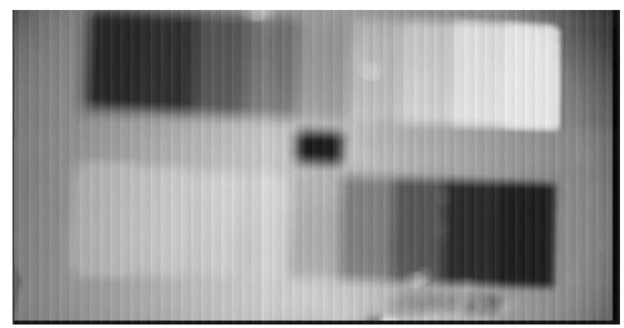
BLACK:

GRAY 1: shotnoise+

GRAY 2: shotnoise+







Peter.centen@thomson.net

Shotnoise

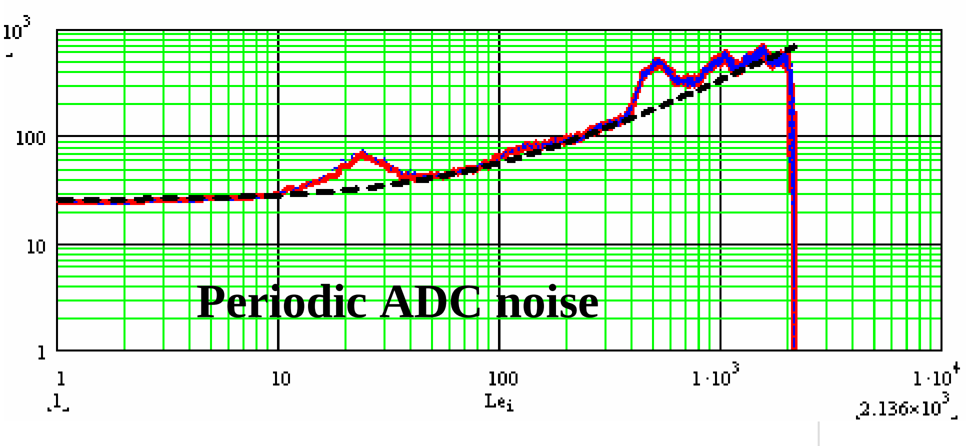
- **Taylor expansion**
  - F(N+dn)=F(N)+F'(N) dn
  - dn is the noise term
  - In case of two gray images which are taken shortly after each other the ONLY difference between the amplitude of pixels in both images at the same postion is the readnoise Nd and the SHOTNOISE: F'(N).(dn1-dn2)
    - The SHOTNOISE is by physics law proportional to square root of the outputsignal.

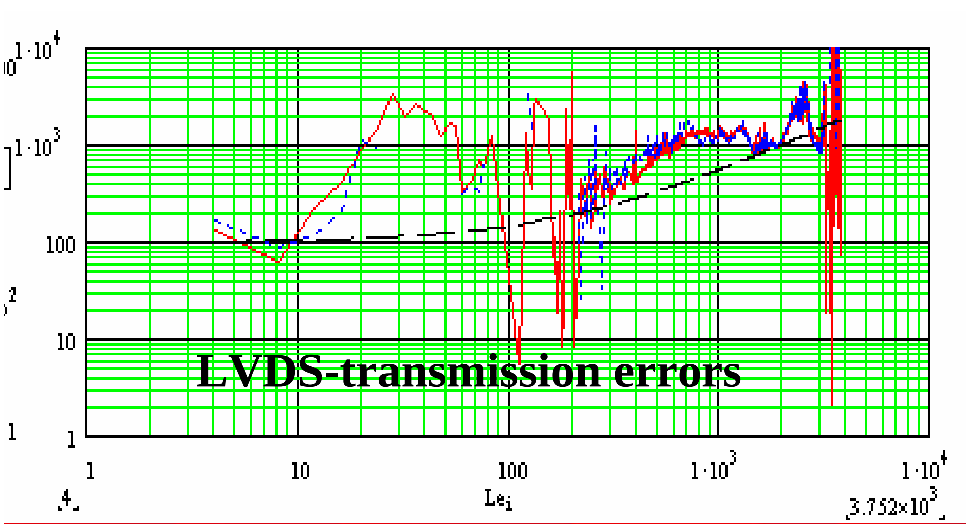
      More precisely given a pixel where a charge packet of N electrons is generated then the shotnoise equals

