Noise at the System Level

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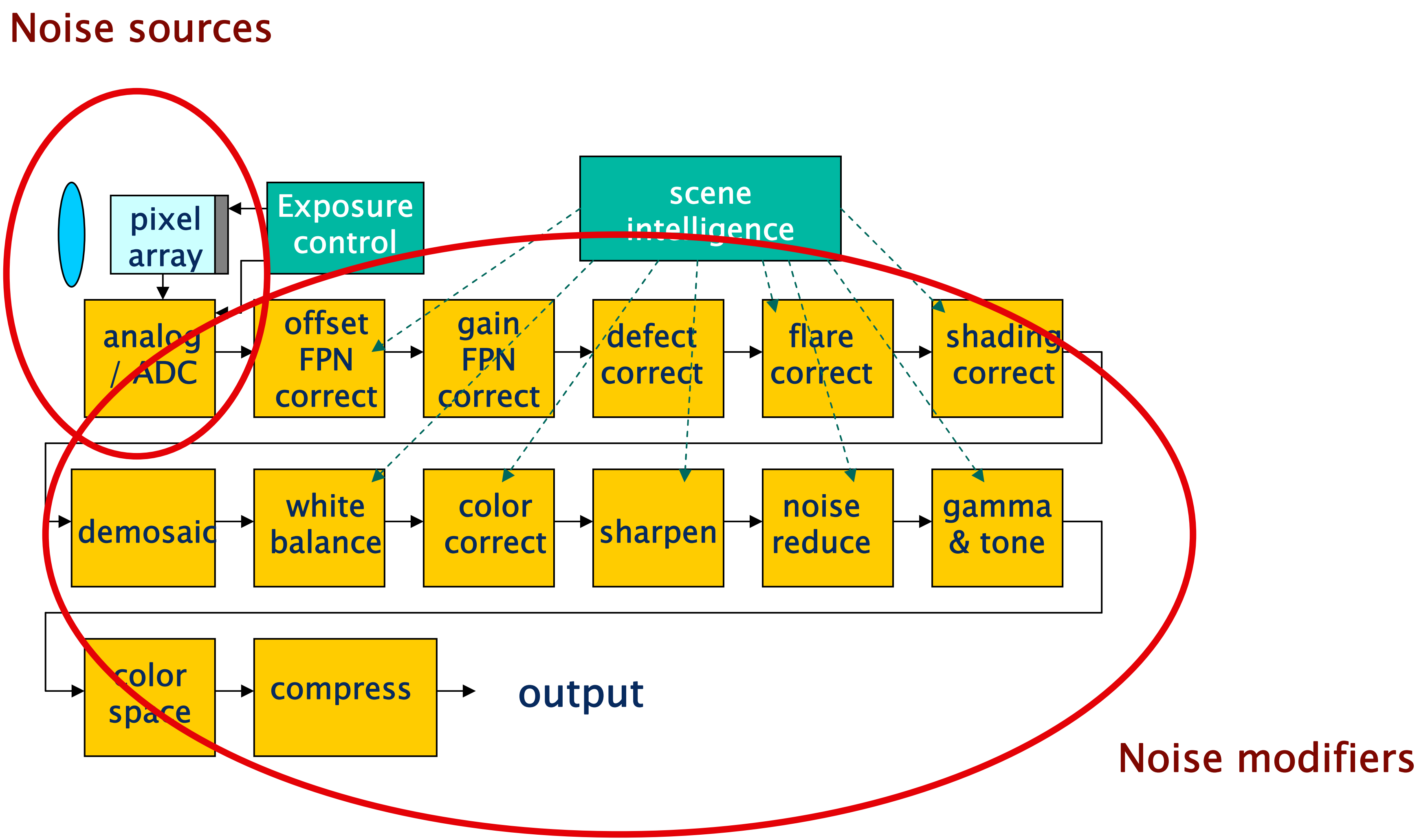
ISSCC 2007 Forum:
Noise in Imaging Systems

Introduction

The systems view



Major CCD and CMOS noise sources

- Both
  - Flare
  - Vignetting
  - PRNU (pixel lithography)
  - Photon shot noise
  - Read noise (thermal, 1/F, kT/C)
  - Row reference
- CCD
  - Column dark current variation
  - Smear
  - Blooming
- CMOS
  - Column gain variation
  - PGA / ADC gain and offset variation

Major noise modifiers

Increases noise:

- White balance
- Color correction
- Sharpening
- Tone mapping

Decreases noise:

- FPN correction
- Noise reduction filtering
- compression

Diffuses noise:

- Pixel reconstruction
- Color space conversion

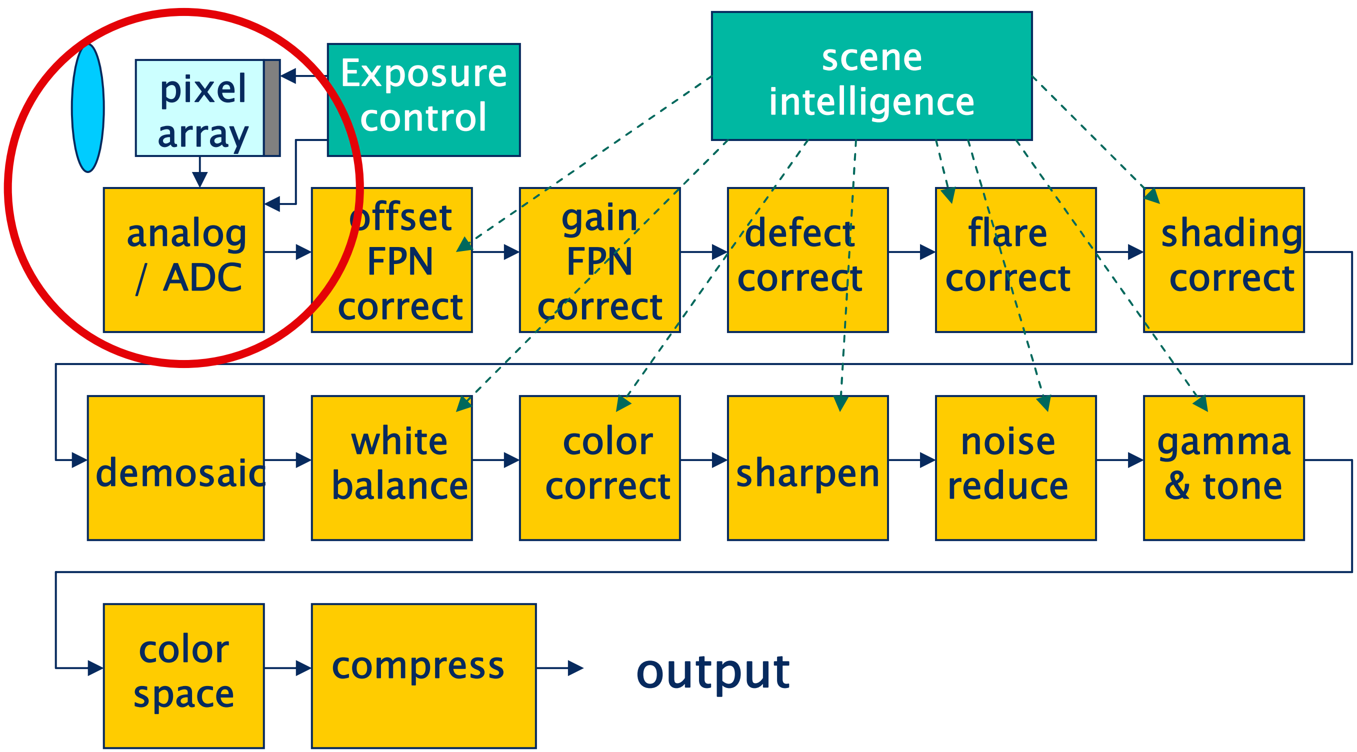
Overview

- There are many sources of noise and interference in imaging systems
- Image processing has a big effect on noise at the systems level
- Noise measurement is complicated by the (unknown) effects of image processing

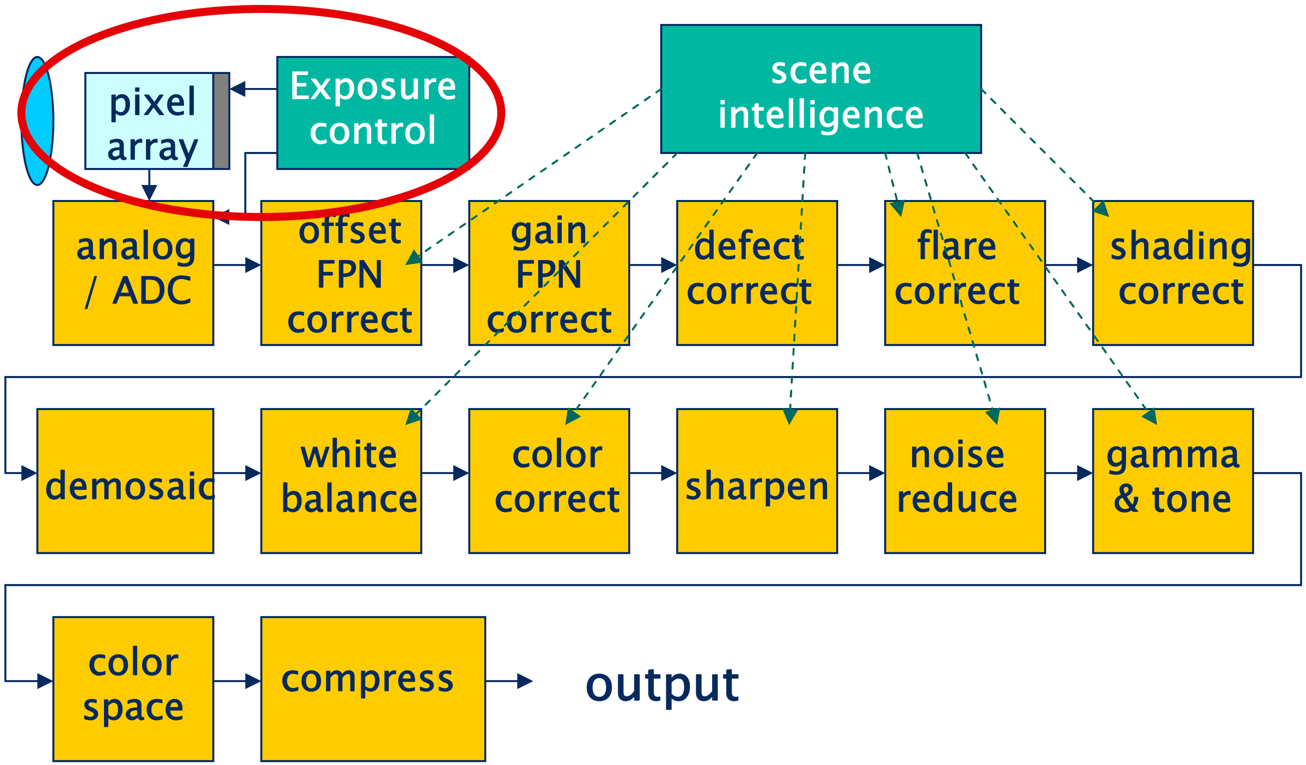
Noise from the perspective of image processing

Pixel / circuit noise sources

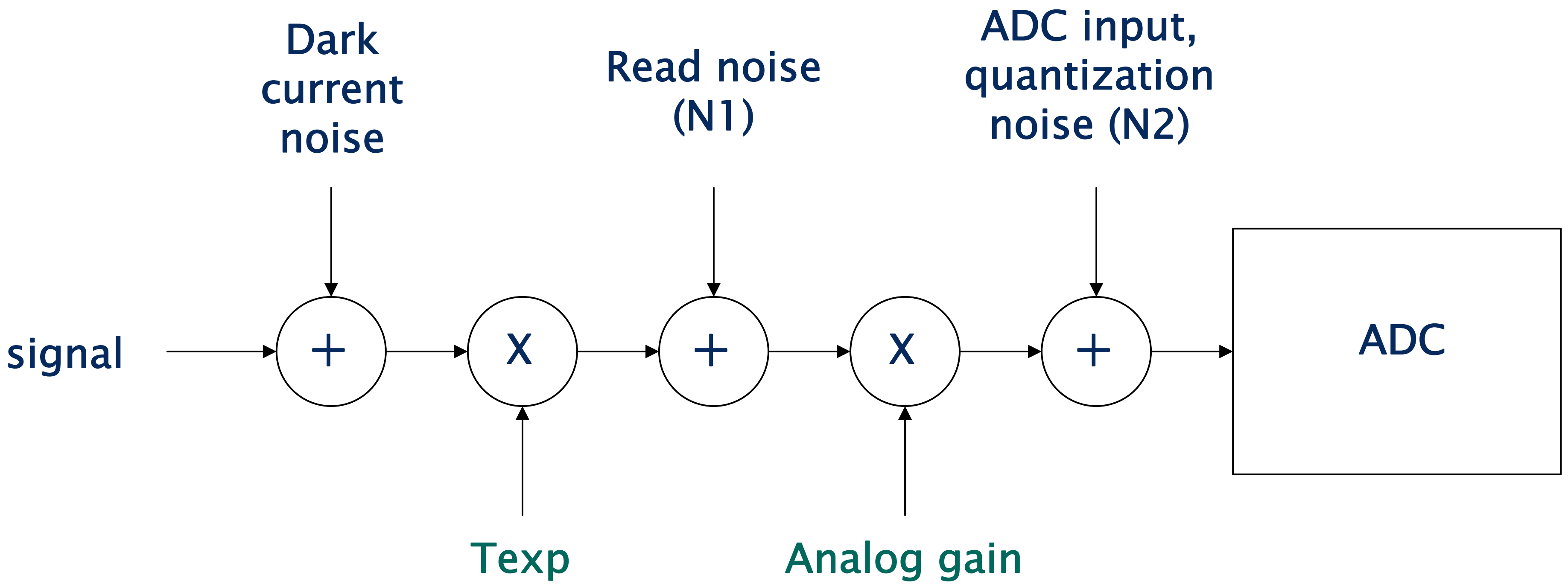
(reviewed in other ISSCC noise forum presentations)



Exposure control



Simplified noise / exposure control model

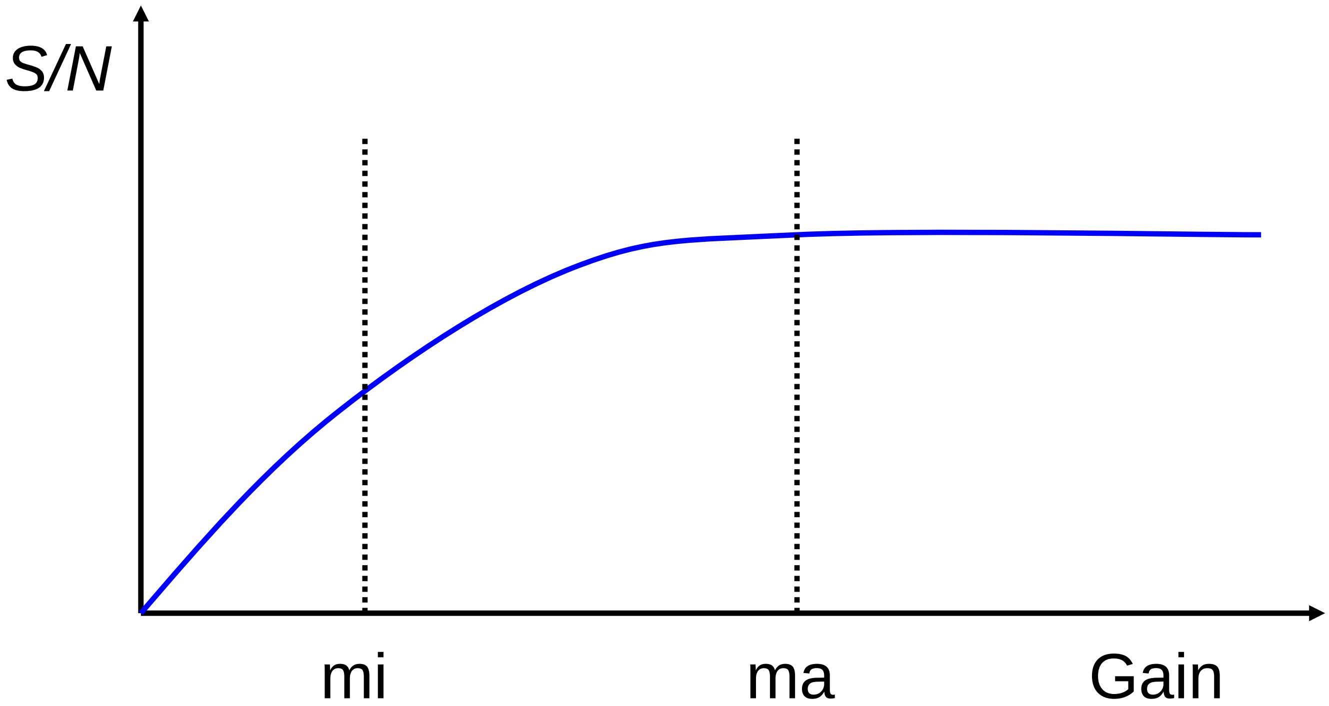


Exposure controls

SNR variation

$$S/N = \mathrm{S} / \sqrt{\sigma_{\mathrm{N1}}{}^{2} + \frac{\sigma_{\mathrm{N2}}{}^{2}}{\mathrm{G}^{2}}}$$

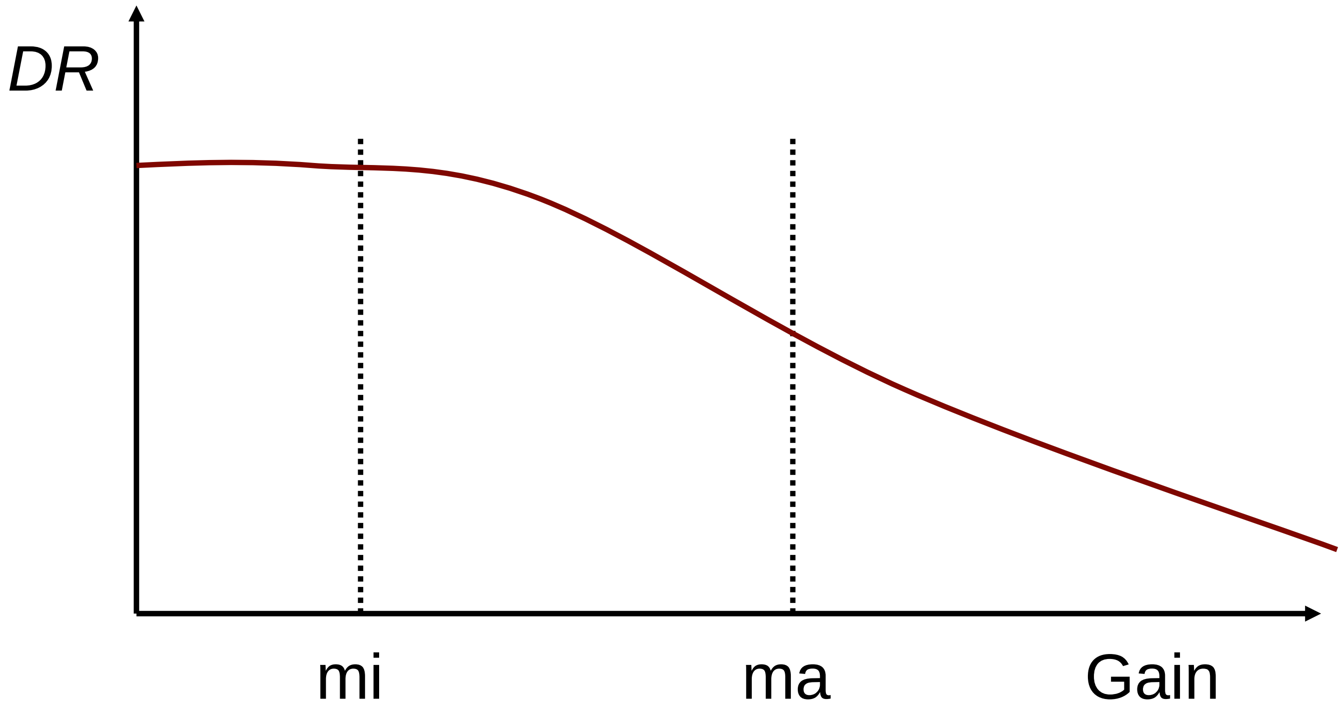
The signal to noise ratio increases with gain until it is limited by noise source N1.



DR variation

$$DR = \frac{255}{k} / \sqrt{G^2 \sigma_{N1}{}^2 + \sigma_{N2}{}^2}$$

The dynamic range decreases with gain.



