ISO Speed

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Outline

Introduction

Understanding ISO speed

ISO speed characterization

ISO speed and image processing

Summary

Introduction

- ISO speed is useful in still photography because it determines the nominal exposure conditions.
- The ISO (ASA) speed metric was originally developed to describe the sensitivity of silver-halide film. The relationship between speed and image quality is only implicit.
- The ISO 12232 standard defines an ISO speed metric for digital cameras (and solid-state image sensors) that is explicitly related to image quality.
- ISO speed does not apply to imaging at non-visible wavelengths.

Understanding ISO speed

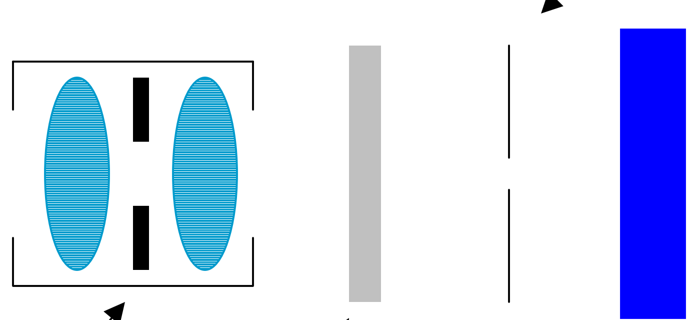
Exposure controls & metering

ISO speed of film

ISO speed of a solid-state image sensor

Basic exposure controls

Exposure ~ number of incident photons



shutter (period)

sensor

aperture (f#)

n.d. filter (density)

Why control exposure?

Dynamic range

Shutter speed control

Aperture control – depth of field

Underexposure

Correct exposure

Overexposure

Slow shutter

Fast shutter

Wide aperture

Narrow aperture

Exposure index

How exposure is controlled with a lightmeter:

1. **Set the exposure index (nominally equal to ISO speed)**
2. **Select an aperture (f#) and read the shutter speed**

-or-

2. **Select a shutter speed and read the aperture**

aperture value

sensor/film exposure index

$$\frac{(f\#)^2}{t} = \frac{\mathrm{EI}\ \langle La \rangle}{15.4}$$

shutter speed

average scene luminance

What is the exposure index?

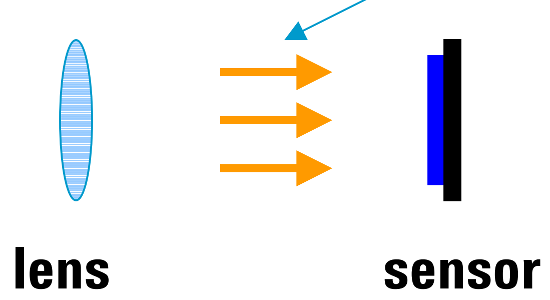
$$\mathrm{EI} = \frac{8}{\langle H_g \rangle} \approx \frac{10}{\langle H_a \rangle}$$

used in electronic imaging systems, ISO 12232

Where: $\langle H_g \rangle$ = geometric mean focal plane exposure

$\langle H_a \rangle$ = arithmetic mean focal plane exposure

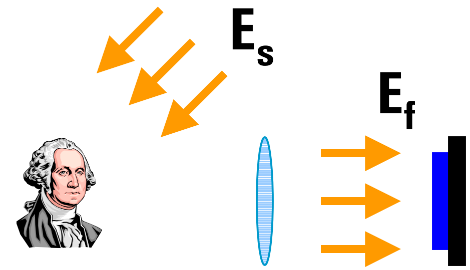
E_f (focal plane illuminance) [lux]



$$\langle Ha \rangle = \langle E_f \rangle \cdot T_e$$

[lux-seconds]

Relationship between scene illuminance and focal plane illuminance



focal plane illuminance (lux)

scene illuminance (lux)

scene reflectivity (lux)

image magnification

$$E_f = \frac{E_s \, R}{4 \, (f\#)^2 \, \left(1 + |m|\right)^2}$$

Typical scene illuminance levels:	
Direct sunlight	100,000 lux
Indirect sunlight	10,000
Overcast	1,000
Office	300
Pub	10
Full moon	0.1