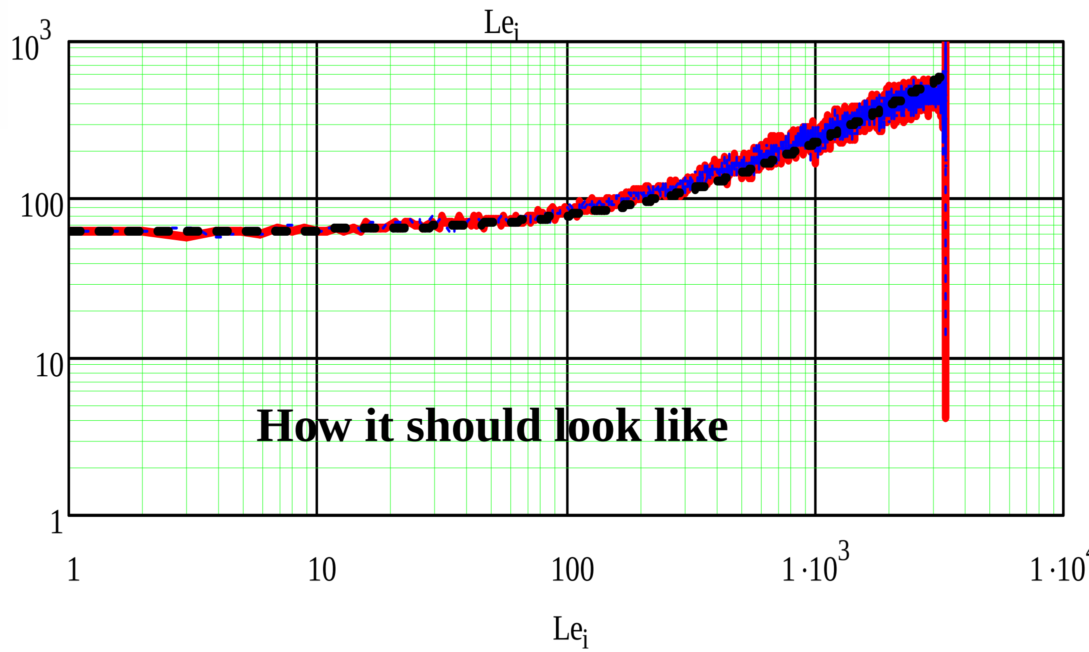
      $$\sqrt{N}$$
  - $<(dn1-dn2)^2>=2*N+2*Nd^2$
  - IN the lineair case the outputsignal and noise
    - Outputsignal=F(N)=K*N and Noise_Power=K^2*(N+Nd)
- Ratio Noise_Power/Outputsignal approaches the gain K asymptotical
  - But in case of anomalies the noise increases

Peter.centen@thomson.net

Shotnoise transfercurve







r.centen@thomson.net

Shotnoise transfercurve

- Generalized through allowing almost any type of image
  - Constraints:
    - no sharp edges….in case of vibrations and
    - no illumination differences between the two ‘gray images’
- Grab the 3 images: Black, Gray 1 and Gray 2 and process them:
- For i,j = 1,1 to Nrows, Ncolumns do
- Vout= ImageG1[i,j]-ImageB[i,j]);
- Histo(Vout)= Histo(Vout)+1;
- Variance(Vout) = Variance(Vout) +
- +{(ImageG2[i,j]-ImageG1[i,j])-Variance(Vout)} /Histo(Vout);
- End
- NOTE: The Variance is written as a moving average in recursive form!

Generalization of the shotnoise transfercurve

$$V_{out} = K * N$$

Signal: from electrons N to output

$$U_n = K * \sqrt{N + N_d^2}$$

Noise: Shotnoise N and readnoise Nd

$$V_{out} = f(N)$$

$$U_n = \left| \frac{df(N)}{dN} \right| * \sqrt{N + N_d^2}$$

$$\int_0^N \frac{dN}{\sqrt{N + N_d^2}} = \int_0^{Vout} \frac{dV_{out}}{U_n}$$

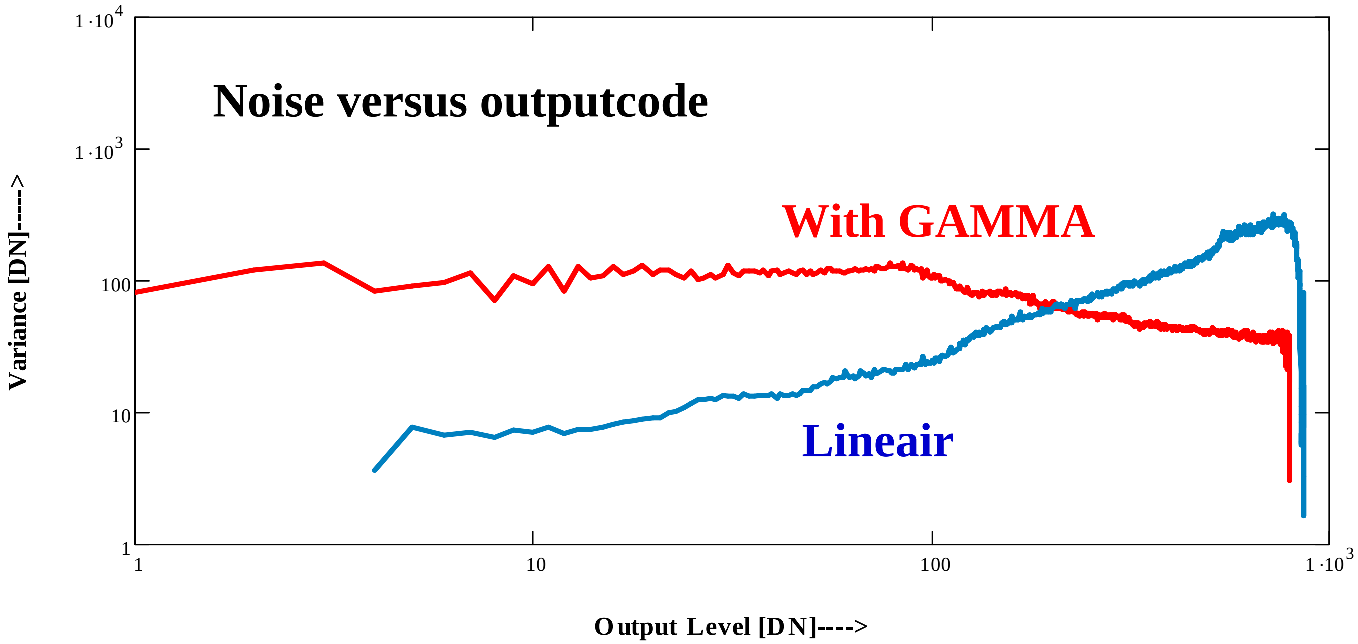
$$N = \left(\frac{1}{2} * \int_0^{Vout} \frac{dV_{out}}{U_n} + N_d \right)^2 - N_d^2$$