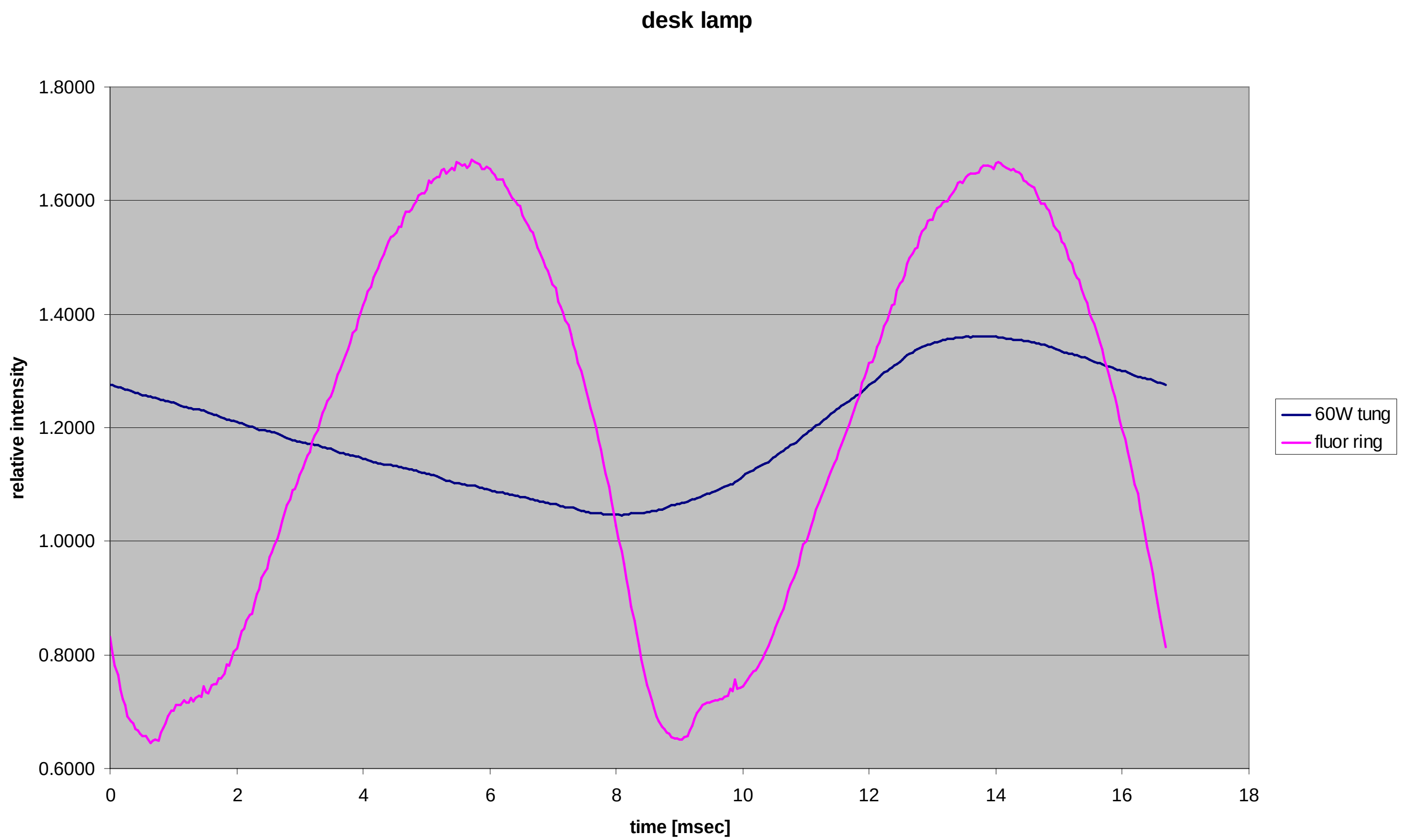
Exposure

Short exposure
(noise, quantization)

Long exposure
(clipping)

Ideal exposure

Flicker suppression



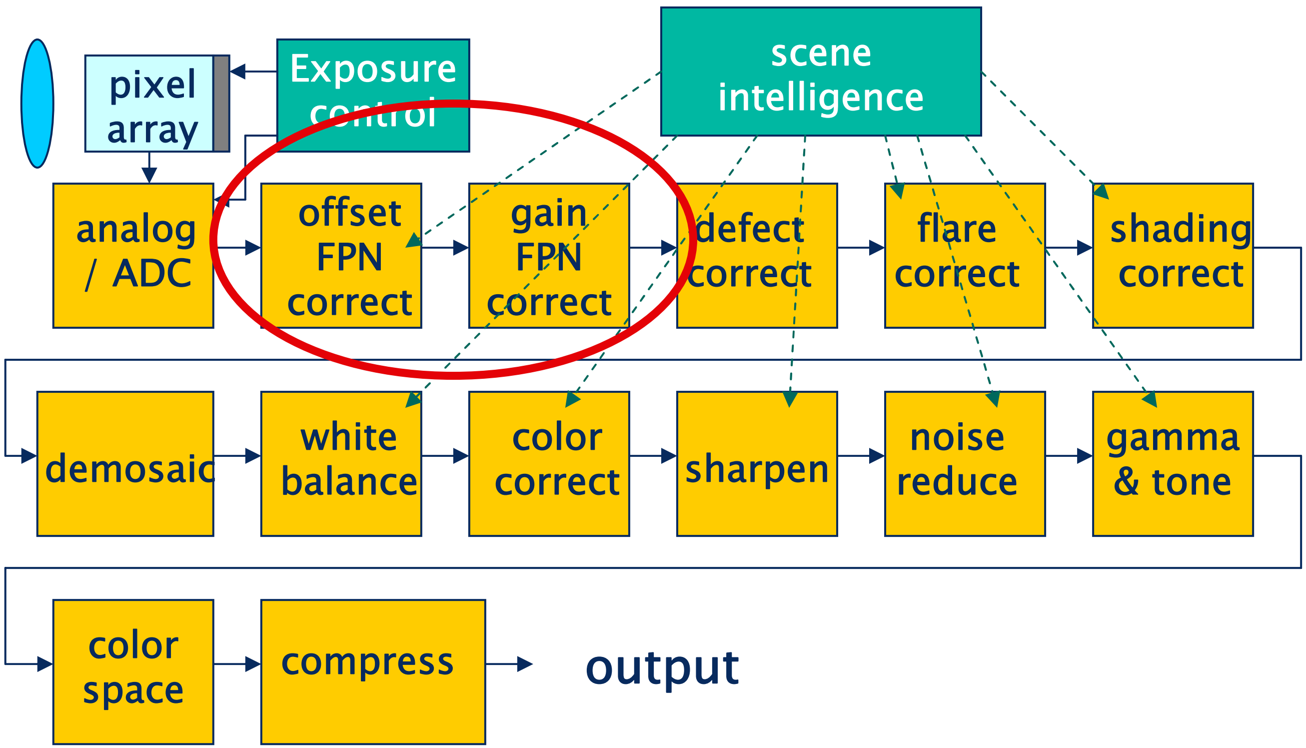
Restrict exposure and frame periods to multiples of the flicker period (e.g. 1/120 Hz)

What's wrong with this picture?

Importance of exposure control

- Underexposure leads to poor SNR and possibly posterization
- Underexposure may lead to poor color reproduction (due to pixel non-linearity)
- Overexposure leads to clipping
- Incorrect exposure timing may cause flicker to appear

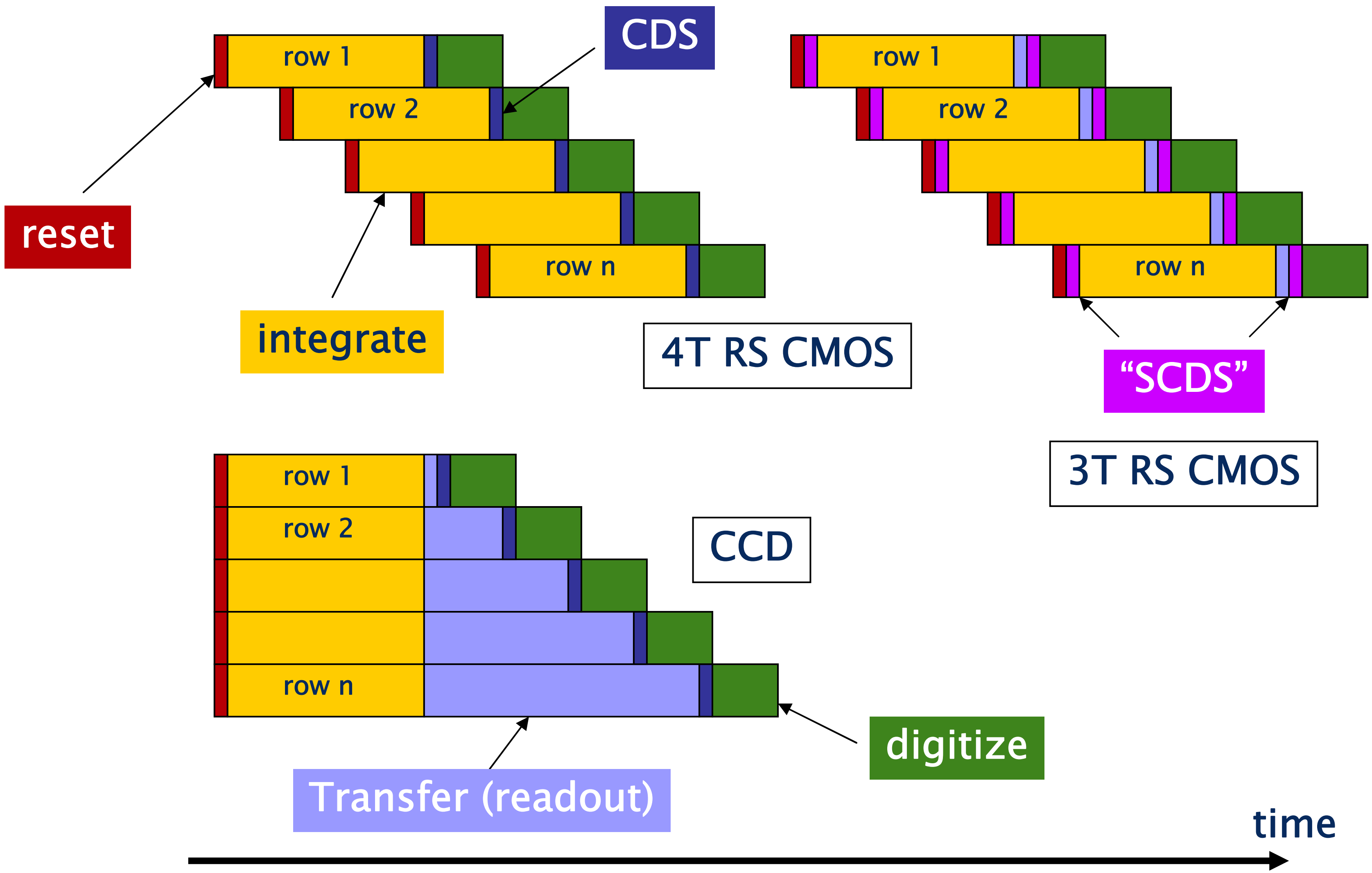
Offset / gain correction



Sources of offset FPN

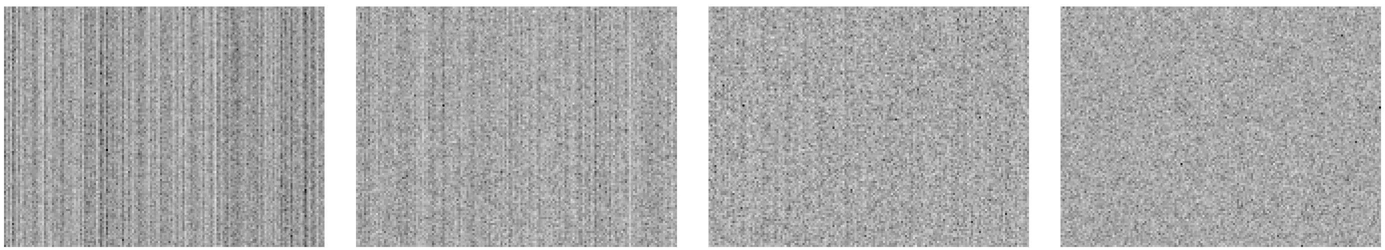
- Row FPN
  - Optical black clamp circuit (CCD & CMOS)
  - Power supply noise (CMOS)
- Column FPN
  - Dark current (CCD)
  - Column offset (CMOS)
- Random FPN
  - Dark current (CCD & CMOS)

CCD and CMOS readout timing



Temporal separation introduces susceptibility to dark current, power supply noise