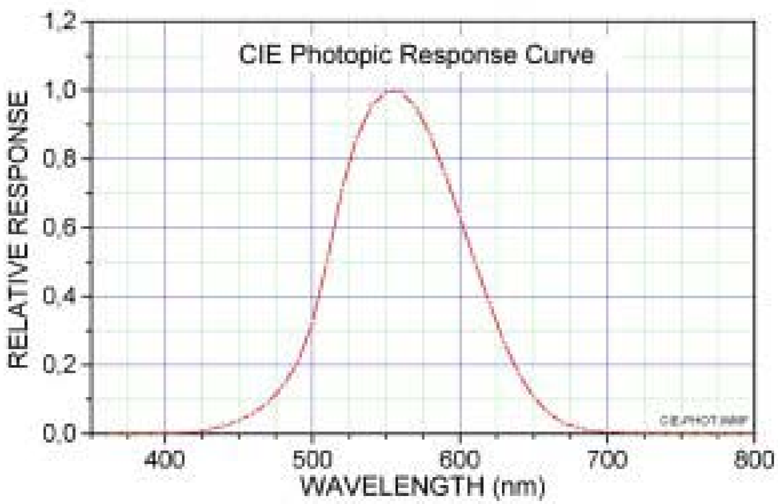
$$\frac{E_f}{E_s} \approx .006$$

For R = 18%, f# = 2.8, m = 0

(1.8 focal-plane lux with office lighting)

Photopic units

y_λ



photopic units (lux) describe light intensity as perceived by a human observer

$$\Phi_v = 680 \int_0^\infty y_\lambda \Phi_e(\lambda) d\lambda$$

luminous flux (lumens)

photopic response function

spectral flux (Watts)

How many photons are there?

1 lux = 1 lumen / m^2 ~ 10000 photons/sec/um^2

(for a spectrally broad illuminant)

Example: office lighting, 10 um^2 pixel, 1/120 second exposure

→ 1500 photons/pixel

ISO speed and exposure index

•The correct exposure for a particular scene determines the exposure index.

exposure compensation

•The ISO speed is equal to the exposure index *for a statistically average scene*.

High-key scene

Low-key scene

Relationship between ISO speed and (digital) image quality

- The gain applied to a solid-state sensor can be adjusted to change the ISO speed
- Image quality (SNR) depends on ISO speed

ISO = 200

ISO = 3200

ISO speed comparisons are meaningless unless image quality is considered!