Given the

-outputlevel Vout

-noiselevel Un

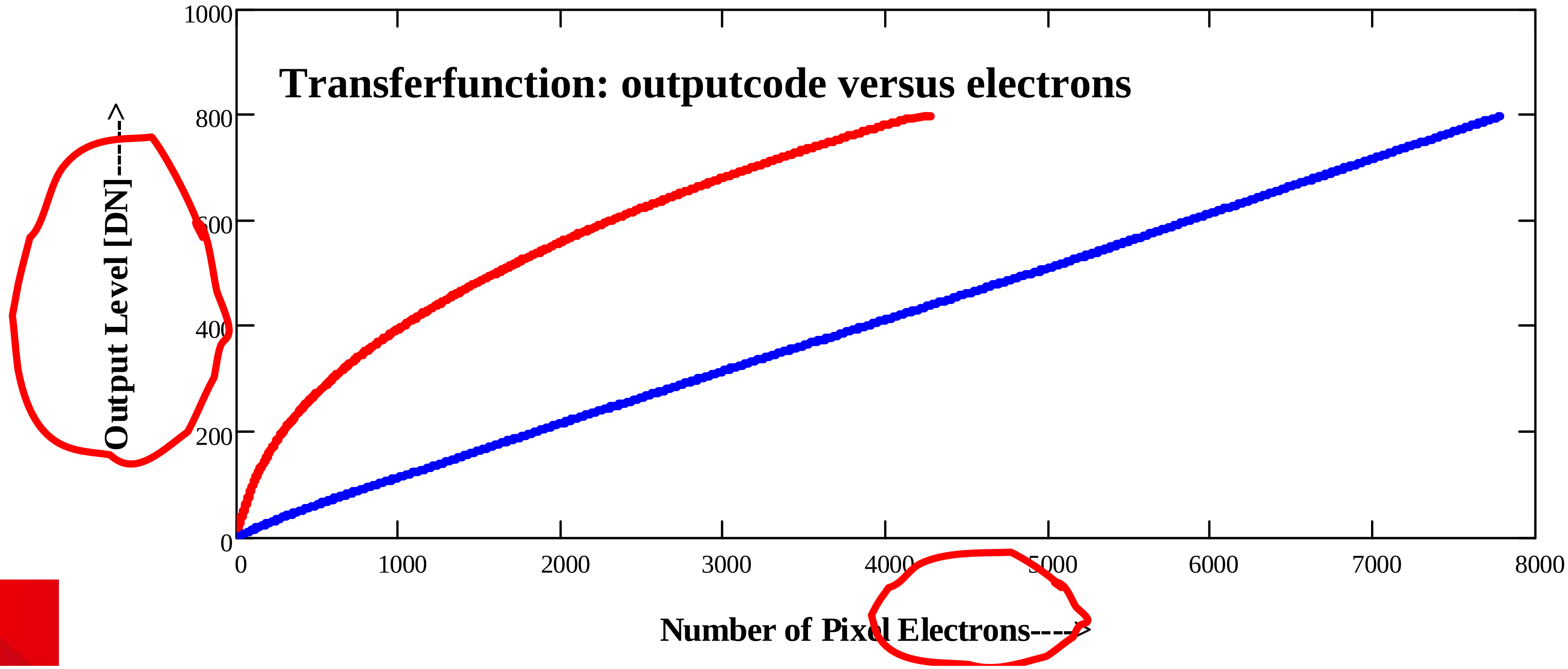
The tranfercurve can be calculated



And

when it looks like

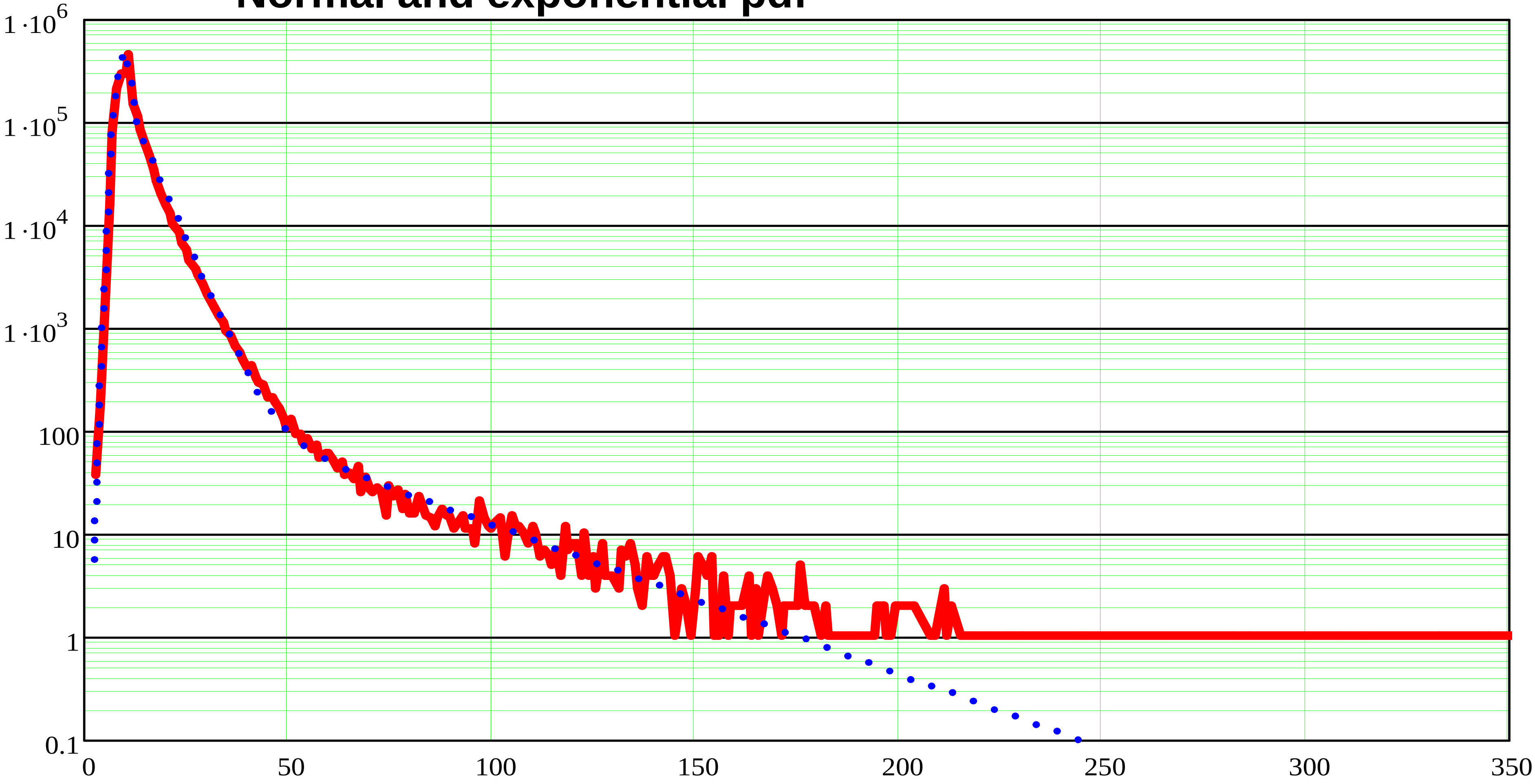
as it should



2-dimensional histogram

1-dimensional histogram

How a 1-dim histogram looks like of the darkcurrent
Normal and exponential pdf



New Technique for Dark Current Investigation

- *2-Dimensional Histogram*
  - *Looking for correlation in two images*
    - *Call them image1 and image2*
  - *Use the pixel amplitude of image1 as position on the X-axis and the pixel amplitude of image2 as position on the Y-axis*
  - *Count how often the same "position" occurs*
    - *The same pixel in image1 and image2 represents one point in this x,y*