Visibility of row/column FPN

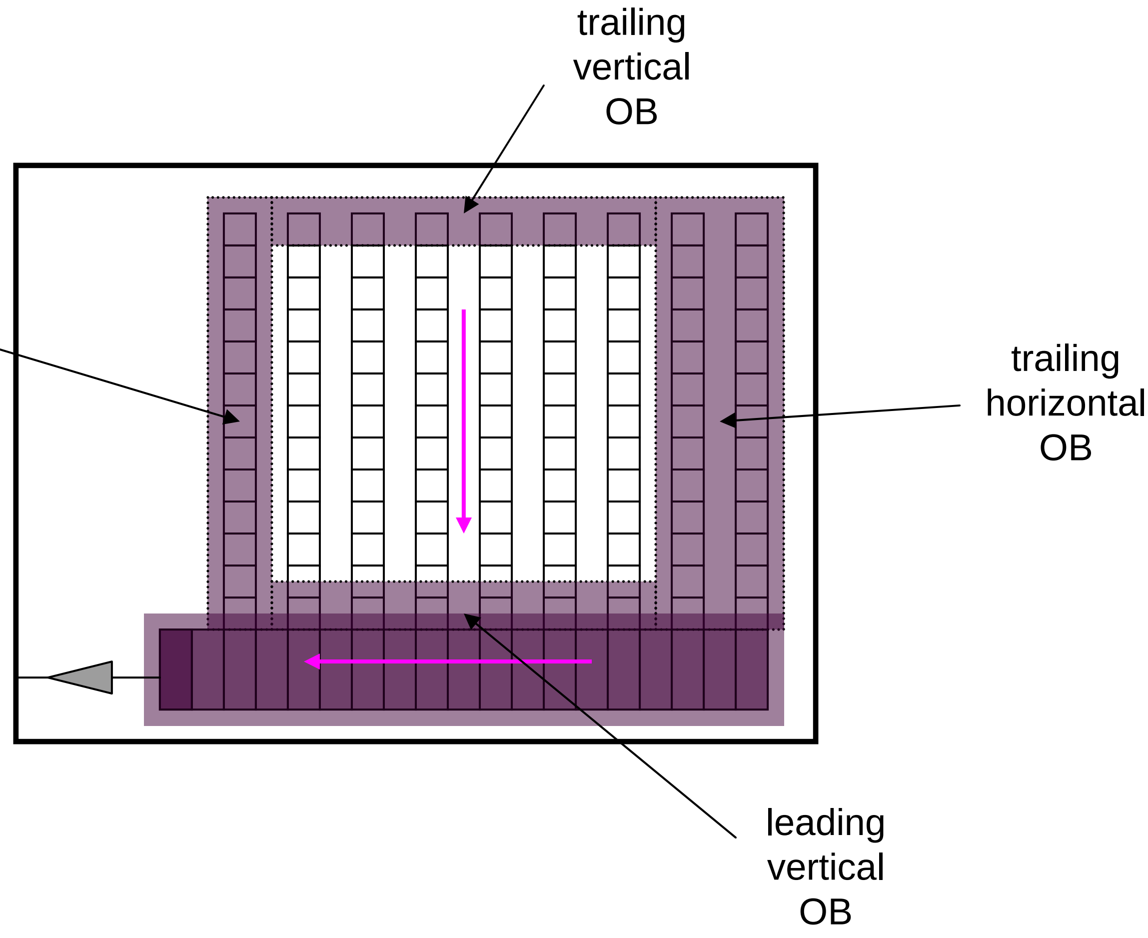


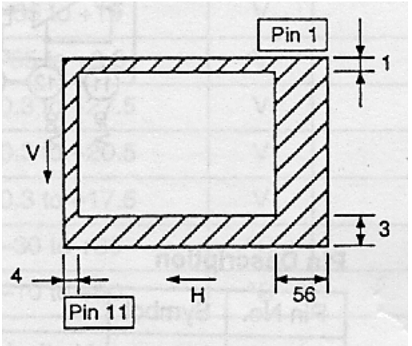
1 2 5 10

random / row ratio

Row noise is still visible, even when it is buried in 5x random noise

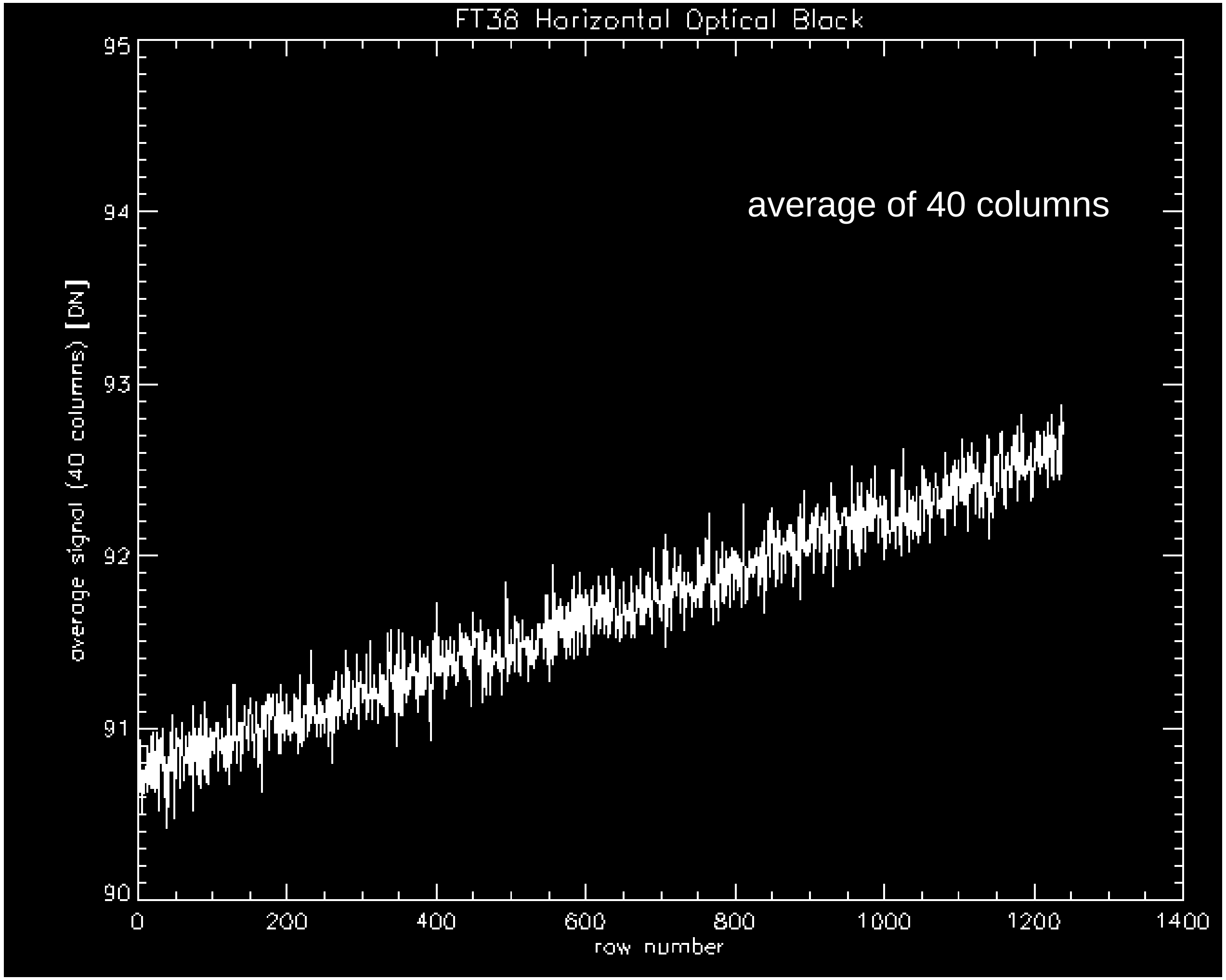
CCD optical black reference pixels



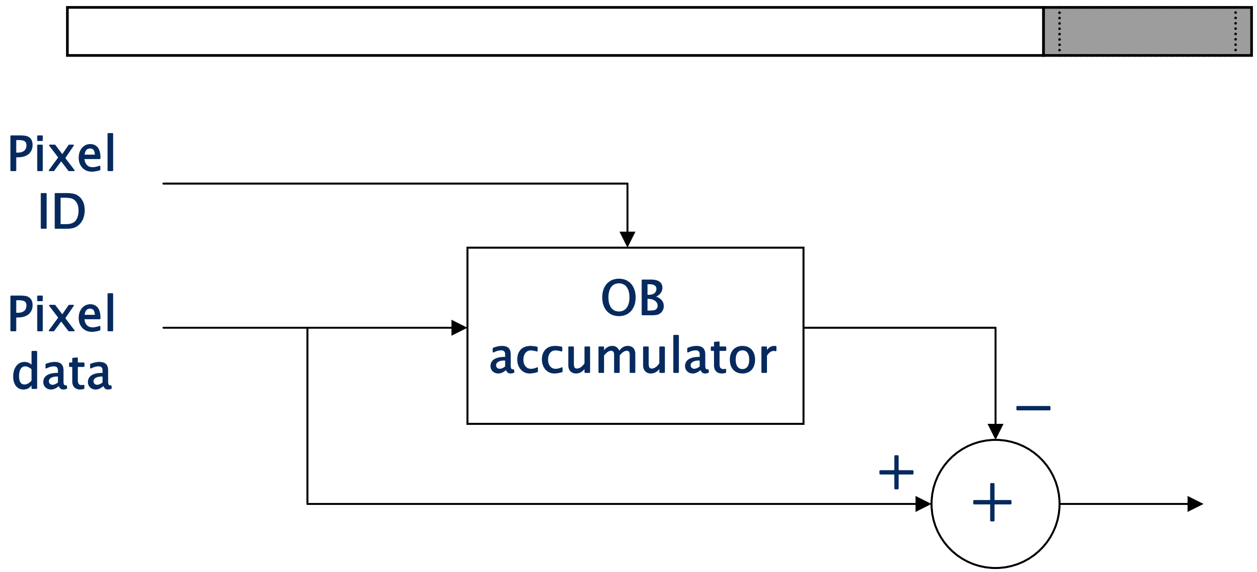


Sony ICX085

Horizontal optical black signal vs. row number



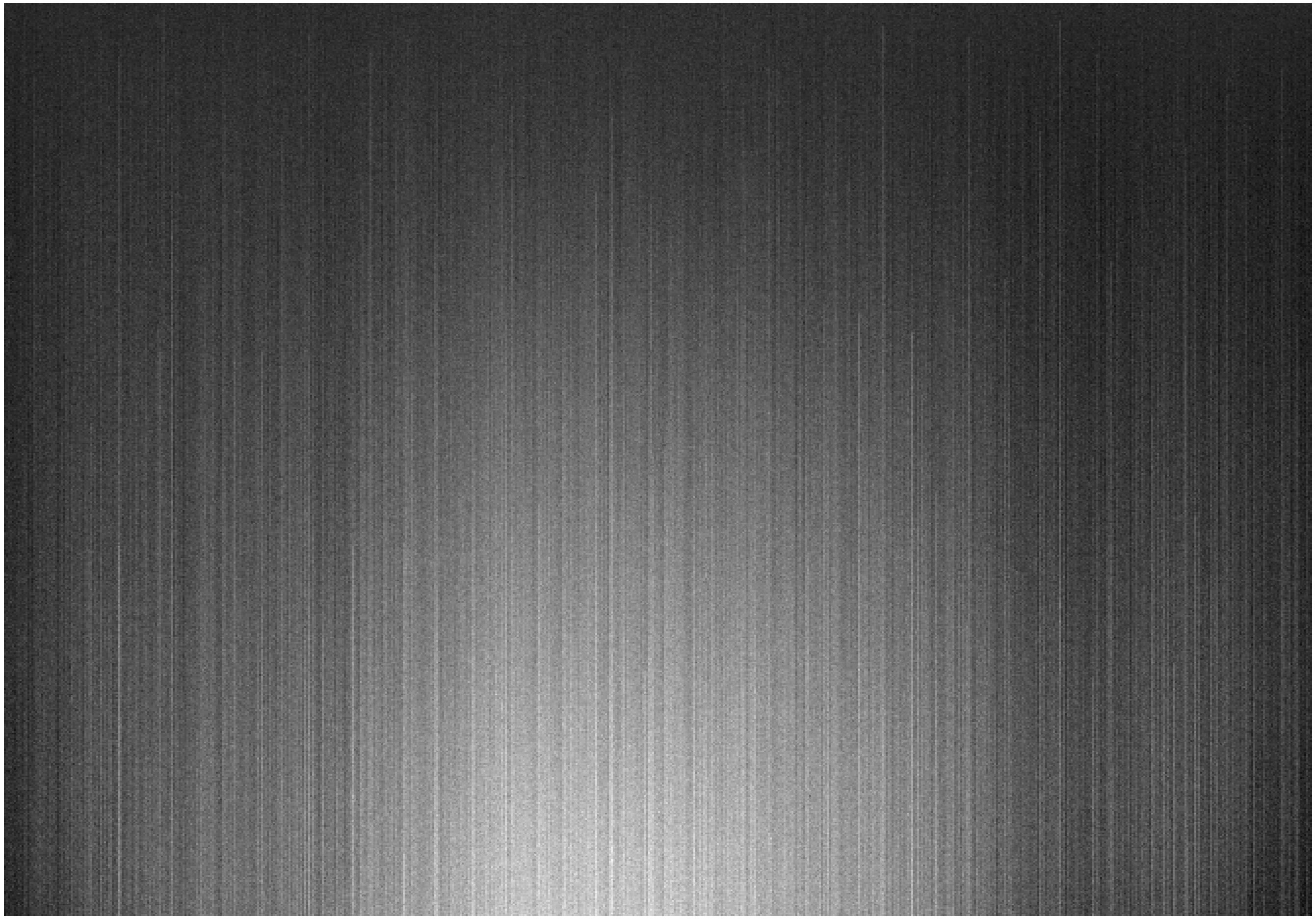
CCD row FPN offset correction (OB clamp)



Methods:

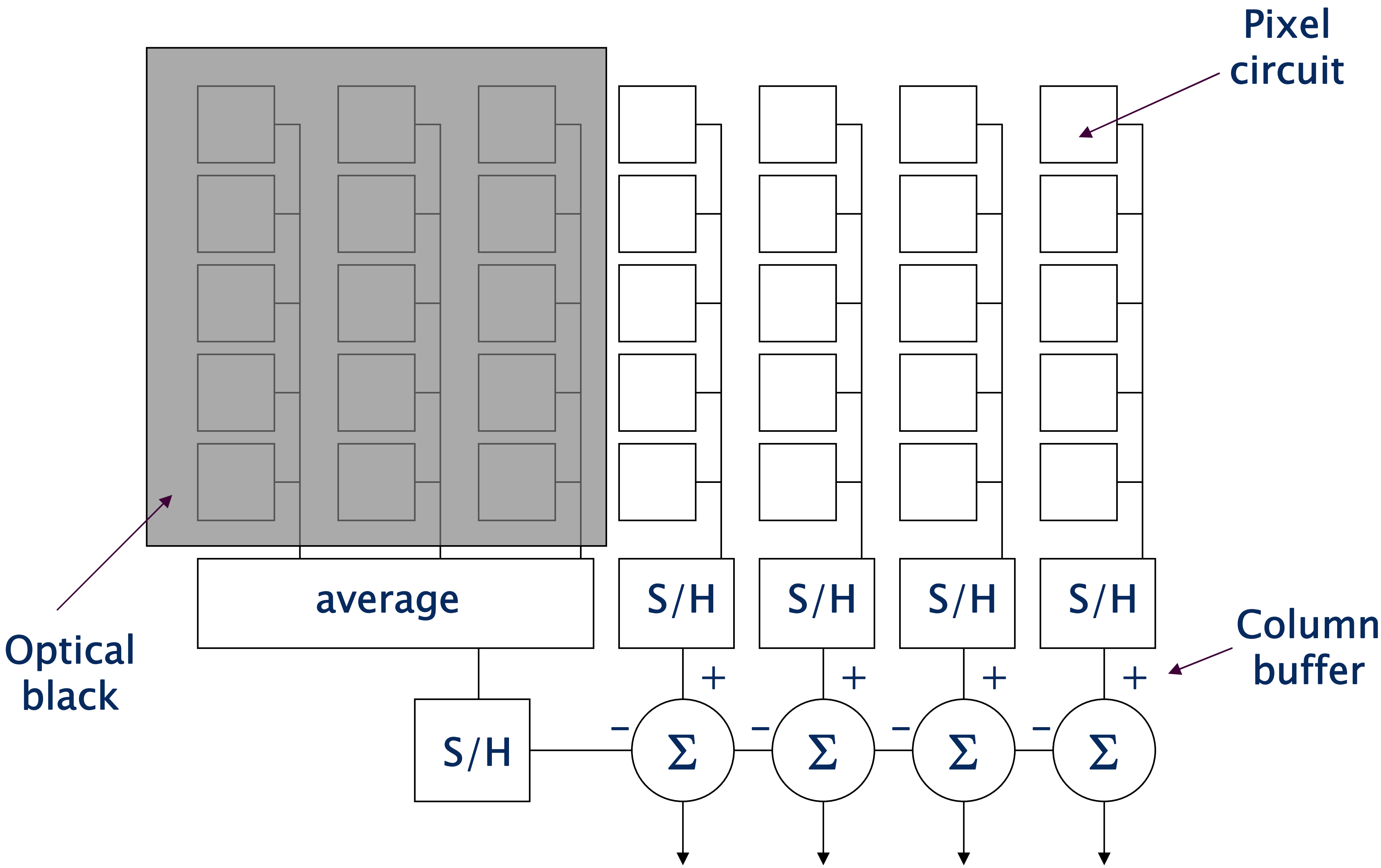
1. Accumulate leading/trailing OB pixels (analog / digital)
2. Multi-row running average (digital)
3. Exclude outlying pixels (digital)

CCD column FPN (vertical register dark current)



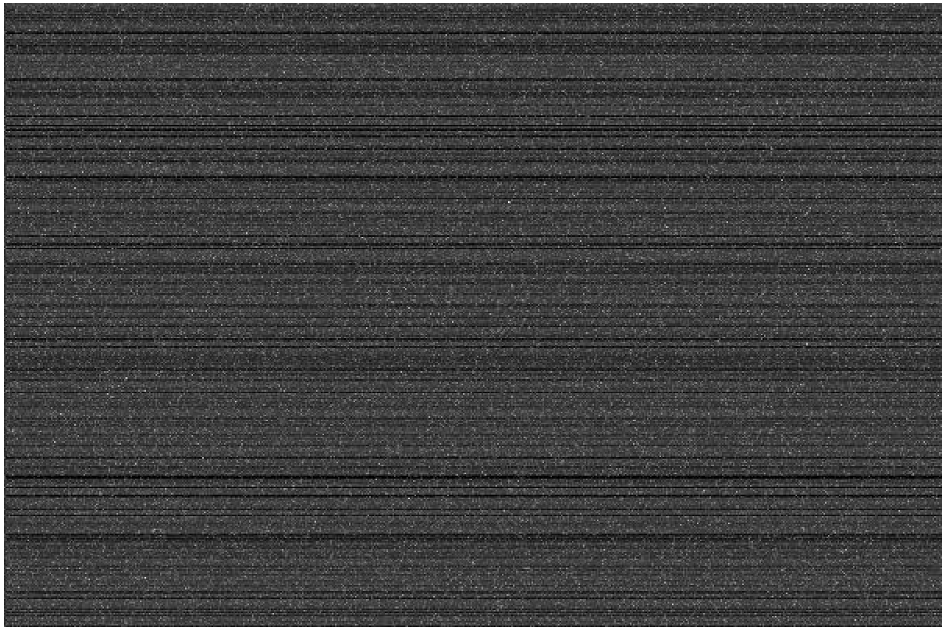
Generally buried in read noise: visible at high temperatures

CMOS row FPN offset correction



CMOS row offset features

- Analog or digital offset subtraction
- Provides power supply noise rejection (for 3T CMOS)
- Dark current clamping isn’t required
- Dark current can introduce row noise!

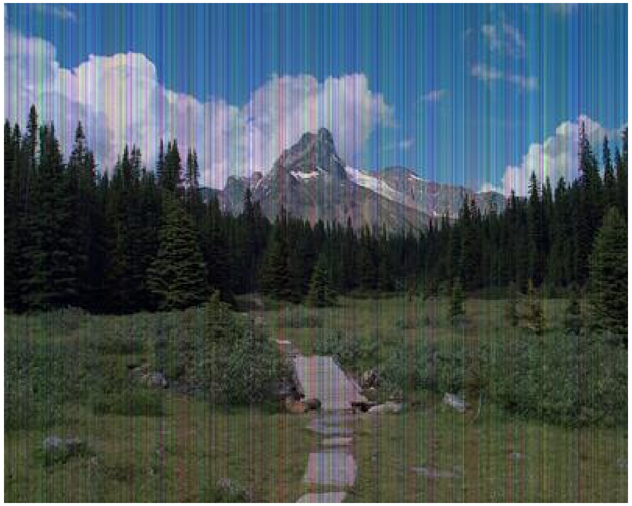


Sources of gain FPN

- PRNU (random)
- Column gain variation (column)
- ADC/PGA gain variation (block / color plane)

Gain FPN (multiplicative noise)

PRNU

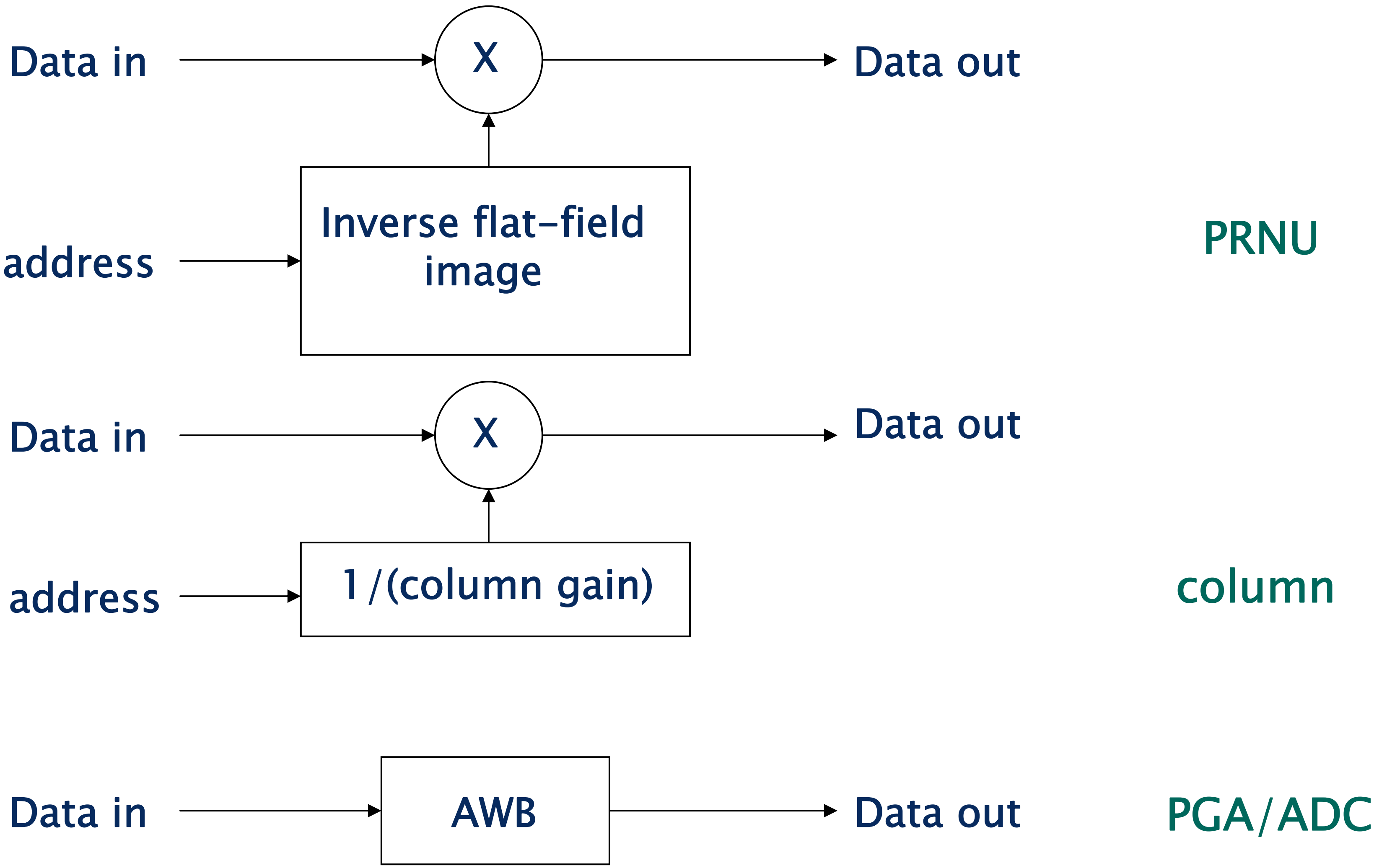


Column gain

ADC/PGA gain (four blocks)

Assign each color plane to a separate ADC/PGA to avoid visible gain errors.

Gain FPN correction

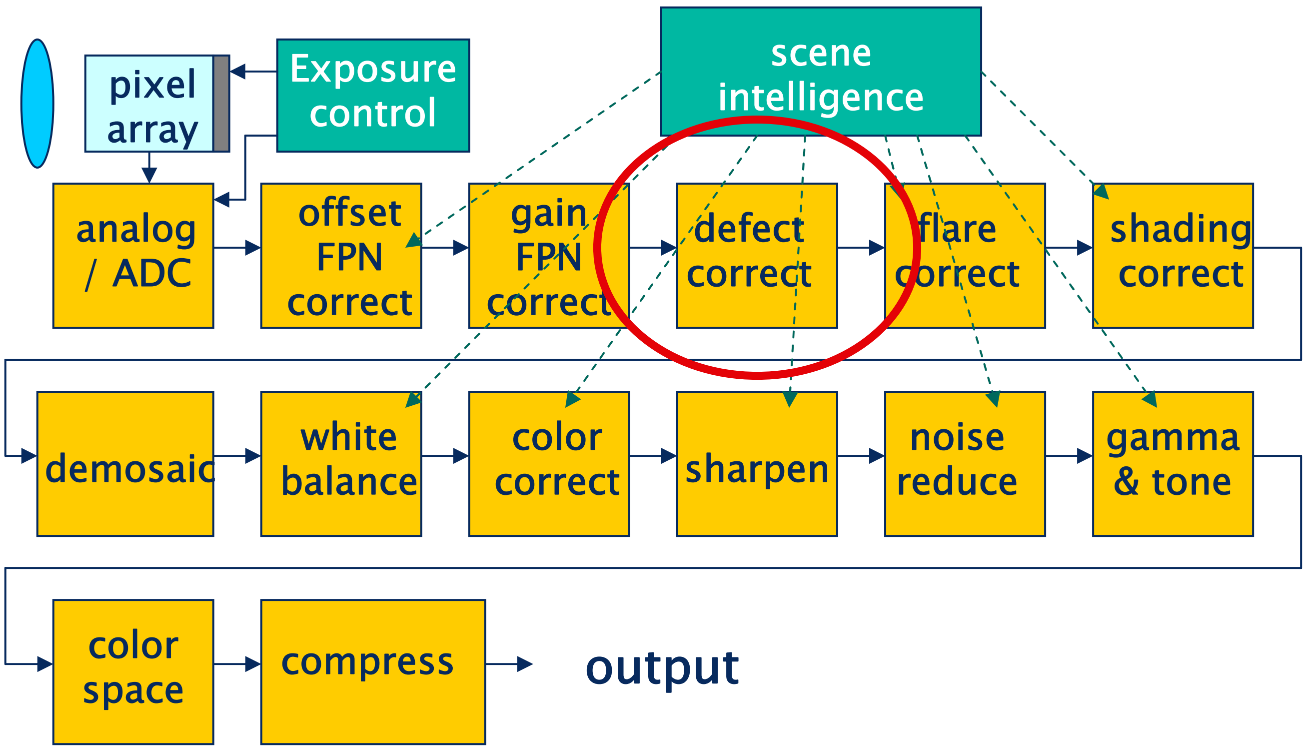


Digital correction and *memory* is required!