ISO speed of film

Speed range of commercial film

Speed versus quality tradeoff

ISO measurement procedure

Color negative film

ISO 100 → **ISO 1600**

B&W film

ISO 400

Speed versus quality

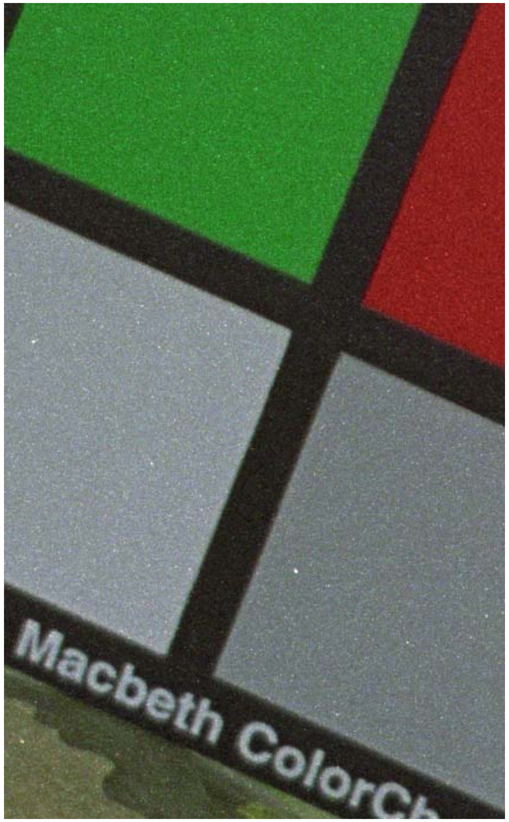
Film response is nonlinear

Film is a threshold detector

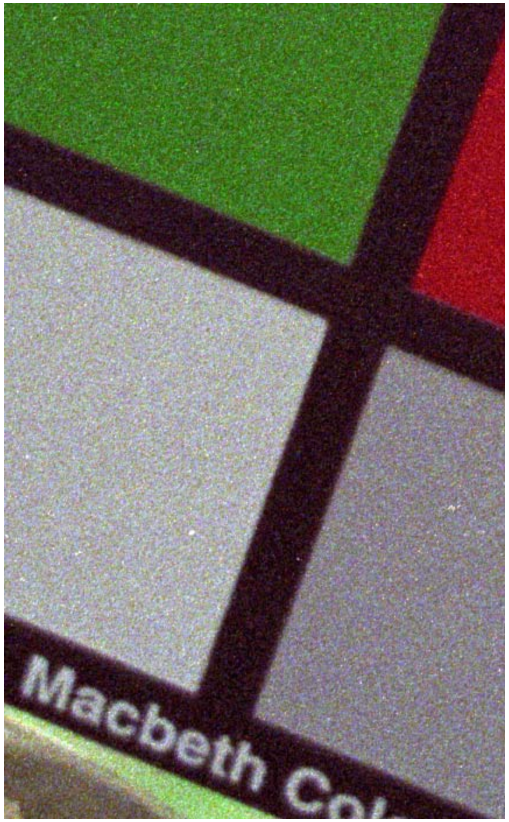
Grain noise is more important than shot noise