Evaluation Techniques: 2-dimensional histogram

Used to test the dependence on ONE parameter in a graphical way

Normal histogram

For I:=1 to nr_of_rows

For J:=1 to nr_of columns

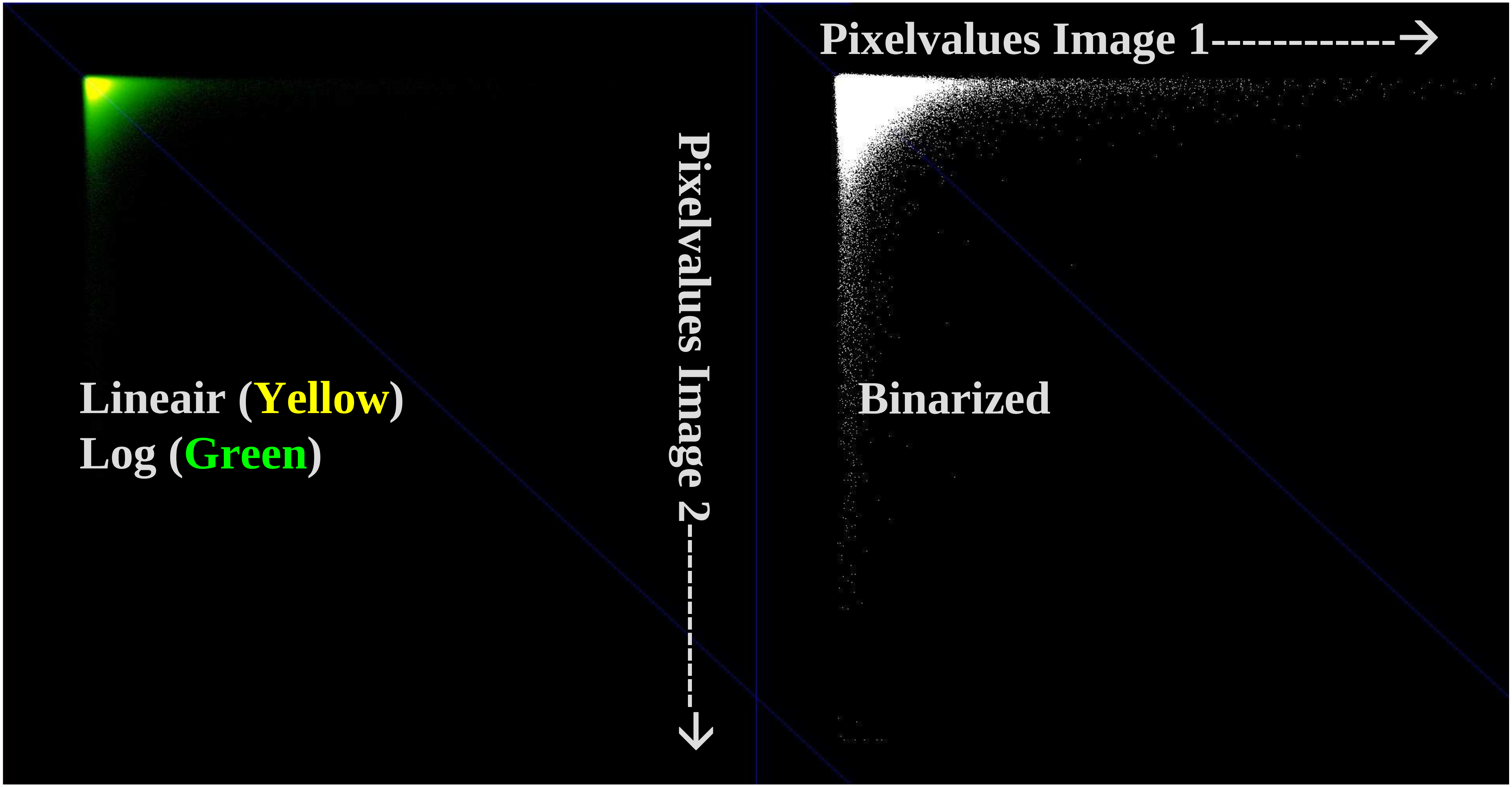
INTENSITY[**IMAGE1[I,J]** ; **IMAGE2[I,J]**]**:= HISTO2D[IMAGE1[I,J] ;IMAGE2[I,J]]+1**