Effect of offset / gain correction

- FPN that would otherwise be intolerable may be almost completely eliminated
- Row FPN correction circuits may introduce their own FPN
- Spatially random offset / gain correction (dark current / PRNU) requires large memories (and large digital multipliers)
- Offset correction may suppress power supply noise

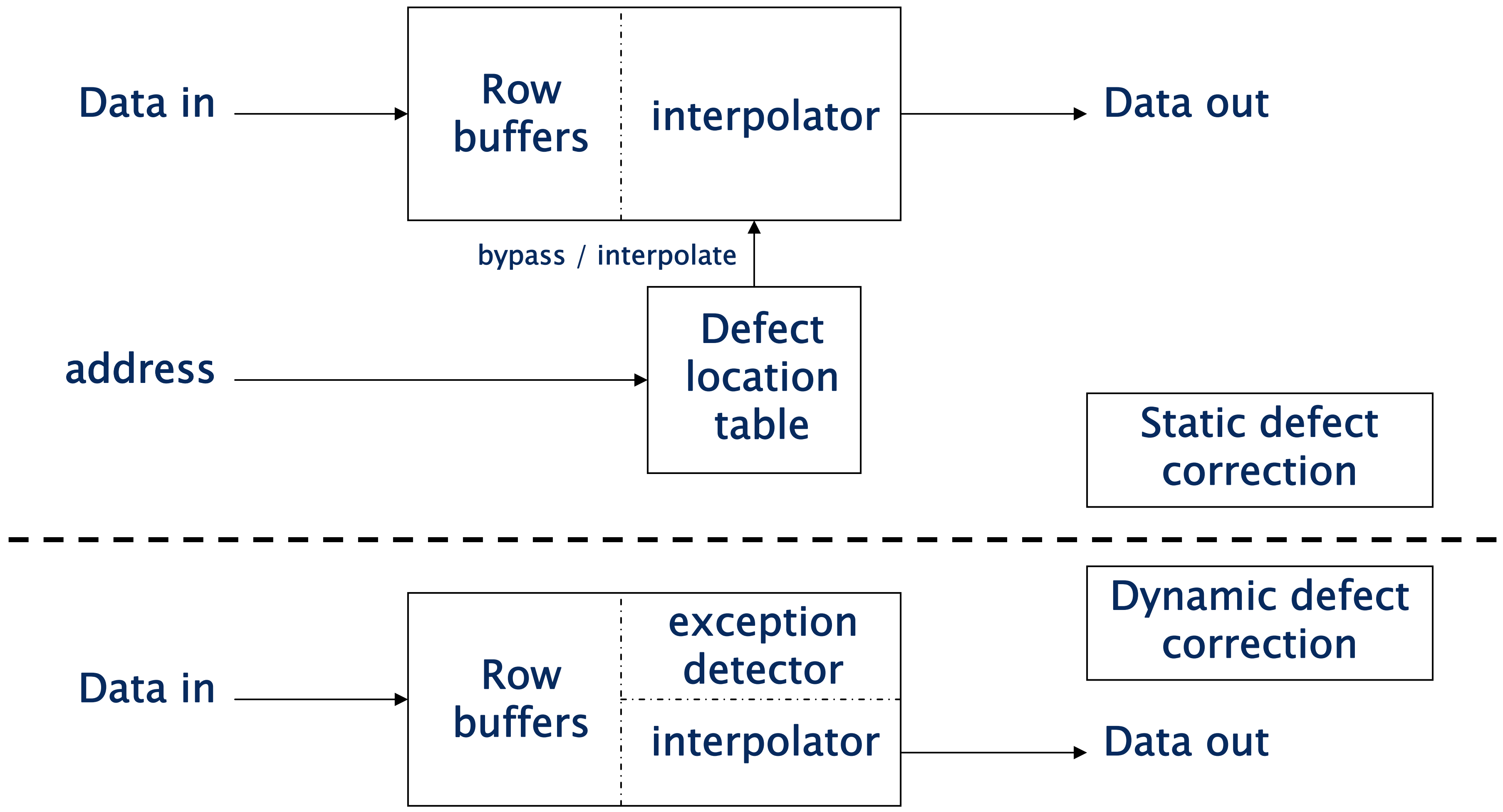
Defect correction



Defect correction

- Static defect tables
- Dark current – works best on extraordinary pixels, not on distribution tail
- On-the-fly correction
  - Threshold problems (video mode)
- Effect of correction (interpolation -> spatial correlation)

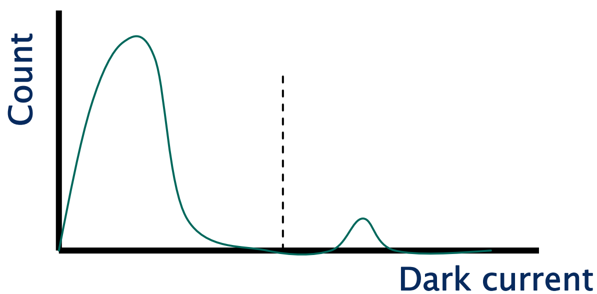
Defect correction

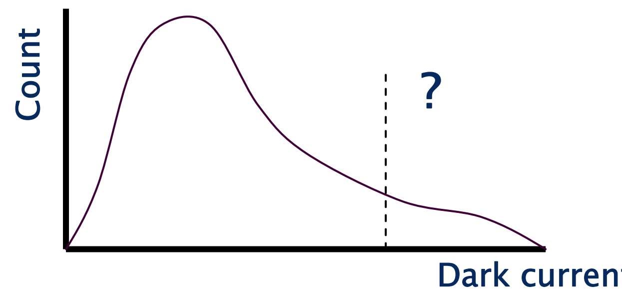


Defect characteristics

White defects

- Caused by dark current “tail”, impurities, dislocations
- Temperature dependent
- Generally single pixels
- Correction works best on isolated “hot” pixels





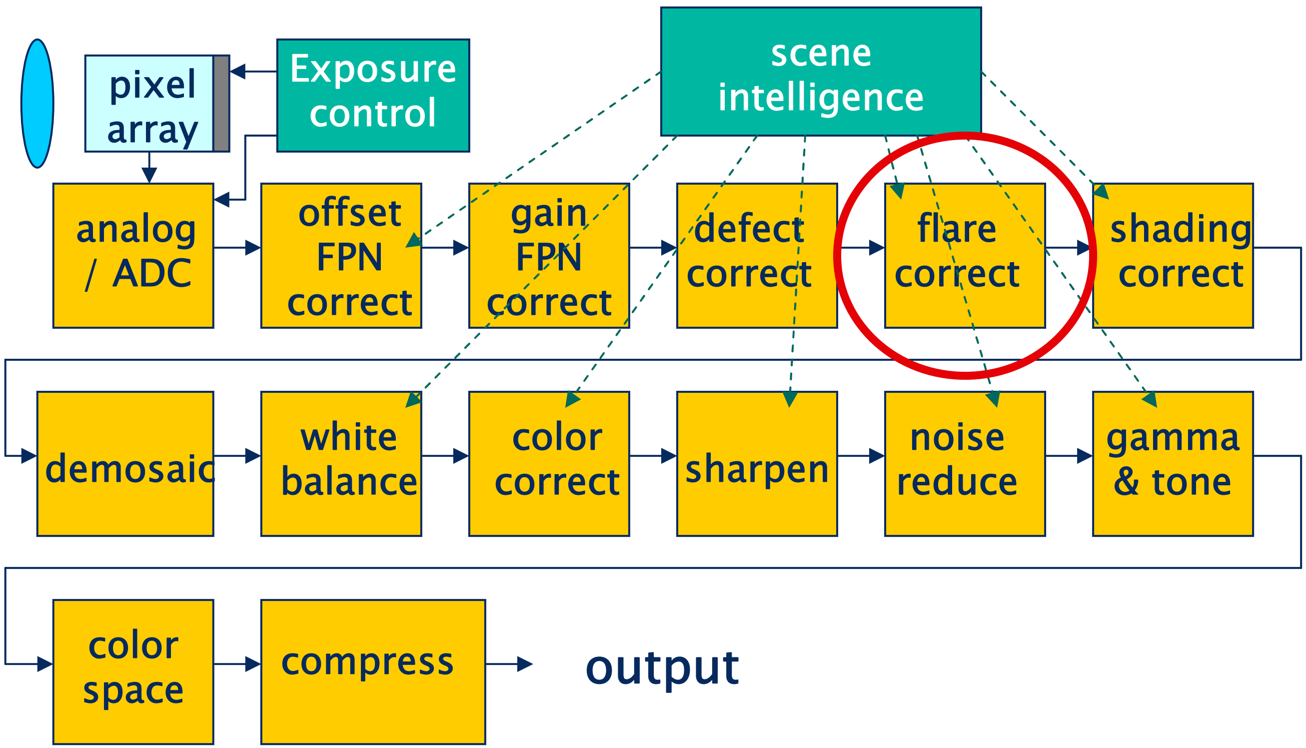
Black defects

- Caused by occlusions
- Generally clusters of pixels

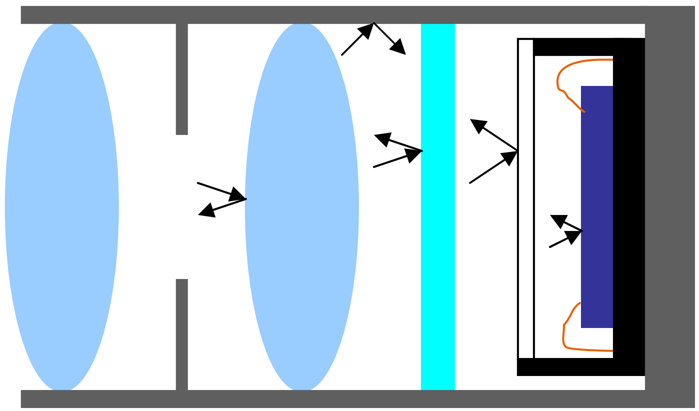
Effects of defects / defect correction

- Defective pixels contribute additive or multiplicative noise
- Defect correction replaces bad pixels with interpolates of neighboring values, results in resolution loss.
- Resolution loss isn't visible unless the number of defective pixels is large (> 0.1%).
- On–the–fly defect correction may introduce temporal noise (blinking pixels)

Flare Compensation (ABL)



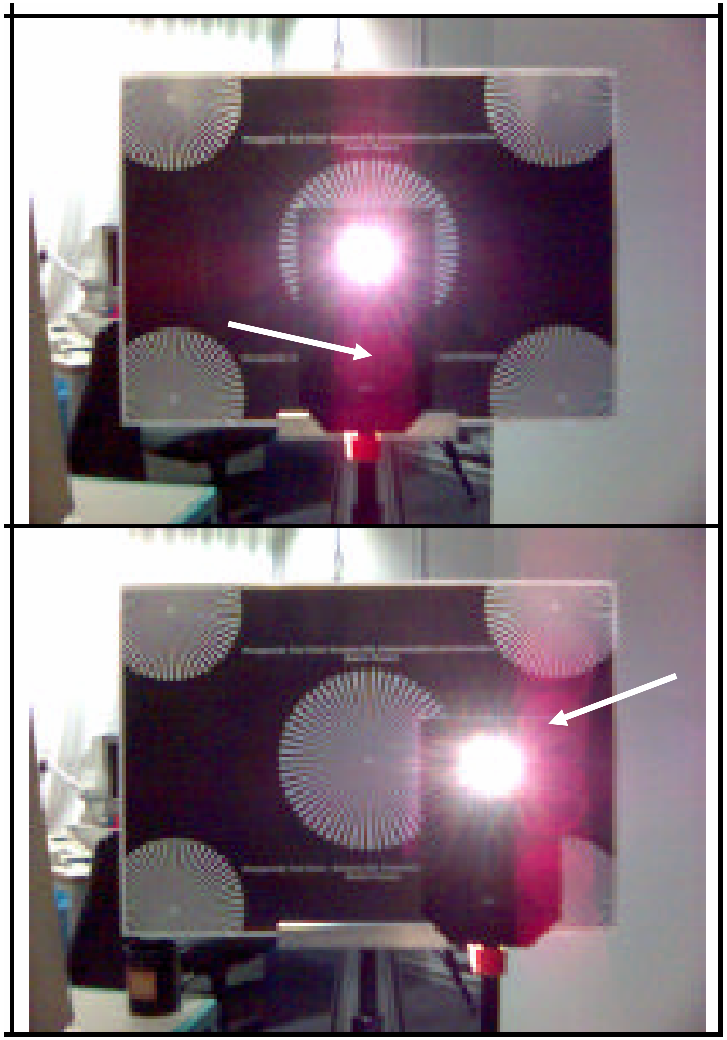
Sources of flare



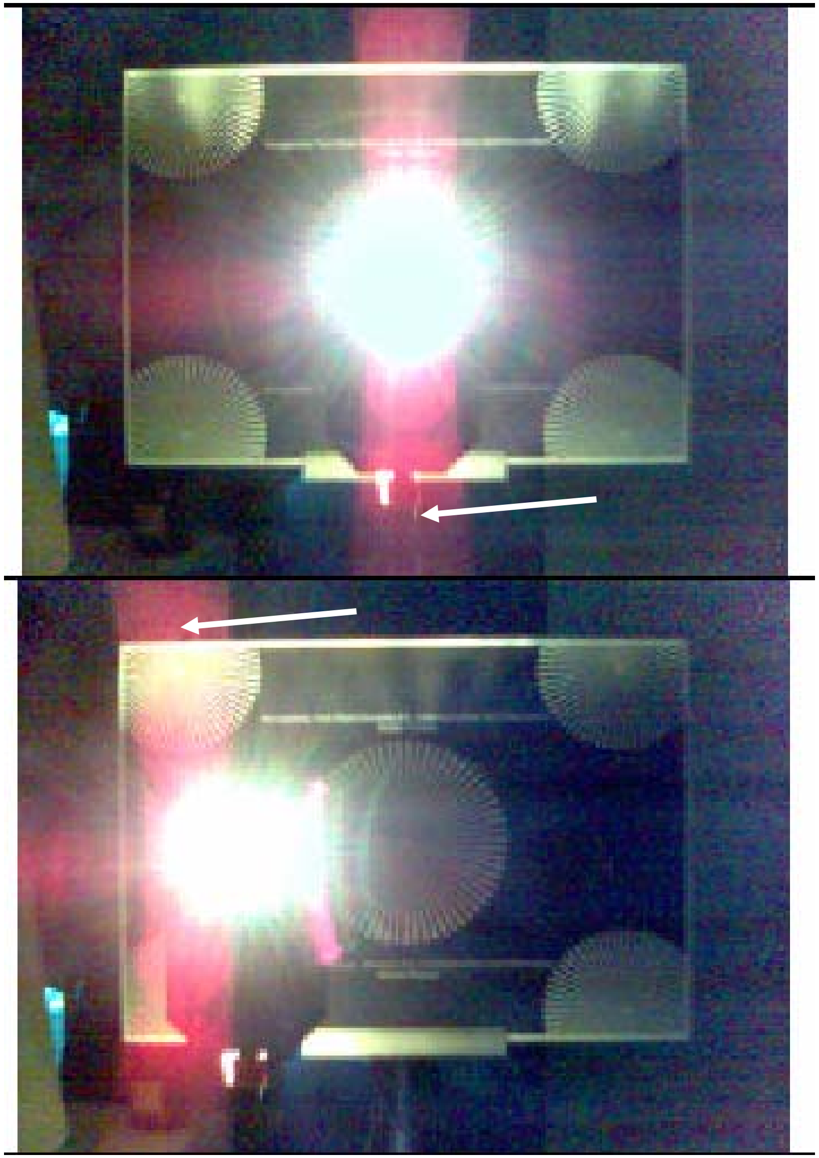
Reflections from:

- Lens surfaces
- Lens barrel
- Aperature
- IR filter
- Cover glass
- Sensor
- Bond wires and pads

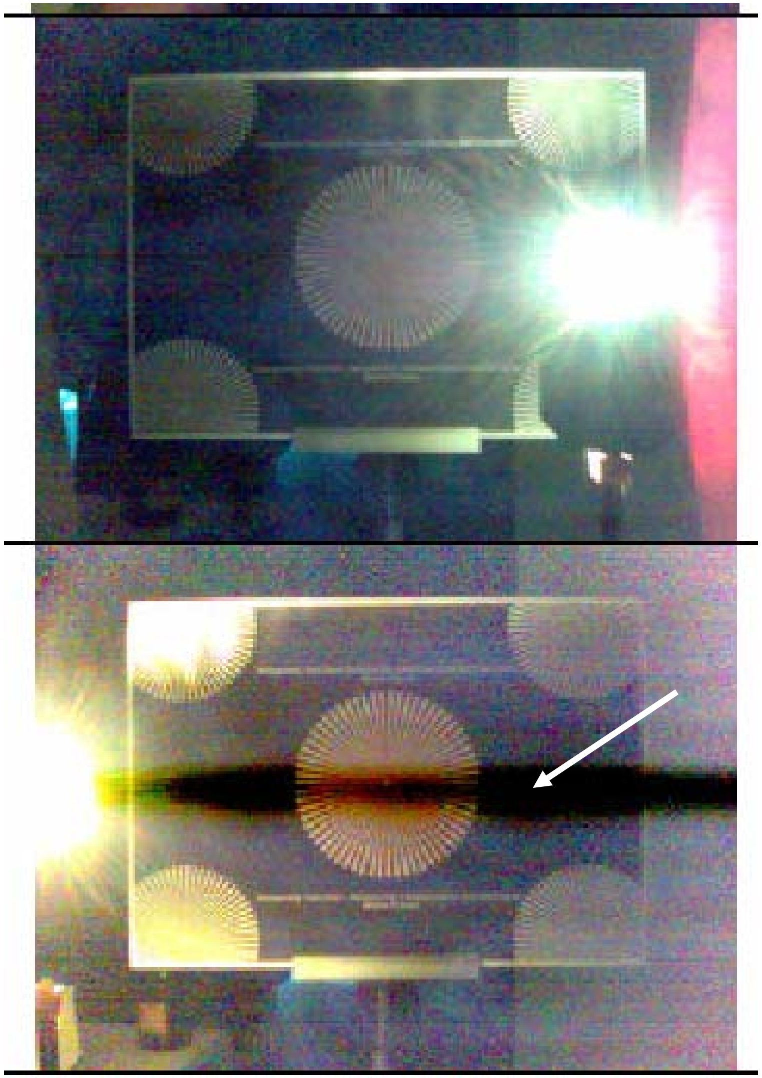
Ghost images



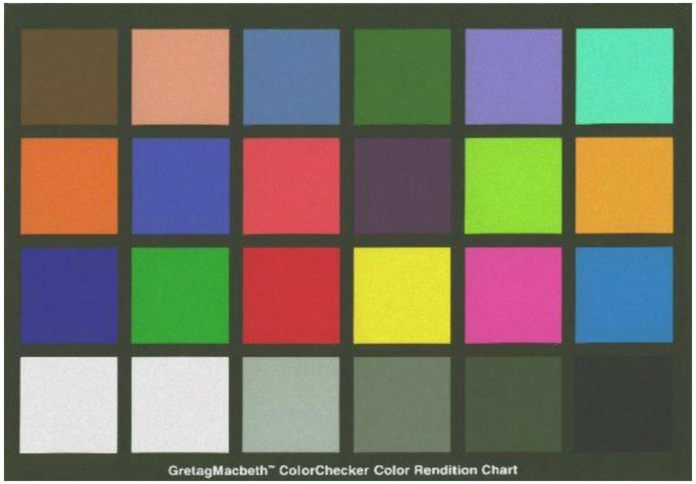
Non-uniform flare



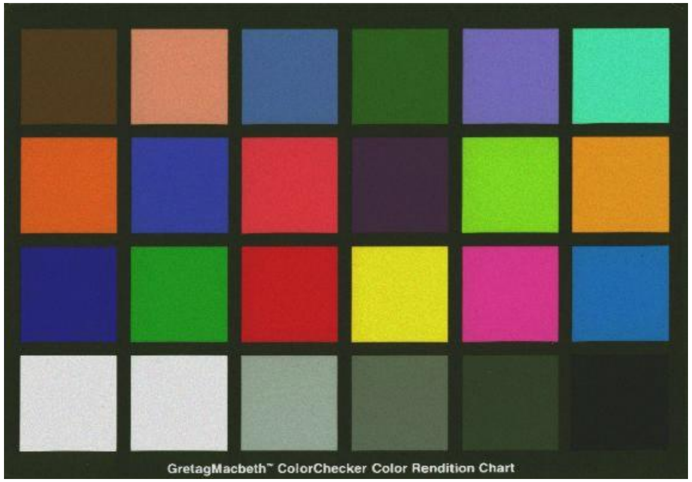
Reference column leakage



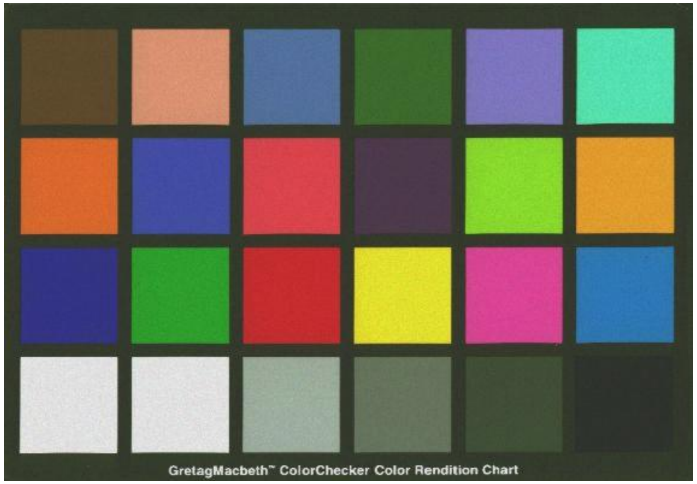
Uniform flare compensation



10% flare



−10% flare

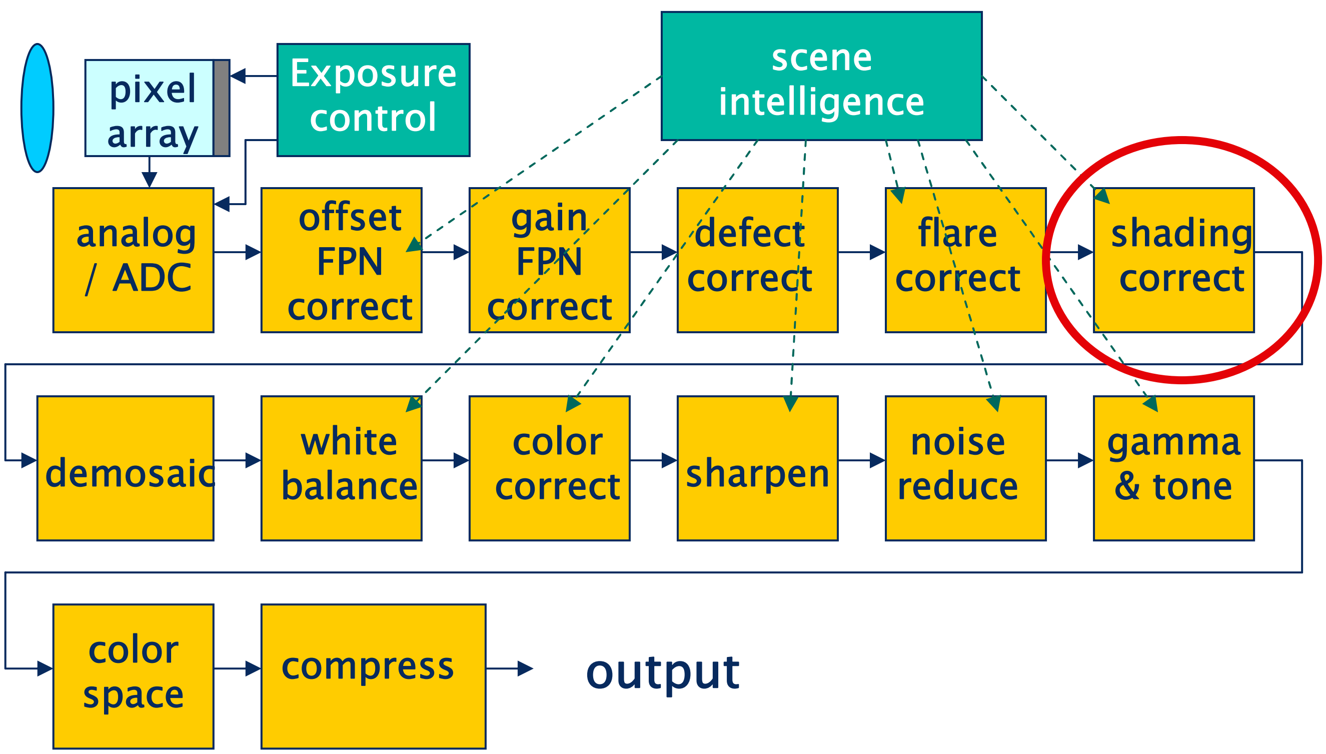


0% flare

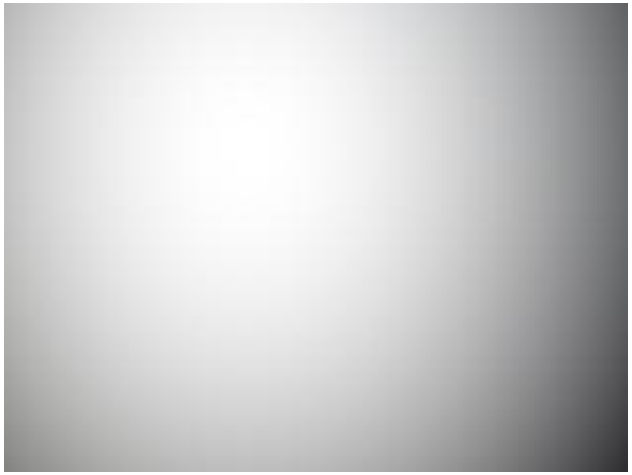
Effects of flare

- Uniform flare adds signal-dependent offset (noise)
- Uniform flare can be subtracted. Over-subtraction reduces color accuracy.
- Specular sources may produce ghost images which can’t be removed.
- Black row effects may appear because of light leaking into row reference pixels.