Grain size increases with film speed

Scanned film

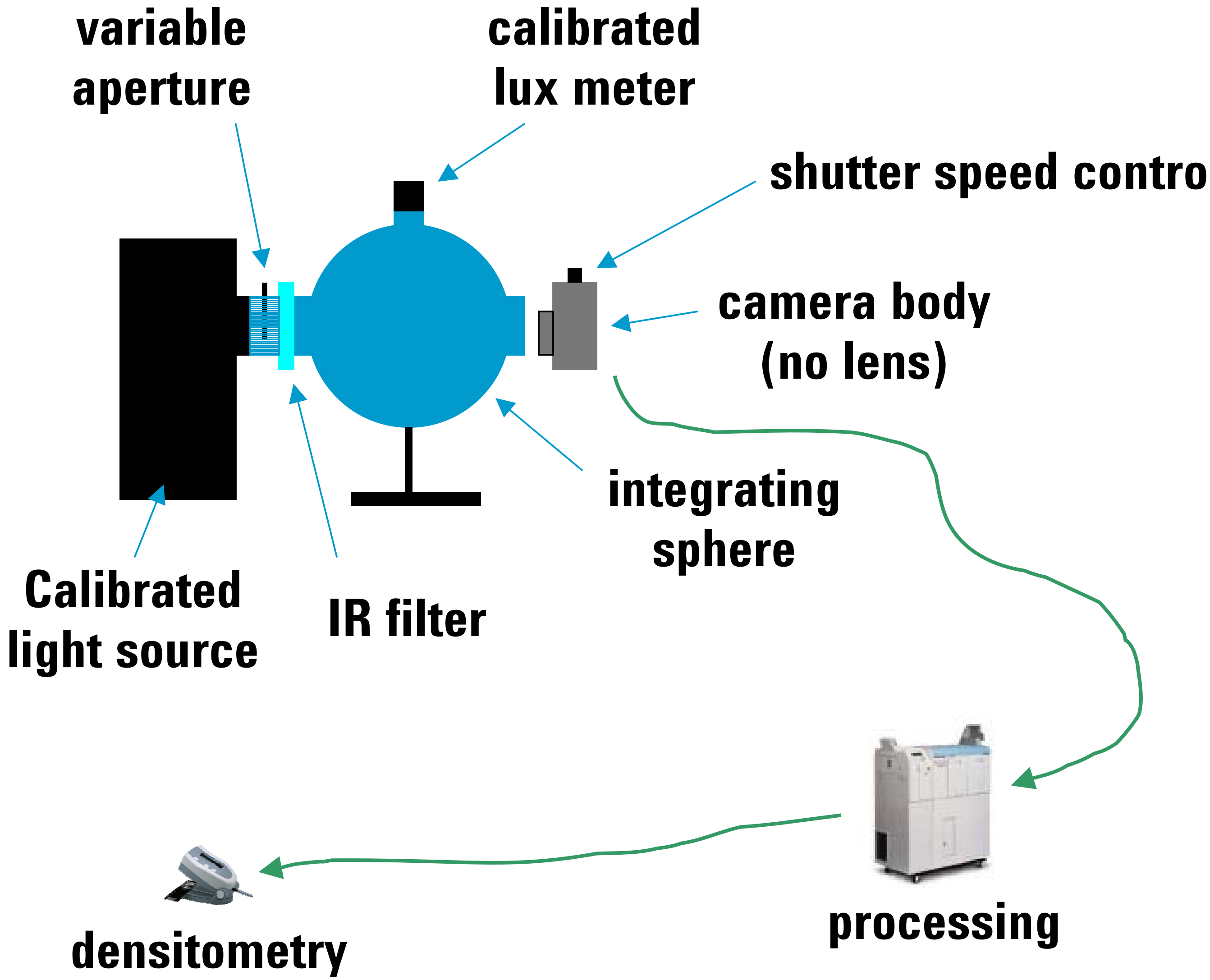


(ISO 100)



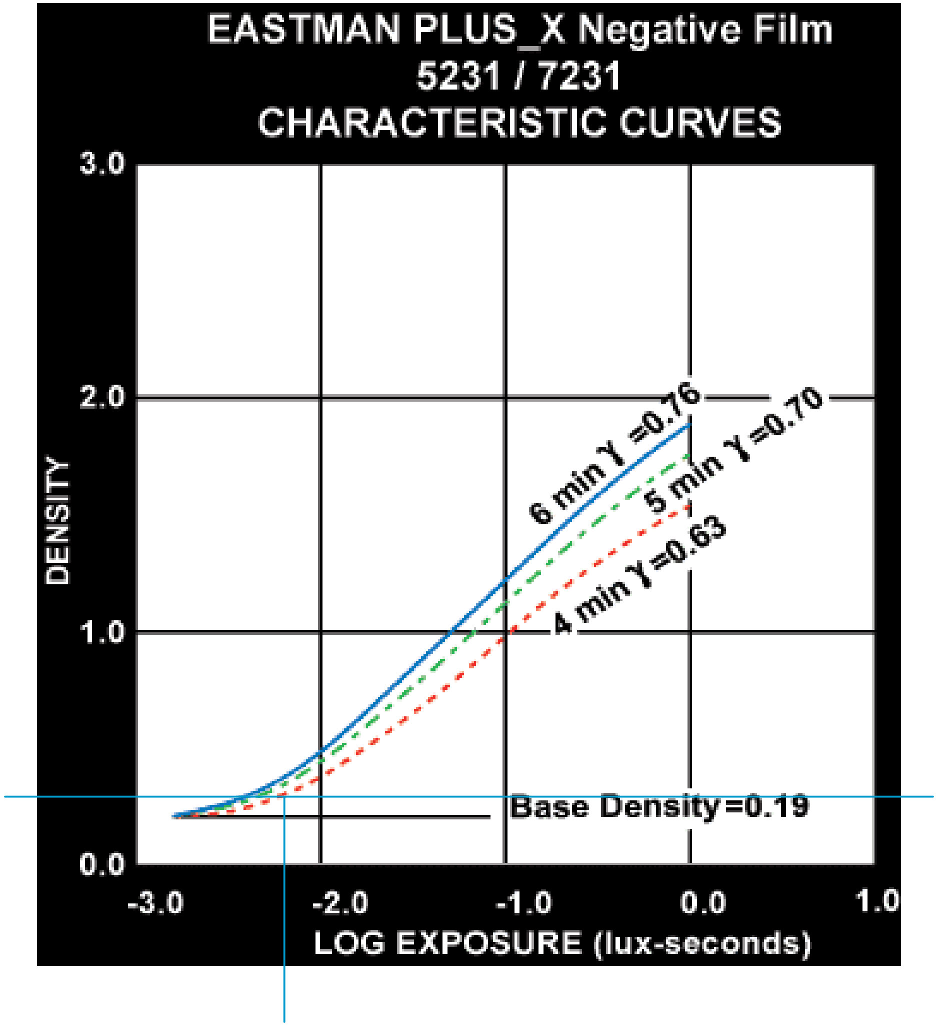
(ISO 800)