Binarized histogram

For I:=1 to nr_of_rows

For J:=1 to nr_of columns

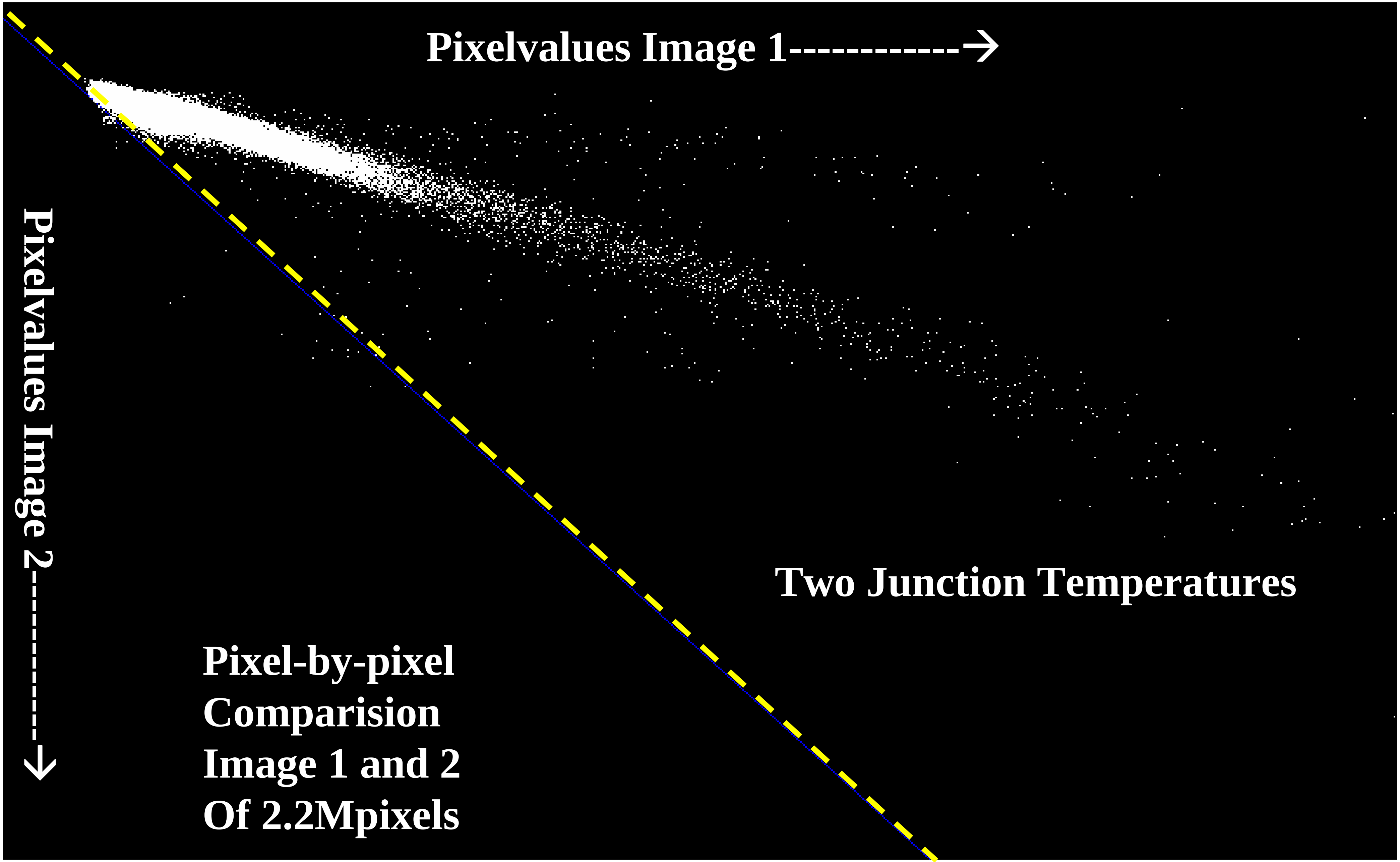
INTENSITY[**IMAGE1 [I, J]** ; **IMAGE2[I, J]**]**:=1**