Shading correction



Vignetting and color shading



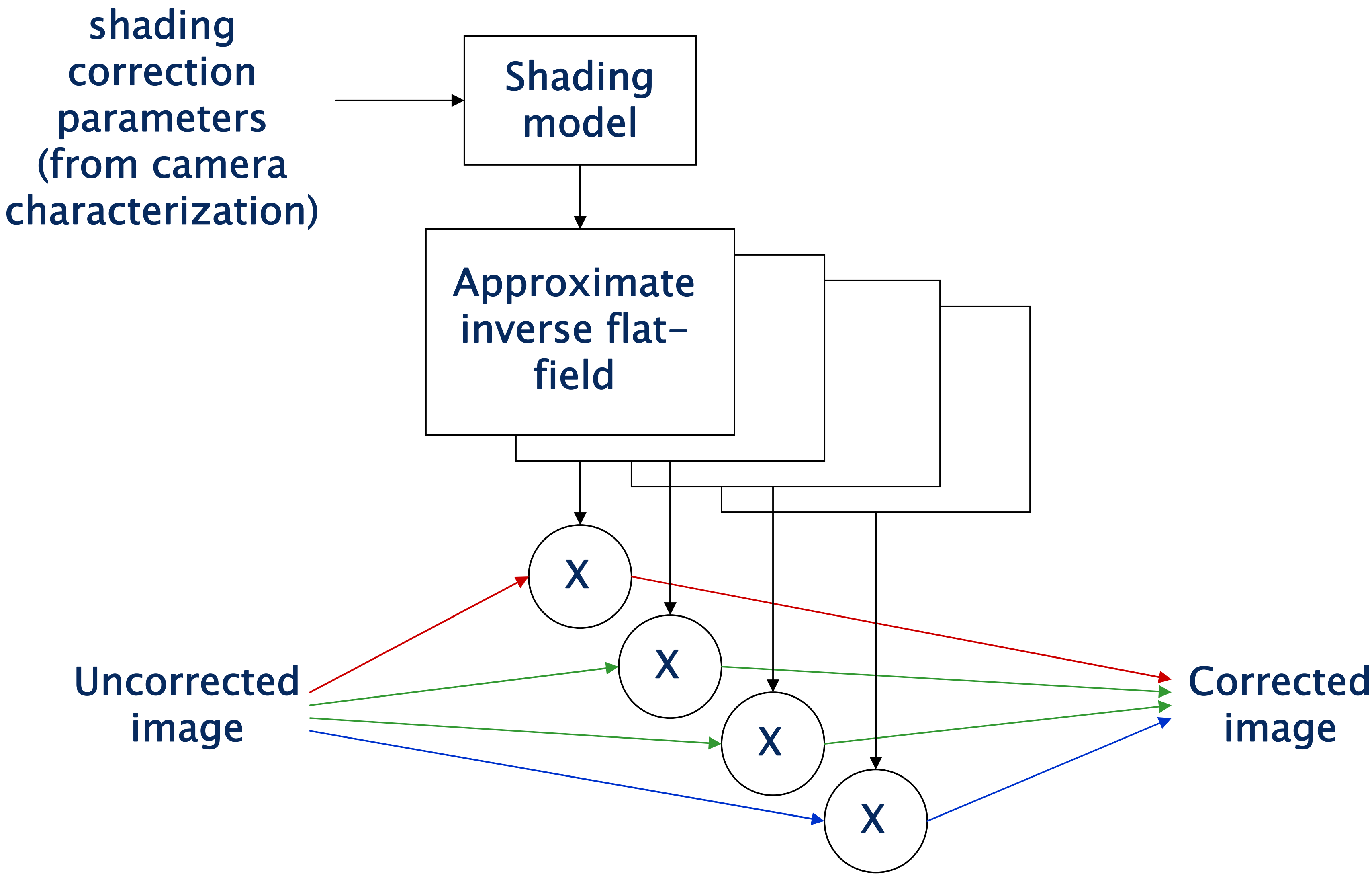
Lens vignetting: color planes share a common center

Sources of shading

- Lens vignetting
- IR filter CRA dependence
- Pixel angular response / asymmetry

Color shading: color planes have different centers (because of pixel asymmetry)

Shading correction



Illuminant-dependent color shading

Shading correction optimized for CWF

D65 - daylight

CWF - fluorescent

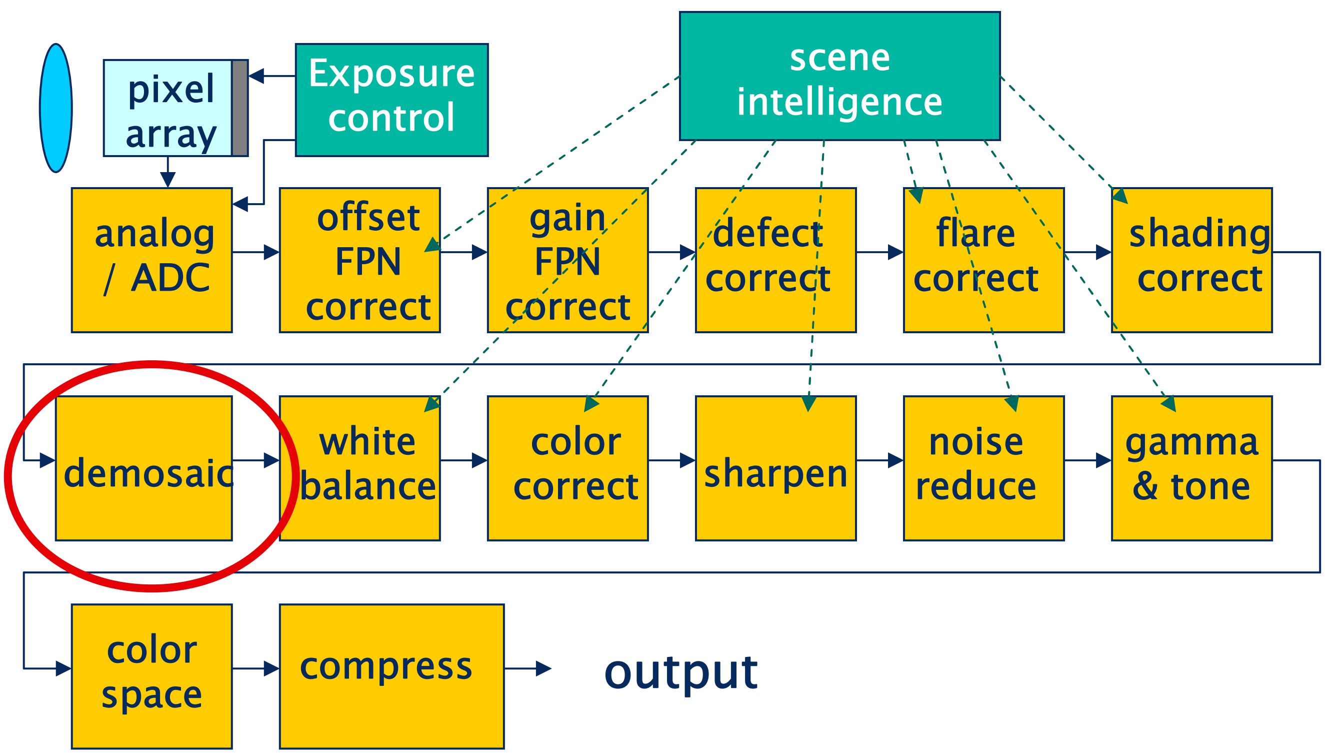
“A” - tungsten

(color saturation increased to enhance visibility)

Effects of vignetting / pixel angular response

- Reduced signal / SNR in corners
- Color shading
- Gr/Gb channel imbalance

Pixel reconstruction



Pixel reconstruction

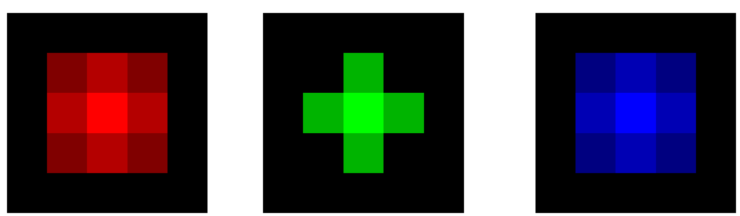
- Undersampling results in artifacts
- Demosaic uses interpolation -> results in spatial correlation of noise.

Color artifacts caused by undersampling

Noise correlation

G	B	G	B	G
R	G	R	G	R
G	B	G	B	G
R	G	R	G	R
G	B	G	B	G

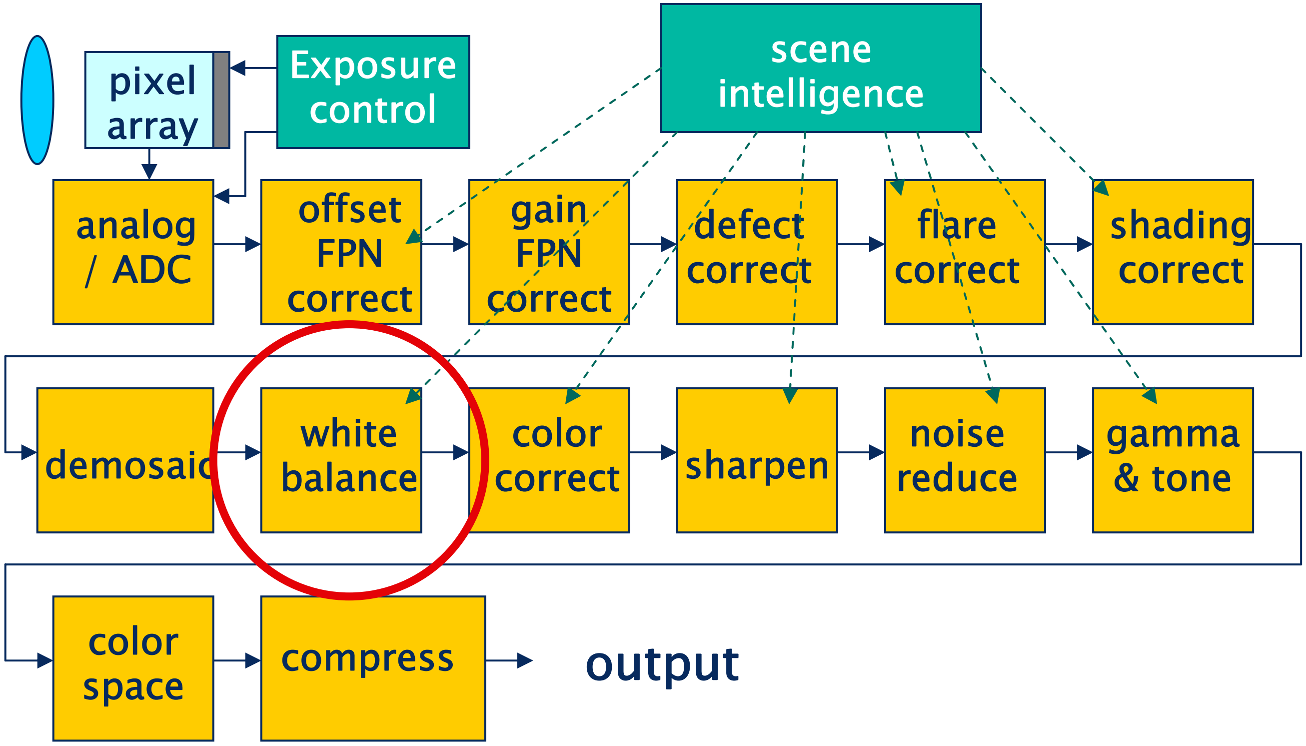
Noise diffuses to adjacent pixels



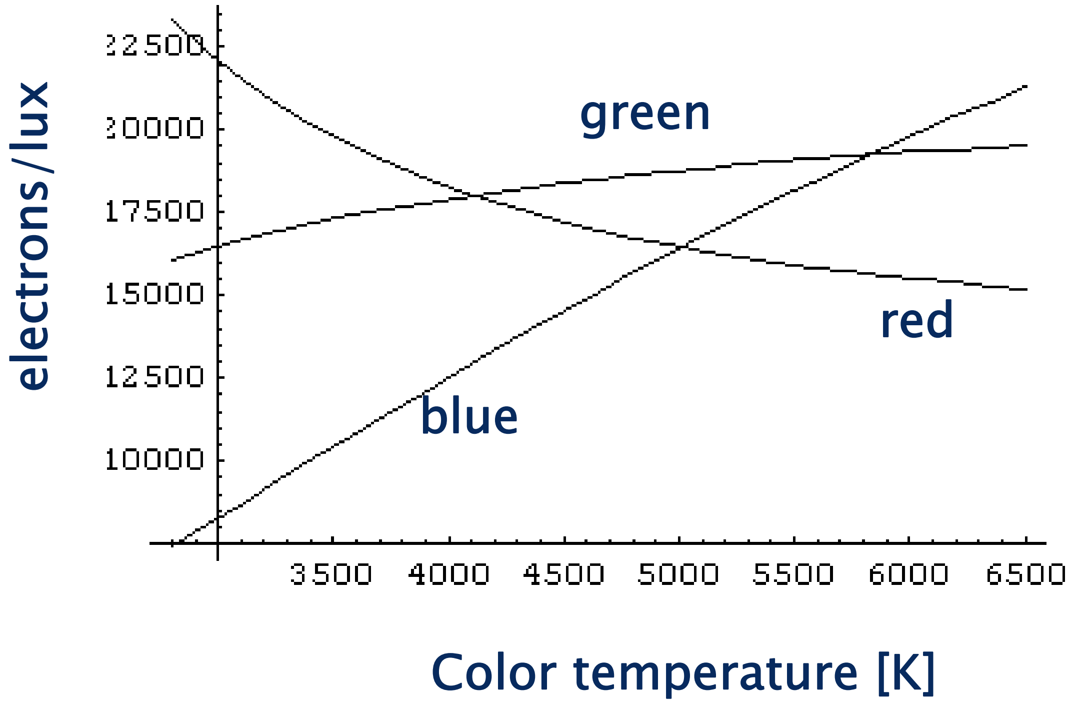
Effects of pixel reconstruction

- Reconstruction may introduce color artifact noise
- Reconstruction diffuses noise to adjacent pixels

White balance

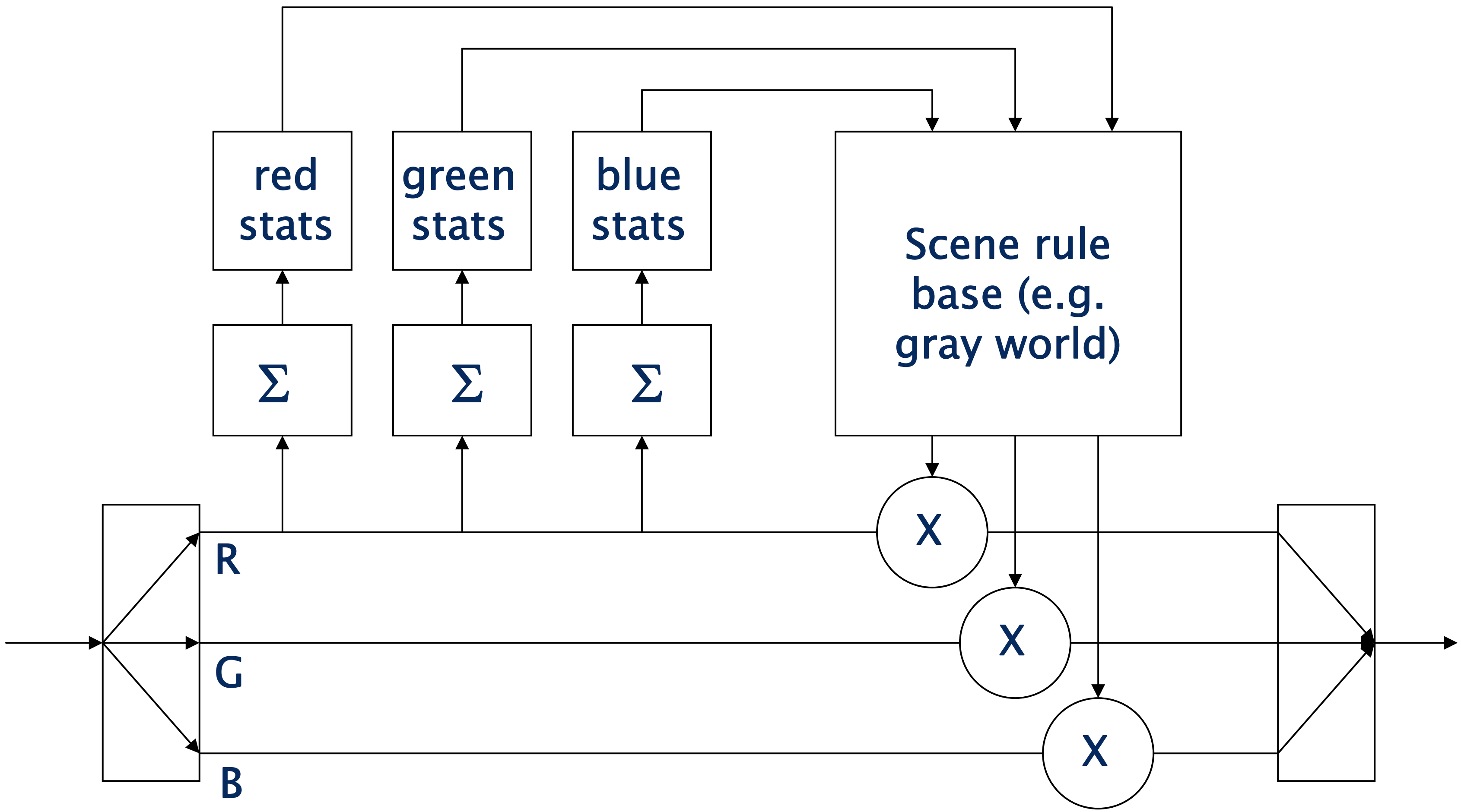


Effect of color temperature on RGB balance



Sony CCD QE curves and CM-500 IR filter

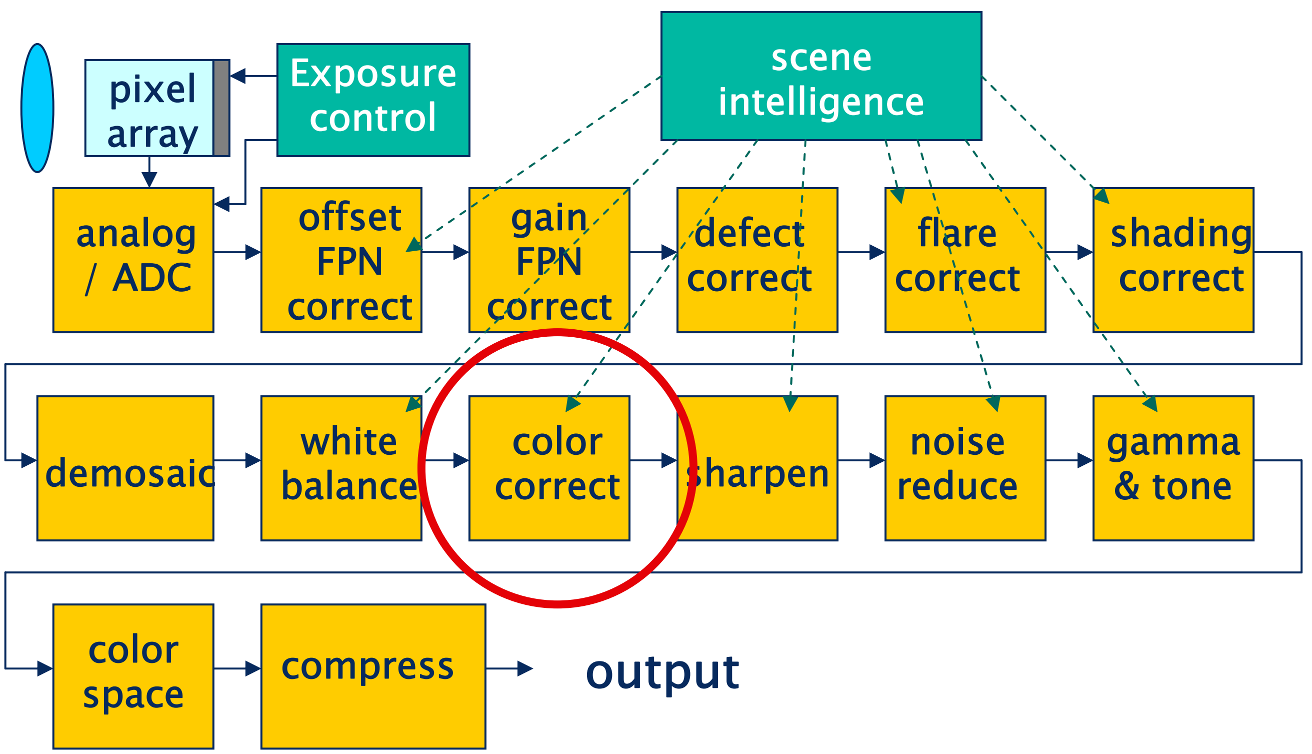
White balance operation



Effect of white balance

- Neutral colors balance to gray
- Amplification of weak color channels increases noise
- Relative color strength depends on spectral response, illuminant color