Measurement apparatus



Measurement procedure

1. Use aperture and shutter to vary focal plane exposure from frame to frame.
2. Process film for gamma = 0.615
3. Measure film density versus focal plane exposure
4. Plot density versus log exposure
5. Determine exposure intercept at (fog + 0.1) density
6. ISO speed = 0.8 / En



$$ISO = 0.8/En = 0.8/10^{-2.2} = 125$$

The ISO characterization methods used for film are not applicable to solid-state image sensors, with linear responses and different noise mechanisms.

ISO speed of a solid-state image sensor

Comparison of film and solid-state sensors

ISO 12232 methodology

Monochrome image sensor model

Color image sensor model

Comparison of film and solid-state image sensors

camera

film

film developer

may incorporate camera functions
(e.g. metering, shutter)

camera

image sensor

image processor

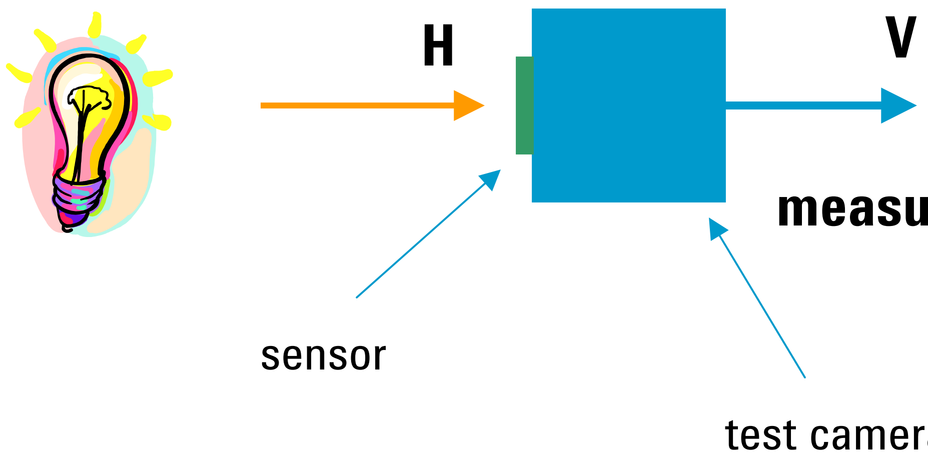
may be integrated!