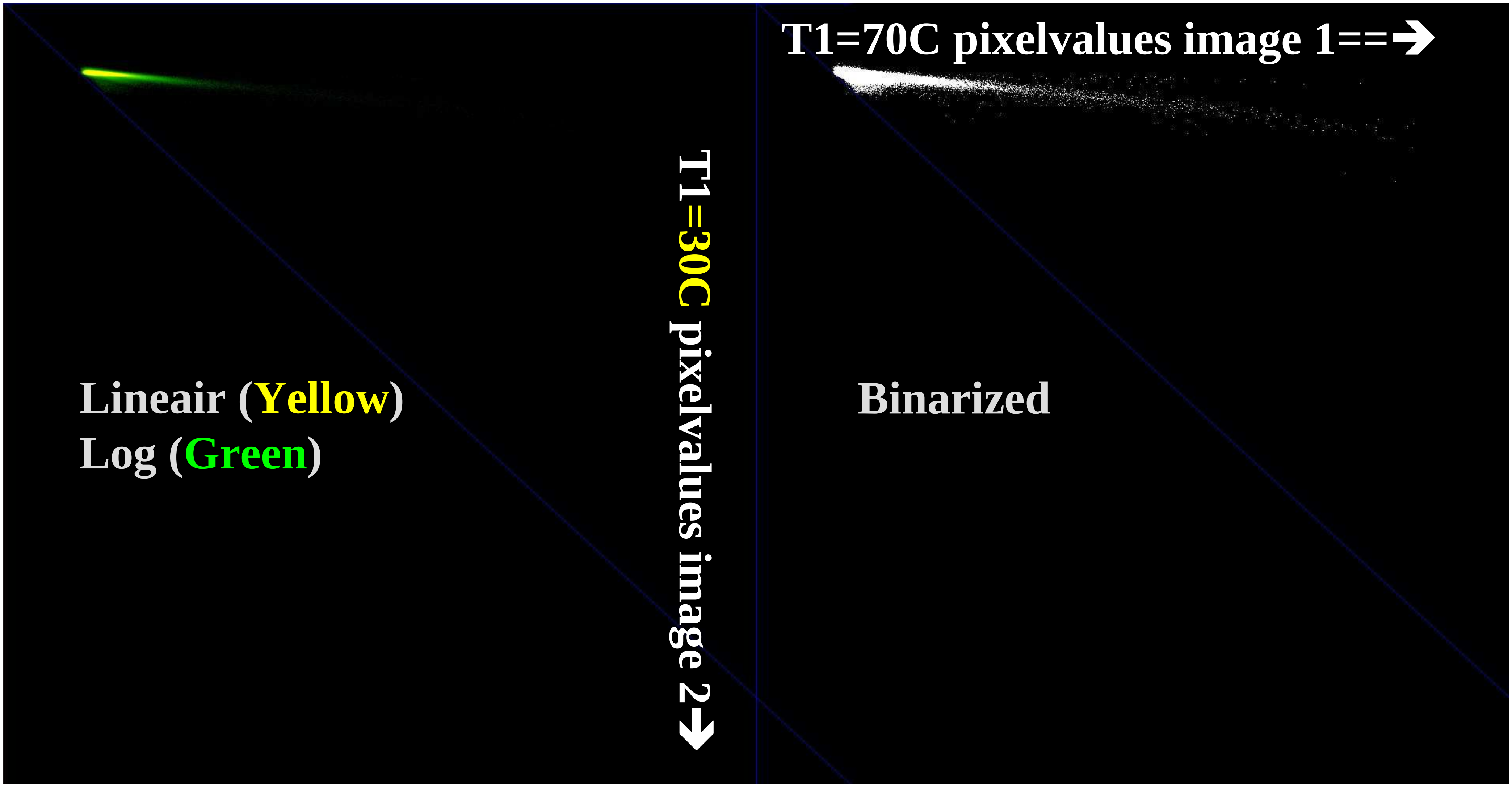
Uncorrelated 2D histogram

Evaluation Techniques: 2-dimensional histogram

- **Assumption:** **the pixelamplitude as a function of temperature is determined through activation energy, Ea. This is known as darkcurrent or leakage current**
  - Pixelamplitude = T^2 EXP(Ea/kT)
  - If the activation energy is the same for all pixels than this means that all pixel amplitudes can be mapped from one temperature to another through a multiplying factor
  - In an 2-dimensional histogram this shows as a straight line with some widening through the noise