Color correction



Color Processing Decreases the SNR

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \overline{\overline{\mathrm{A}}} \cdot \overline{\mathrm{C}}$$

output

sensor

A transformation matrix is required to convert from the sensor color space to the output color space

Consider a two-color world:

$$\mathrm{C}_1 = \mathrm{R} + \alpha \mathrm{B}$$

$$\mathrm{C}_2 = \alpha \mathrm{R} + \mathrm{B}$$

α = pixel crosstalk factor

<u>Transform to color</u>:

$$\mathrm{R} = \frac{\mathrm{C}_1 - \alpha \mathrm{C}_2}{1 - \alpha^2} \qquad \mathrm{B} = \frac{\mathrm{C}_2 - \alpha \mathrm{C}_1}{1 - \alpha^2}$$

$$(S/N)^R = \frac{S_1 - \alpha S_2}{\sqrt{N_1^2 + \alpha^2 N_2^2}}$$

<u>Transform to monochrome</u>:

$$\mathrm{X} = \tfrac{1}{2}(\mathrm{C}_1 + \mathrm{C}_2)$$

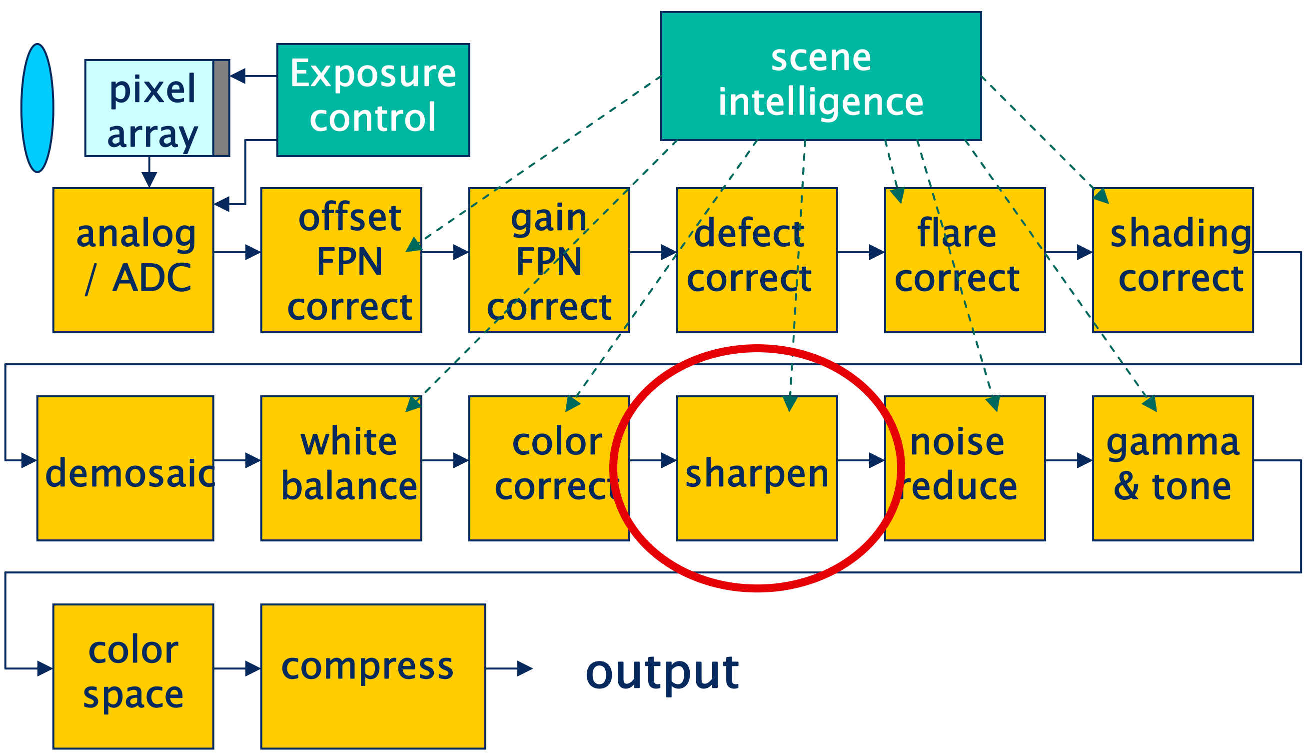
$$\left(S/N\right)^X = \frac{S_1 + S_2}{\sqrt{N_1^2 + N_2^2}}$$

- Color correction decreases the SNR
- The greater the crosstalk, the greater the noise amplification

Effect of color correction

- Color fidelity is improved
- Noise is significantly amplified by off-diagonal matrix terms
- Off-diagonal matrix terms depend on spectral response and pixel-to-pixel crosstalk

Sharpening



pixel array
Exposure control
scene intelligence
analog / ADC
offset FPN correct
gain FPN correct
defect correct
flare correct
shading correct
demosaic
white balance
color correct
sharpen
noise reduce
gamma & tone
color space
compress
output

Sharpening filters amplify noise

original

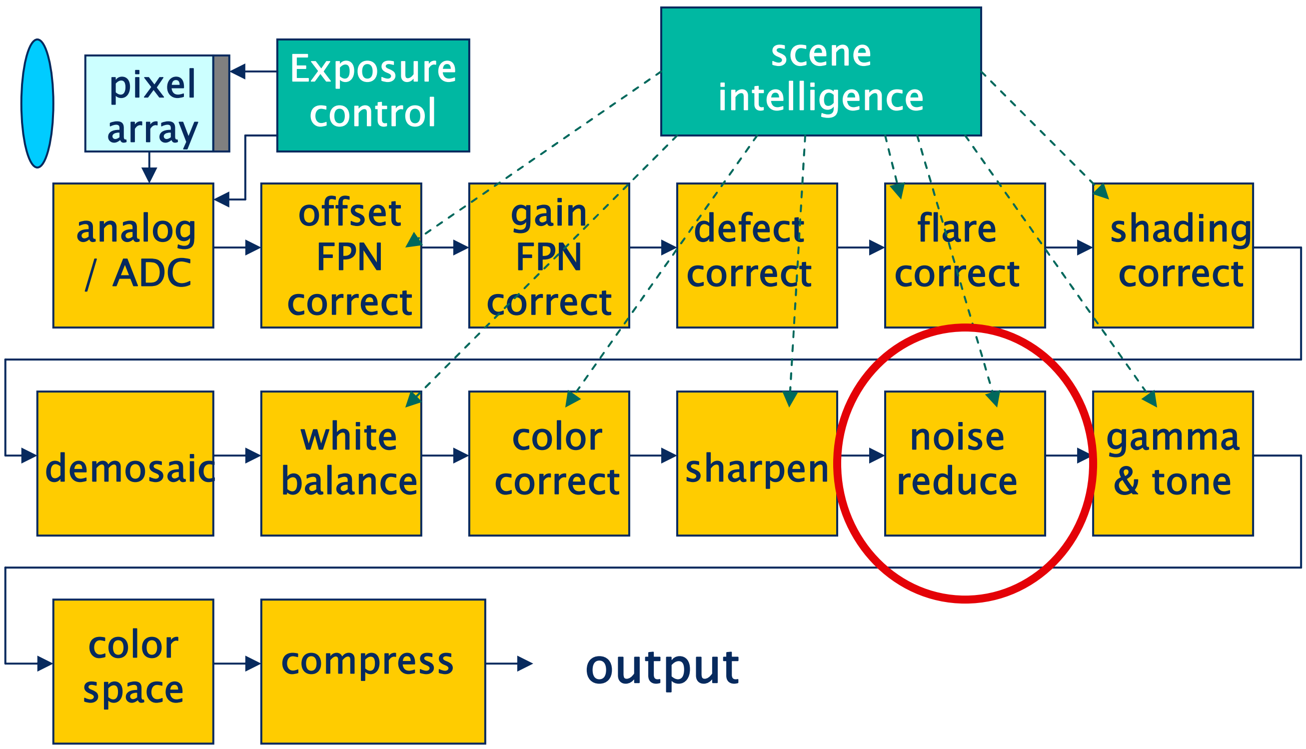
sharpen

original + noise

Effect of sharpening

- The noise has more high–frequency spectral content than the image
- Sharpening filters amplify high–frequencies and therefore amplify noise

Noise reduction filtering



Noise filtering
(topic of Dr. Pizurica's ISSCC presentation)

- Temporal filtering
- Spatial filtering
- Adaptive spatial filtering

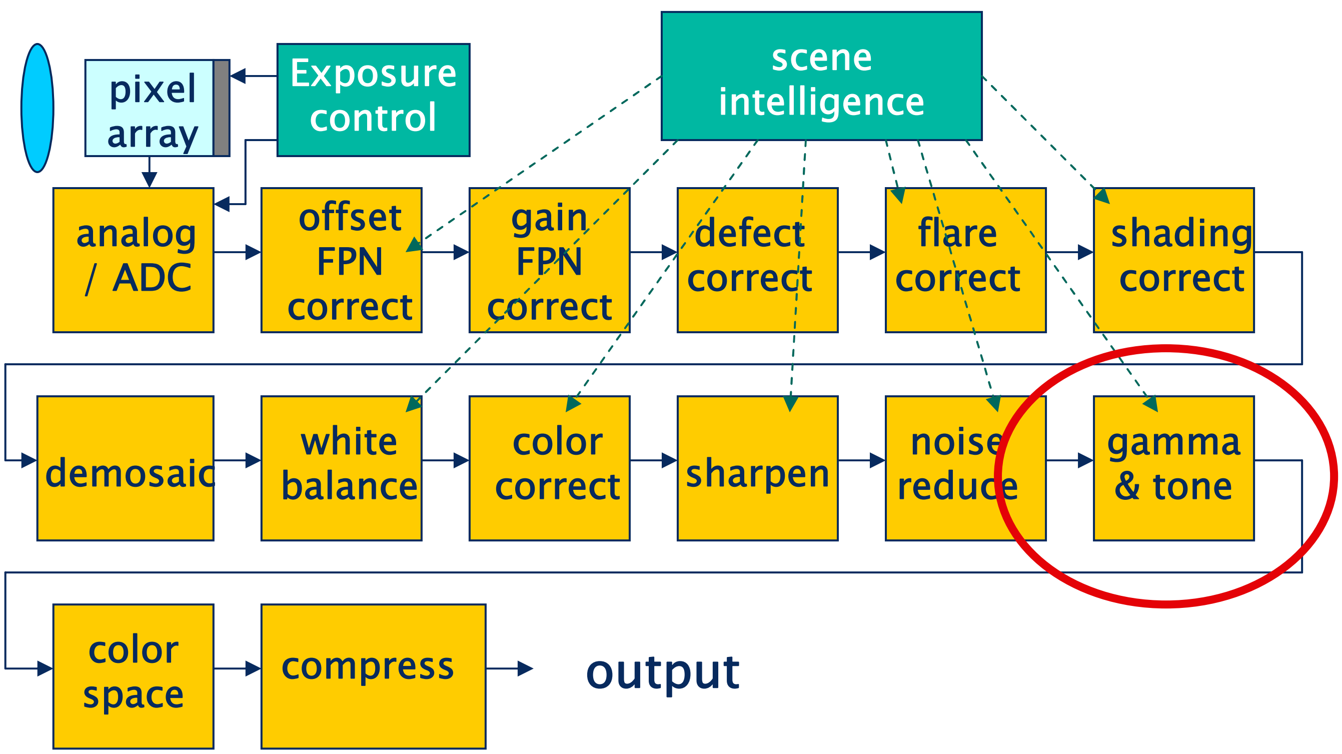
What distinguishes signal from noise?

- The signal is stationary (… but so is FPN)
- The spatial frequency response of the signal is limited by the system MTF
- The color gamut of the signal is limited by the surfaces / illuminants observed in the real world

Effect of noise reduction

- Noise is presumably reduced
- Sharpness may be lost
- Texture detail may be lost

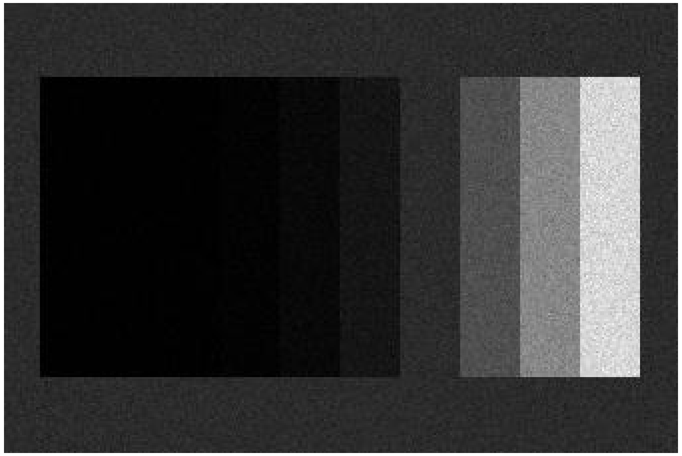
Gamma correction and tone mapping



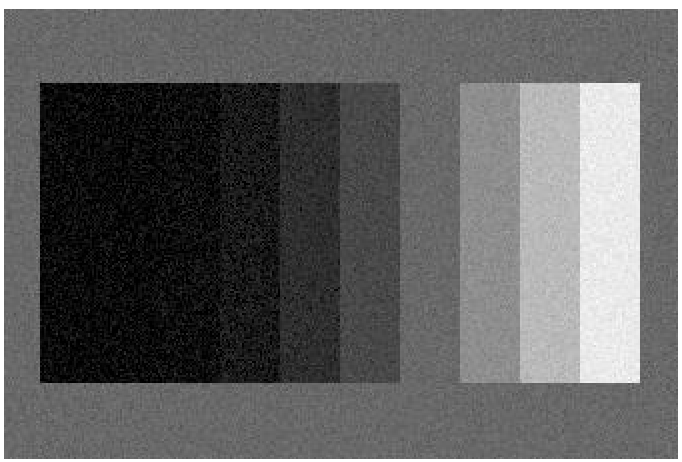
Gamma correction and tone

- Gamma correction – compensates for display device
- Global tone correction – produces pleasing tone reproduction
- Local tone correction (e.g. Retinex) – for high DNR images

Effect of tone correction on SNR

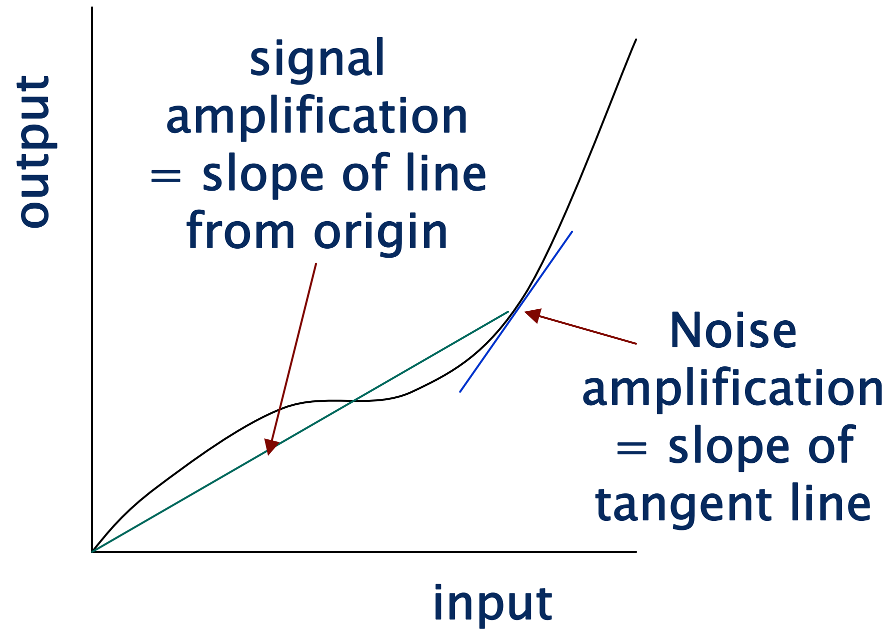


original



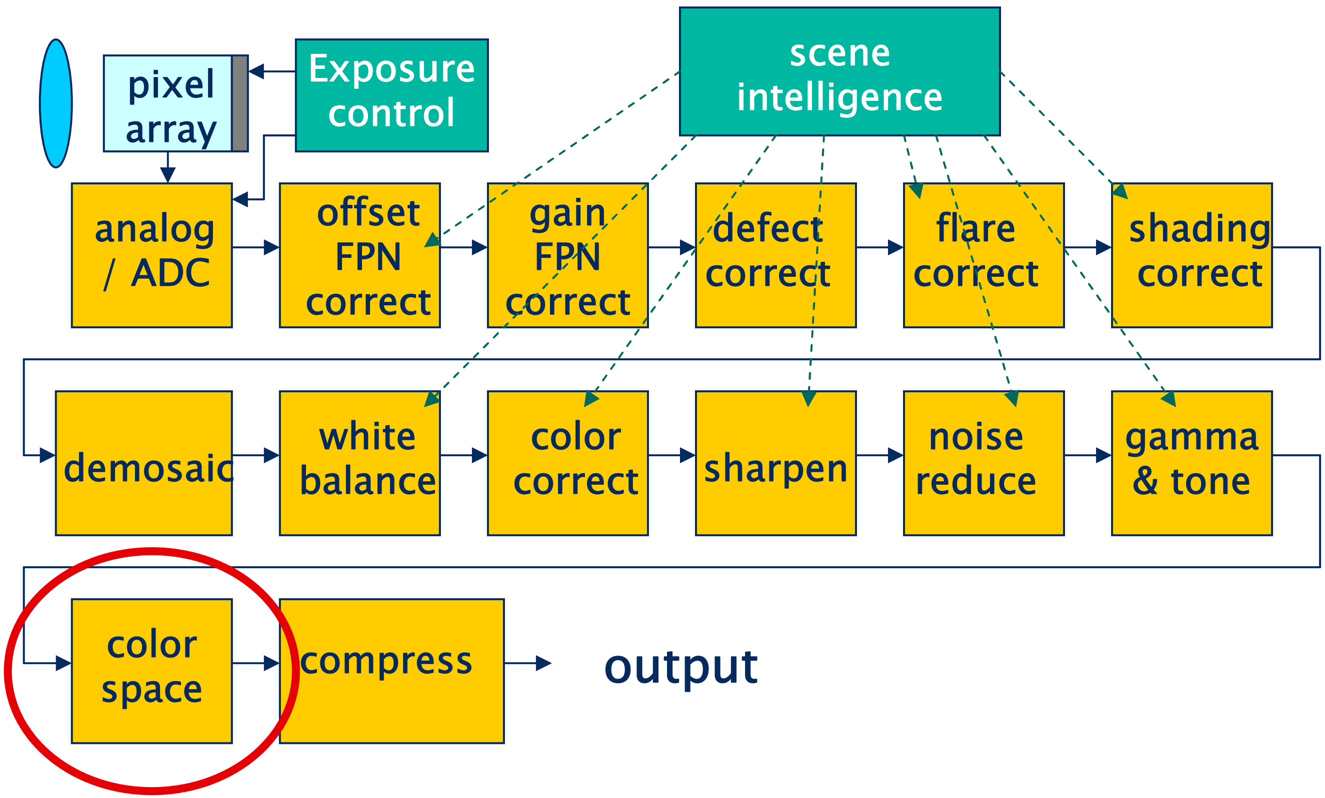
after gamma correction

Gamma / tone function

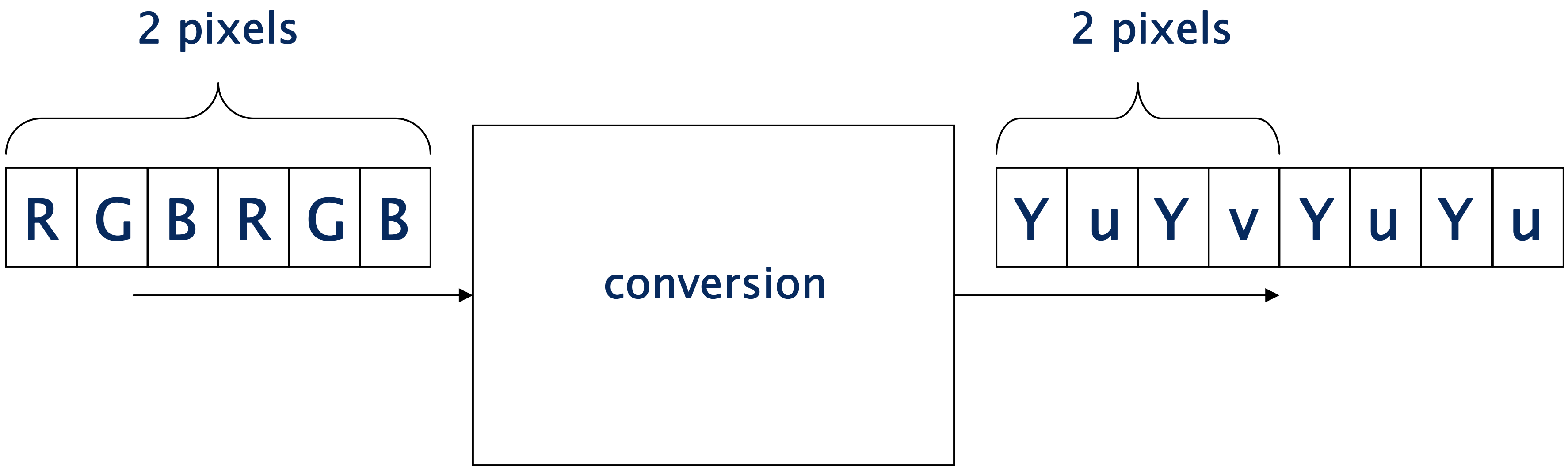


The tone correction function must be reversed to make meaningful noise measurements

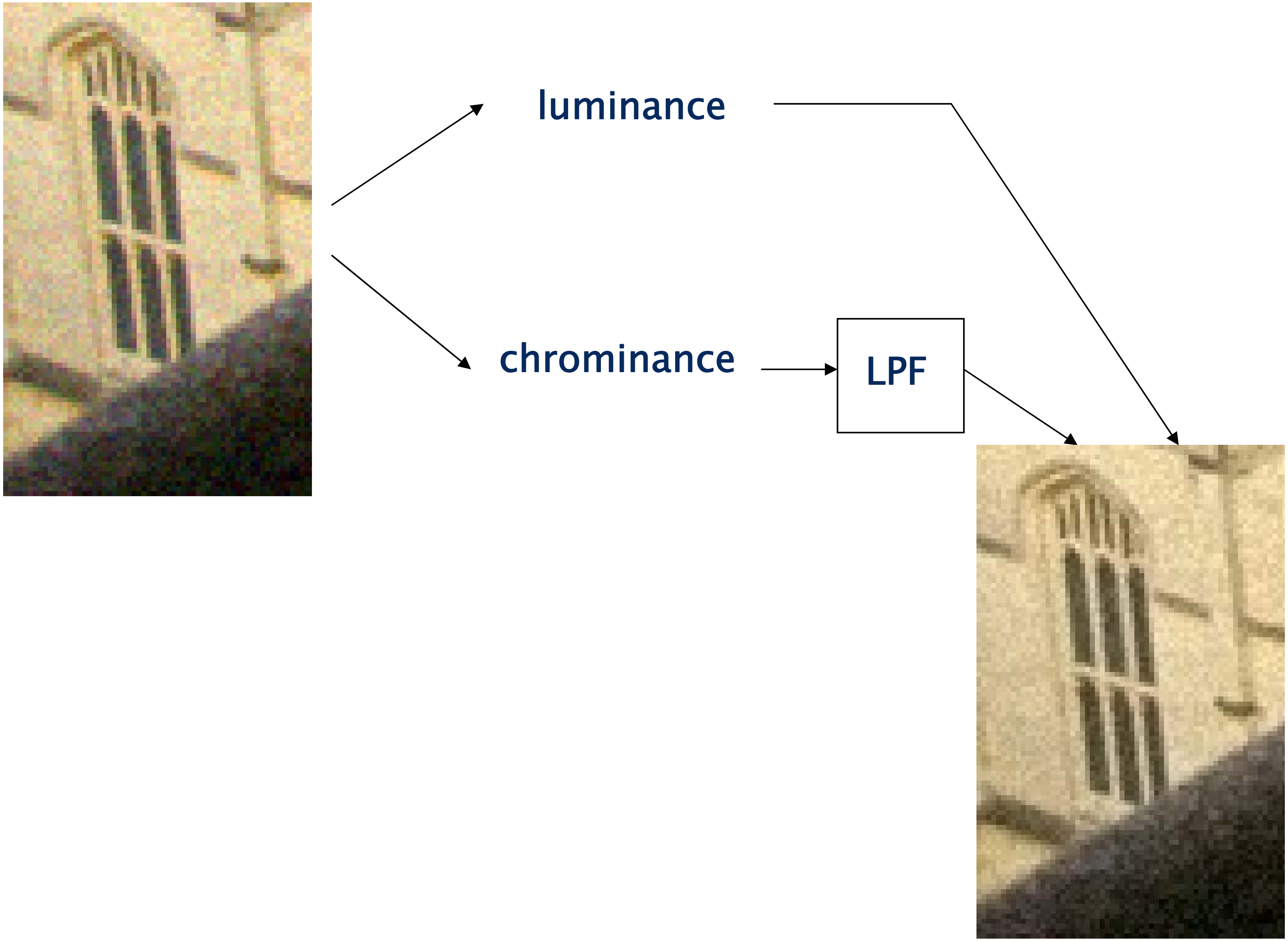
Color space conversion



Color space conversion



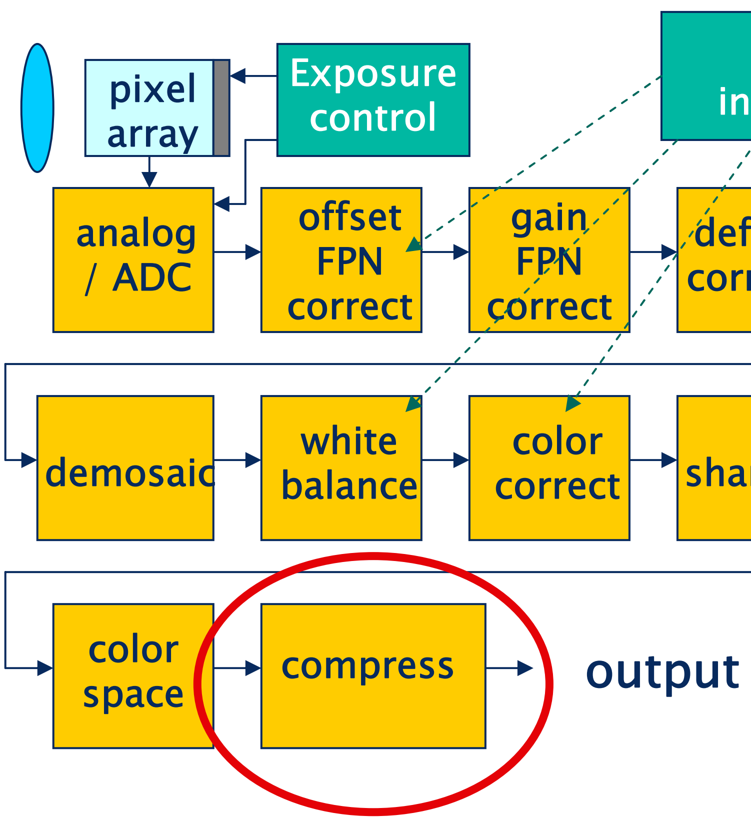
Chrominance filtering



Effects of color space conversion

- Chrominance noise may be reduced
- Noise may be spatially diffused

Compression



Compression

- Noise reduced
- Severe block artifacts

- Noise significantly reduced
- Loss of texture

JPEG compression

27x

JPEG 2000 compression

27x

Effects of compression

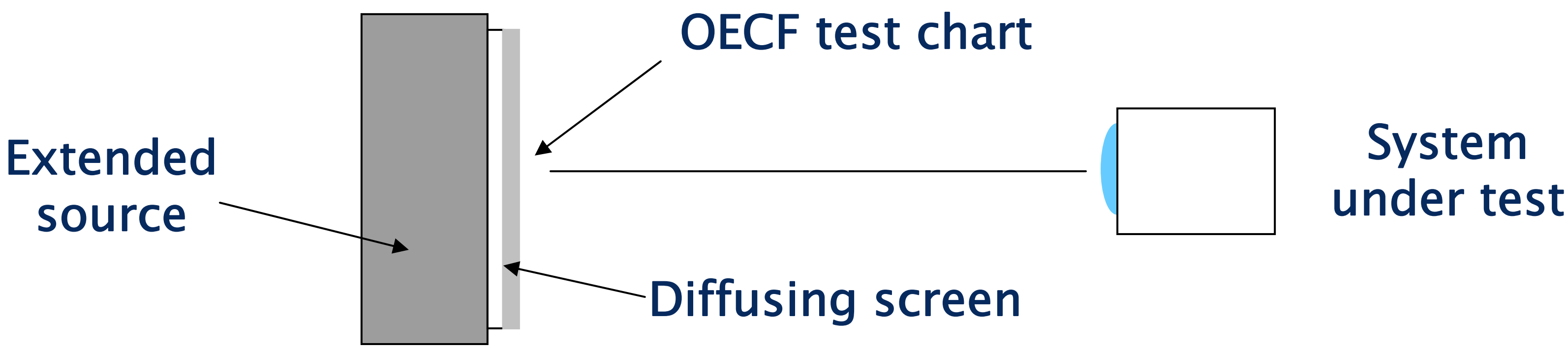
- Noise is reduced (similar to noise reduction processing)
- New sources of noise (block artifacts, quantization) may be added

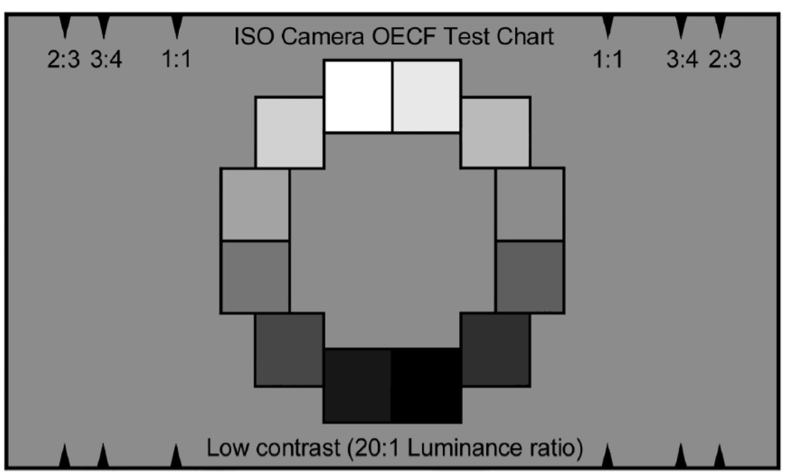
Measurement

Measurement challenges

- Interpretation of luminance versus chrominance noise
- Dependence on viewing conditions (Johnson & Fairchile EI2004)
  - High frequency chromatic noise doesn't effect quality
- Nonlinear processing (un-map gamma)
- Quantization limits on measurement
- Noise decomposition (temporal, fixed, etc.)
- (other practical stuff like shading suppression)
- Compression / adaptive noise filtering

ISO 14524 OECF measurement

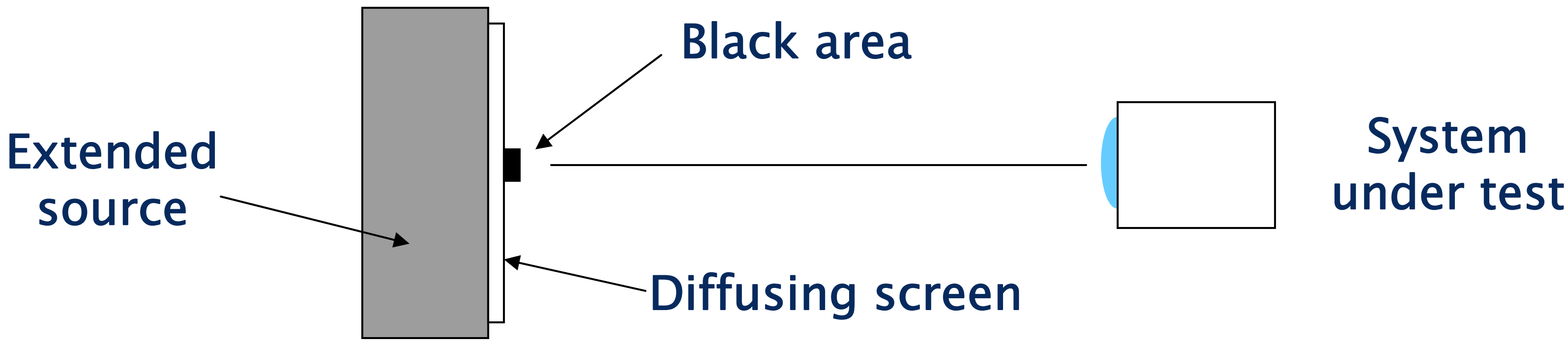




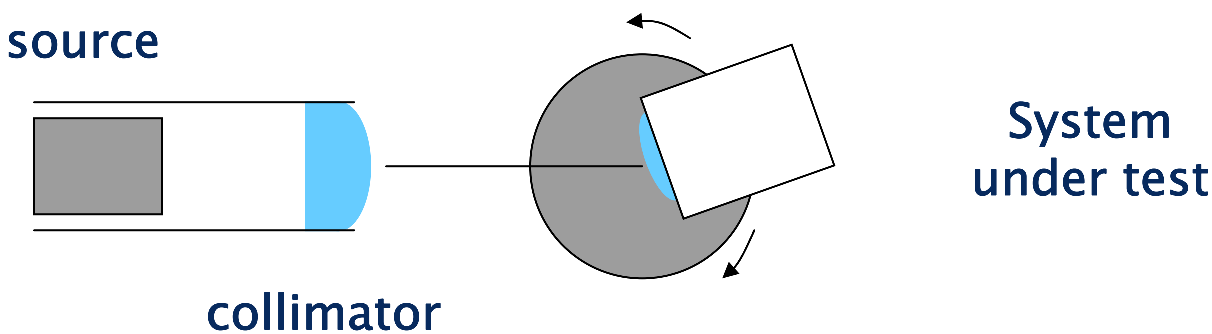
Required to un-map gamma & tone correction functions

ISO 9358:1994 veiling glare measurement

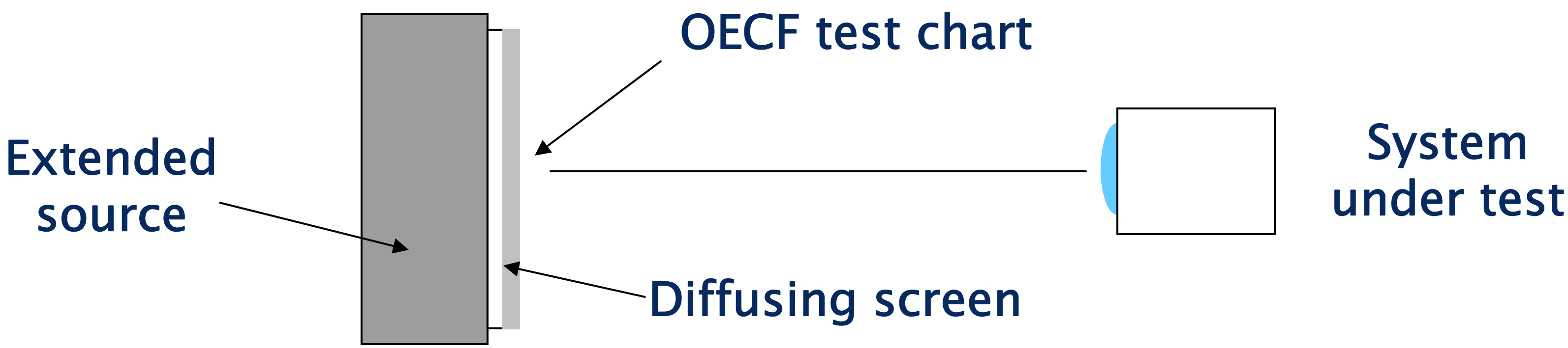
- **Integral method** (suitable for uniformly radiant scenes)

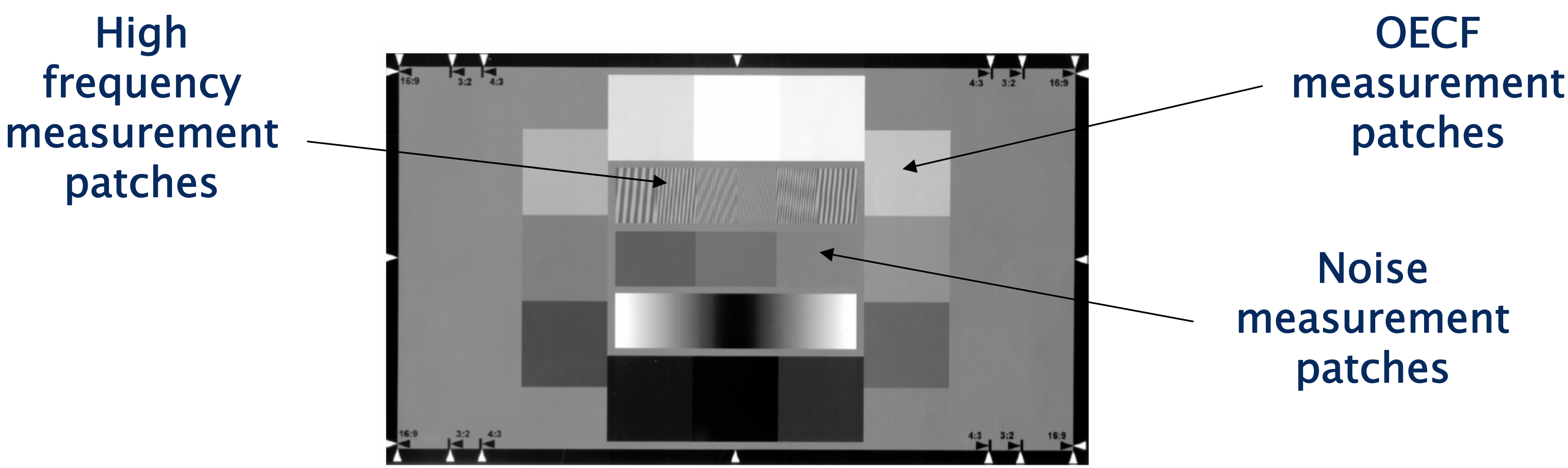


- **Analytical Method** (suitable for intense isolated sources)