Peter.centen@thomson.net



Two Junction Temperatures: T1-T2=70C-30C=40C

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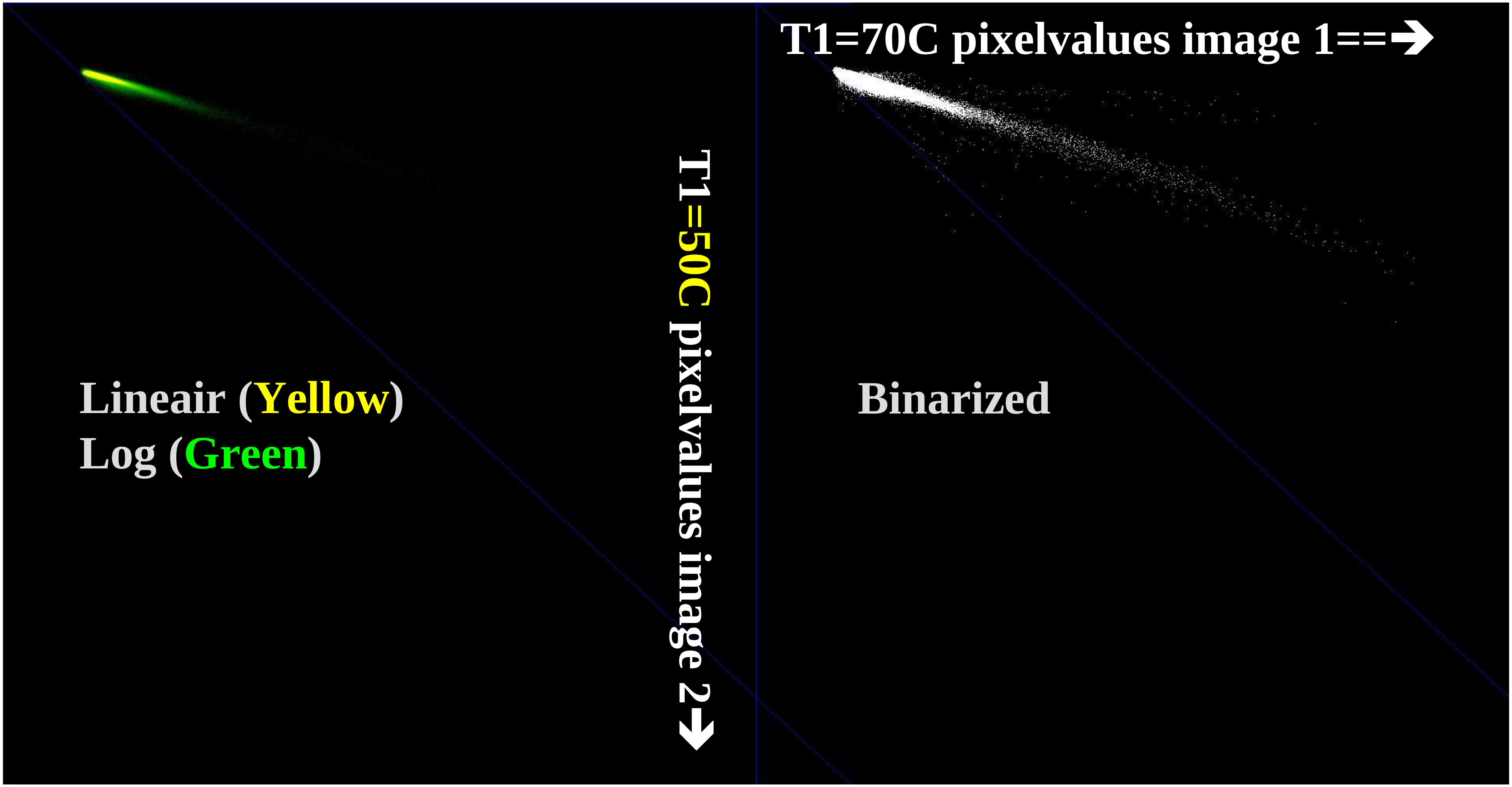
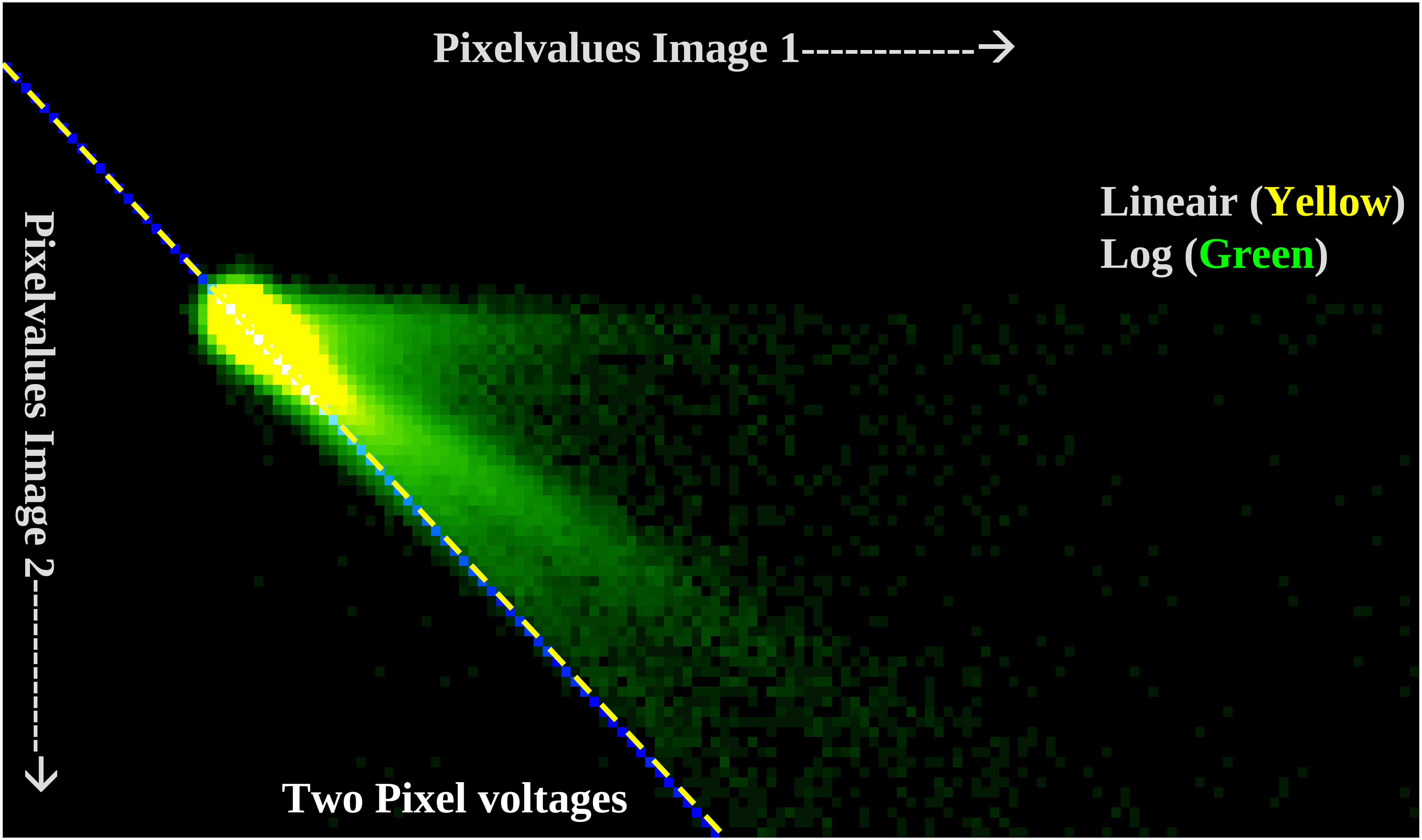


Two Junction Temperatures: T1-T2=70C-50C=20C


Pixelvalues Image 1------------→
Lineair (Yellow)
Log (Green)
Pixelvalues Image 2------------→
Two Pixel voltages

Conclusion

- **Progress of technology showed that CMOS imagers for demanding applications like Broadcast are possible now**
- **A 2/3 inch CMOS image sensor, in 0.18μm 1P4M process, is presented that fulfills full HDTV broadcast quality**
- **Among the many scanning formats are 1080p, 1080i and 720p with matched anti-aliasing properties**
- **The imager has multiple ways for generating High-DR images**
- **A noise level of 4e$^-$ for the pixel and 11.5e$^-$ overall was obtained with off-chip CDS**
- **The maximum raw capture rate is 1080i180, 1080p90 and 720p180**
  - 1080i240 or 1080p120 has been demonstrated
- **Several analyses techniques have been developed to speedup the CMOS imager design**

Peter.centen@thomson.net