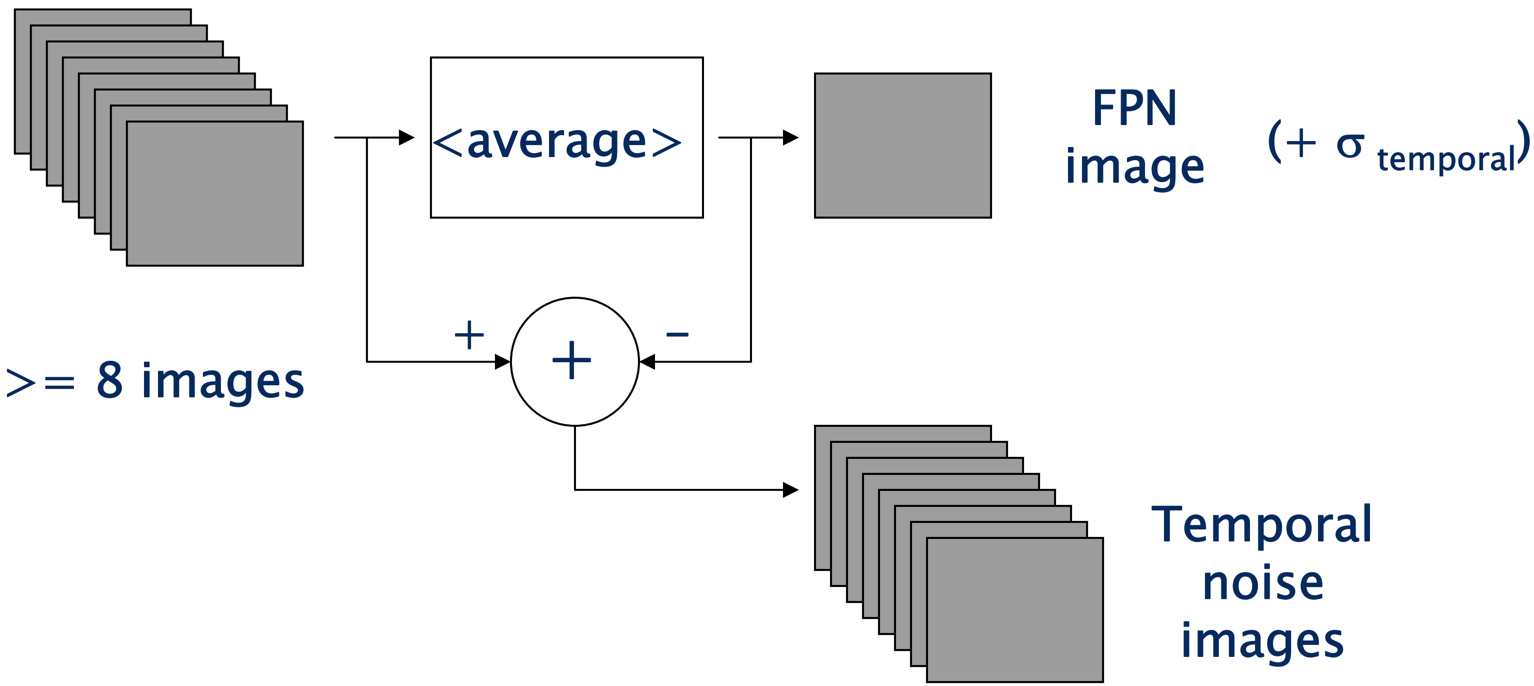


ISO 15739 noise measurement

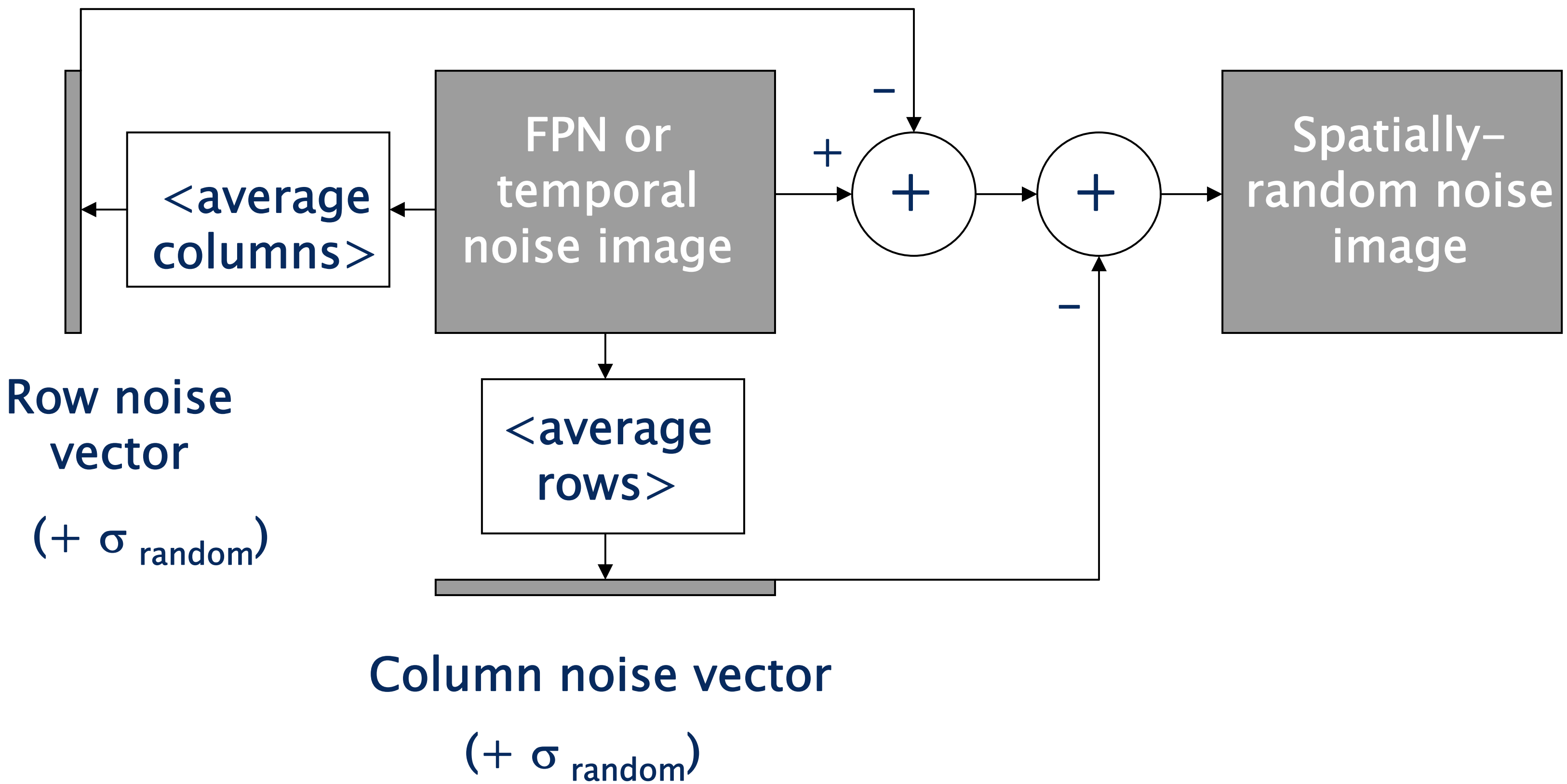




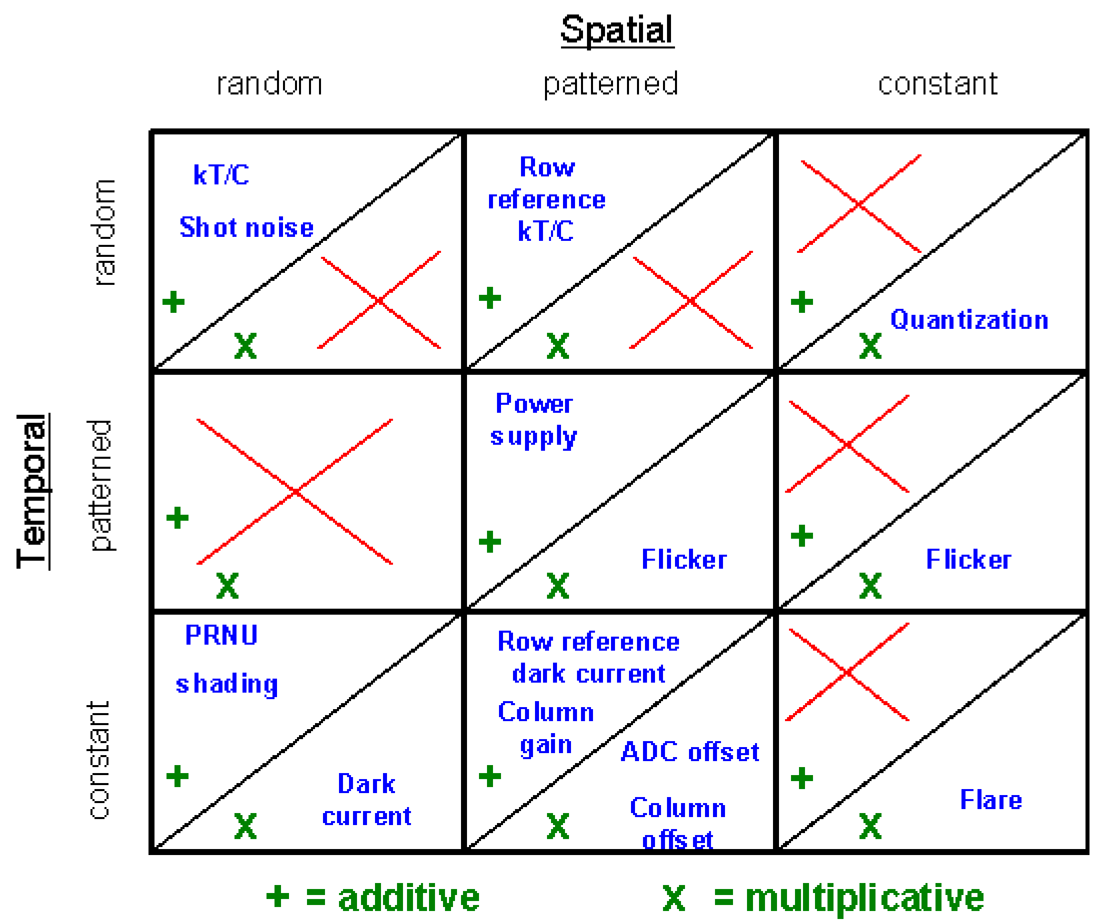
ISO 15739 noise component analysis (1)



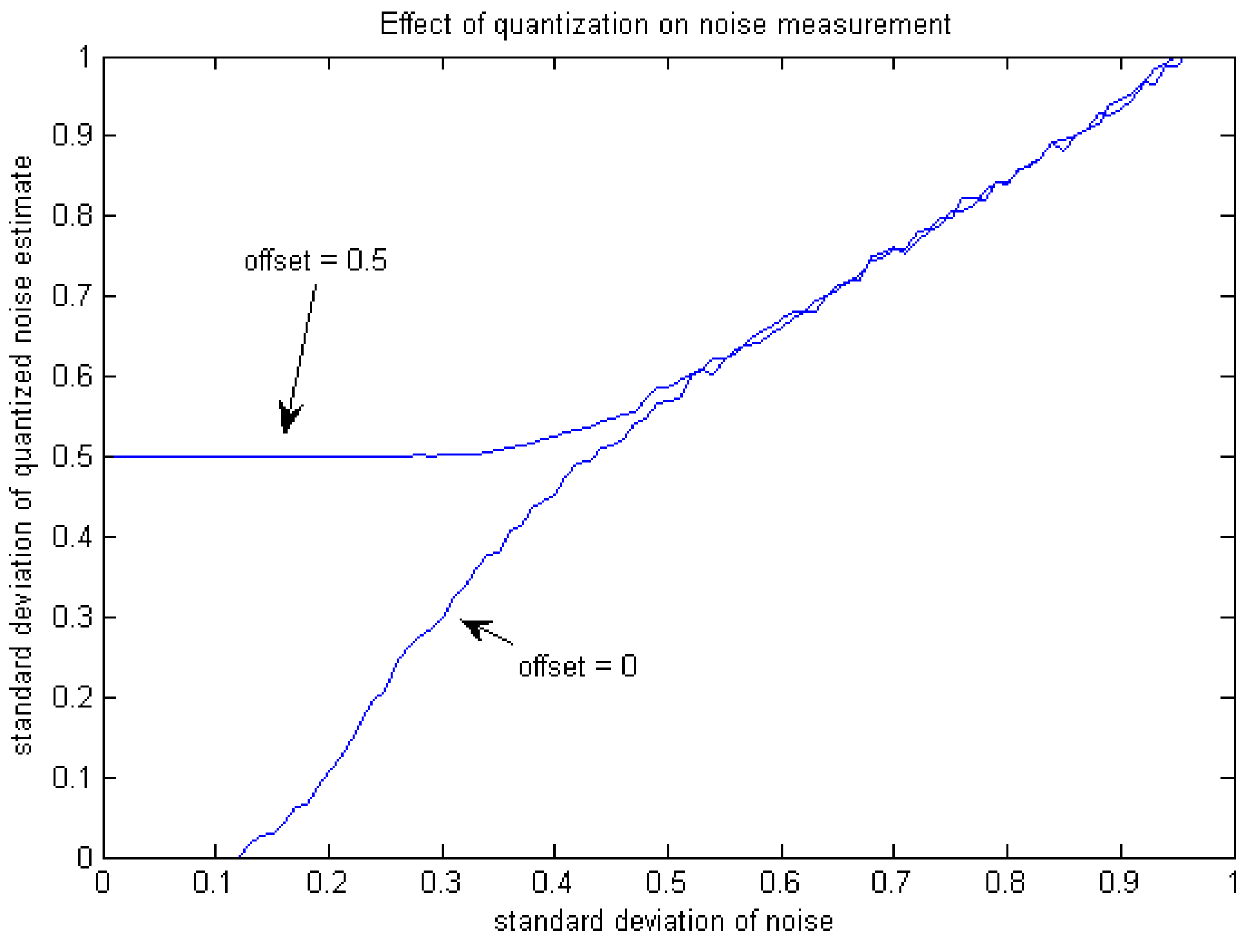
ISO 15739 noise component analysis (2)



Utility of noise decomposition



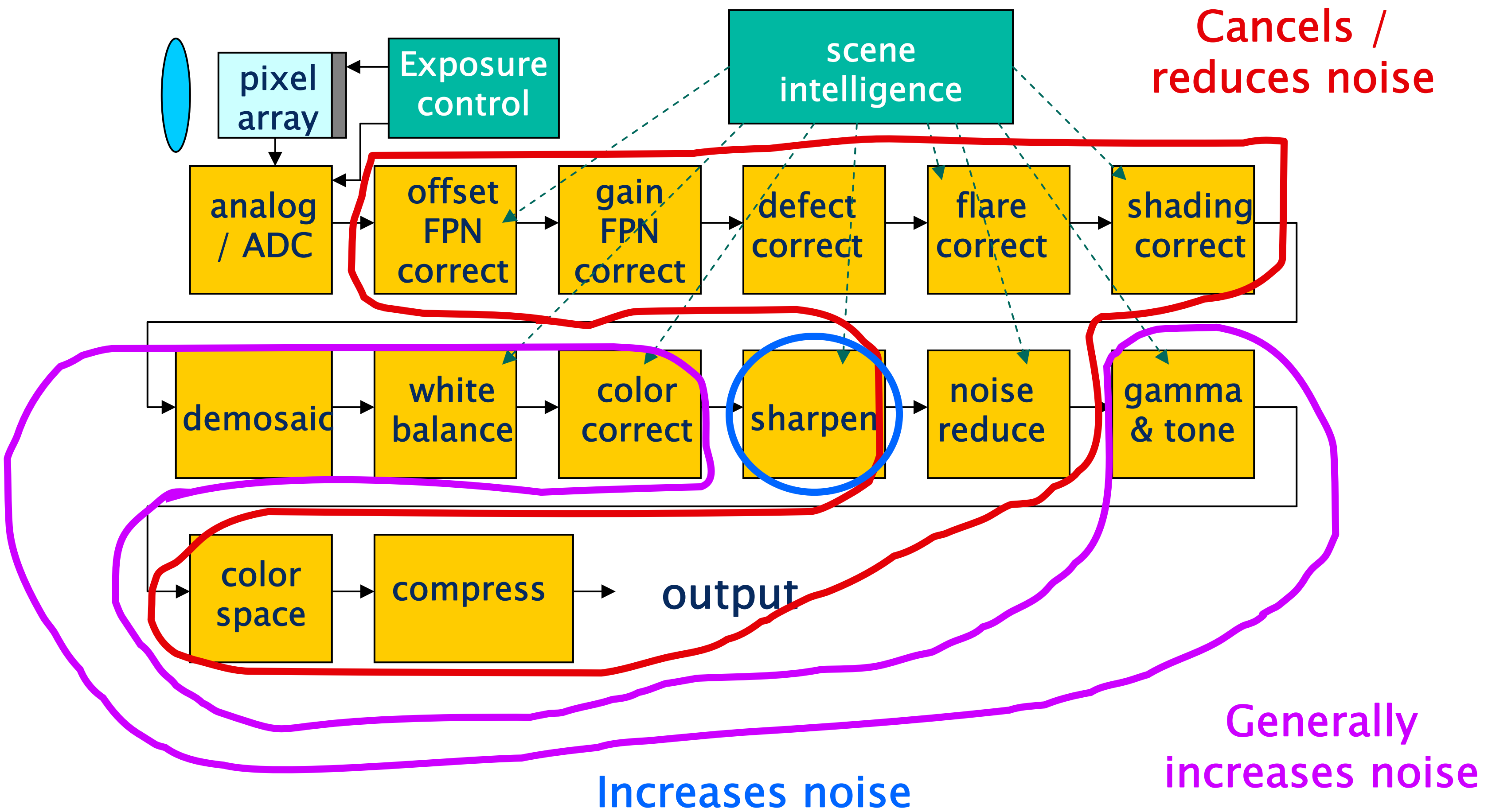
Quantization limits



Noise below ½ LSB can't be *measured*

Conclusions

Image processing modifies noise …

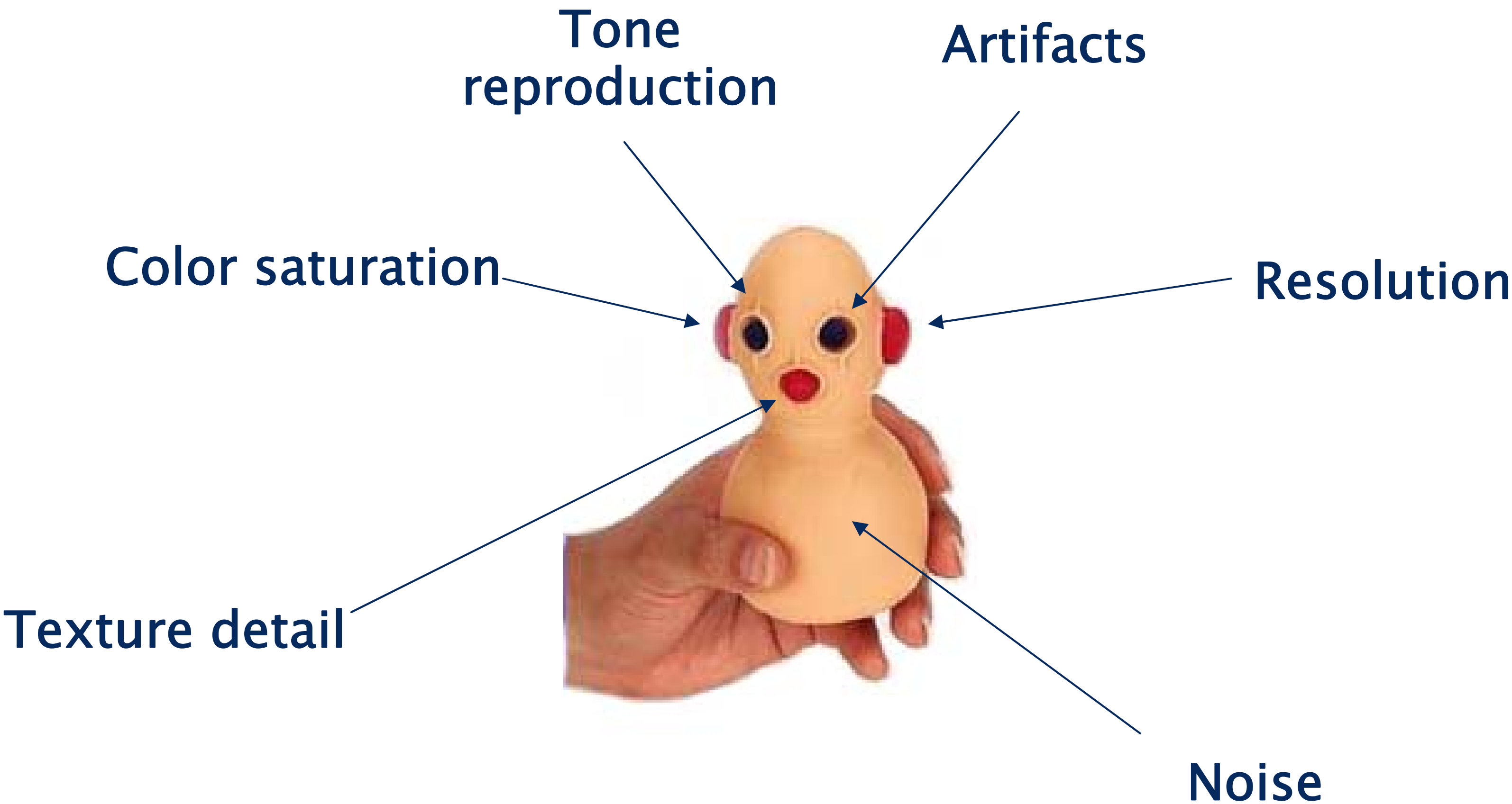


… and makes it difficult to measure!

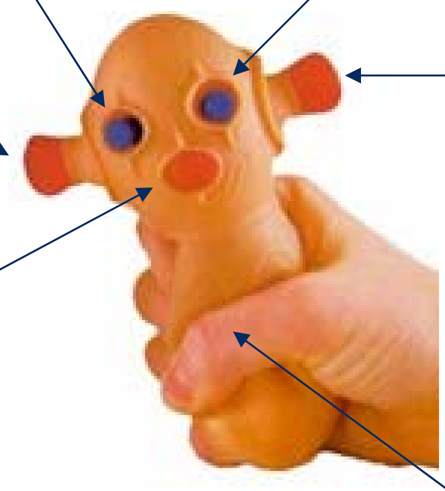
- Opto-electronic conversion function
- Luminance vs. chrominance
- Adaptive processing
- Compression artifacts

The ISO 12232 digital photography speed measurement standard has not been widely adopted because of the difficulty of noise measurement.

Noise is one dimension of image quality …



… but they *all* matter!



References

- J. Nakamura, Image Sensors and Signal Processing for Digital Still Cameras, CRC Press, New York, (2005).
- S. Battiato, M. Mancuso, “An Introduction to the Digital Still Camera Technology”, *ST Journal of System Research* – Special Issue on Image Processing for Digital Still Camera, Vol. 2, No.2, (12/2001).
- G. Williams Jr., Ed., Digital Solid State Cameras: Designs and Applications, Proc. SPIE, Vol. 3302, (1998).
- N. Sampat, J. DiCarlo, R. Motta, Eds., Digital Photography, Proc. SPIE, Vol. 5678, (2005).
- N. Sampat, J. DiCarlo, R. Martin, Eds., Digital Photography II, Proc. SPIE, Vol. 5678, (2006).
- R. Martin, J. DiCarlo, N. Sampat, Eds., Digital Photography III, Proc. SPIE, Vol. 5678, (2007).
- J. Lopez-Alonso, R. Gonzalez-Moreno, J. Alda, “Noise in imaging systems: fixed pattern noise, electronic, and interference noise”, Proc. SPIE, Vol. 5468, p. 399-407, (5/2004).
- ISO 9358 – Optics and optical instruments – Veiling glare of image-forming systems – Definitions and method for measurement.
- ISO 12232 – Photography – Digital still cameras – Determination of exposure index, ISO speed ratings, standard output sensitivity, and recommended exposure index.
- ISO 14524 – Photography – Electronic still-picture cameras – Methods for measuring opto-electronic conversion functions (OECFs).
- ISO 15739 – Photography – Electronic still-picture imaging – Noise measurements.