Image sensors and digital processing compare with film <u>and developing</u>

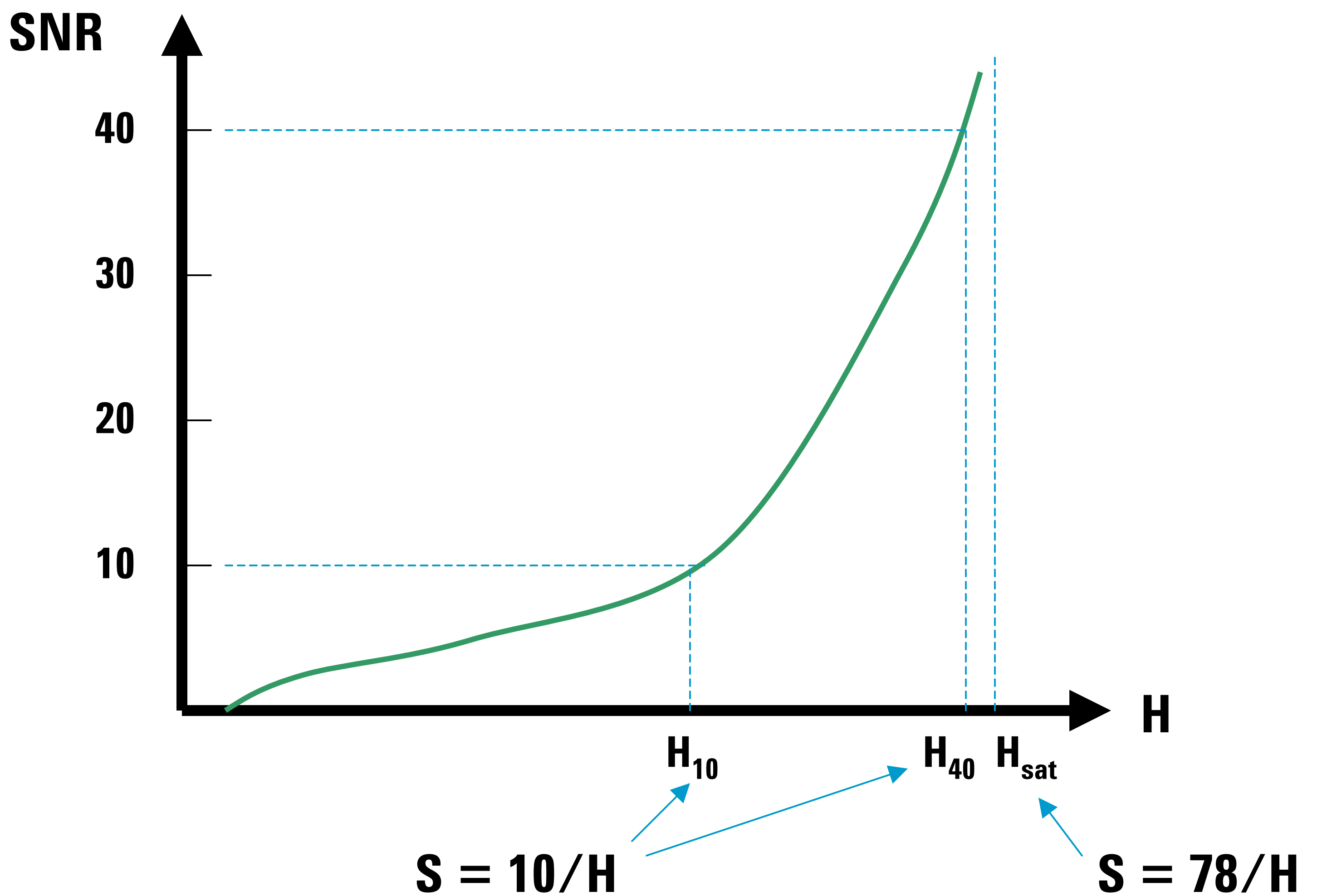
ISO 12232 methodology

- **Determine focal plane exposure (H) required to obtain a particular SNR value**
- **Specify ISO speed range:**
  - $S_{noise10} = 10/H$ @ SNR = 10 (first acceptable image)
  - $S_{noise40} = 10/H$ @ SNR = 40 (first excellent image)
- **Specify ISO speed at saturation**
  - $S_{sat} = 78 / H$ @ saturation

vary illumination, shutter speed to control focal plane exposure

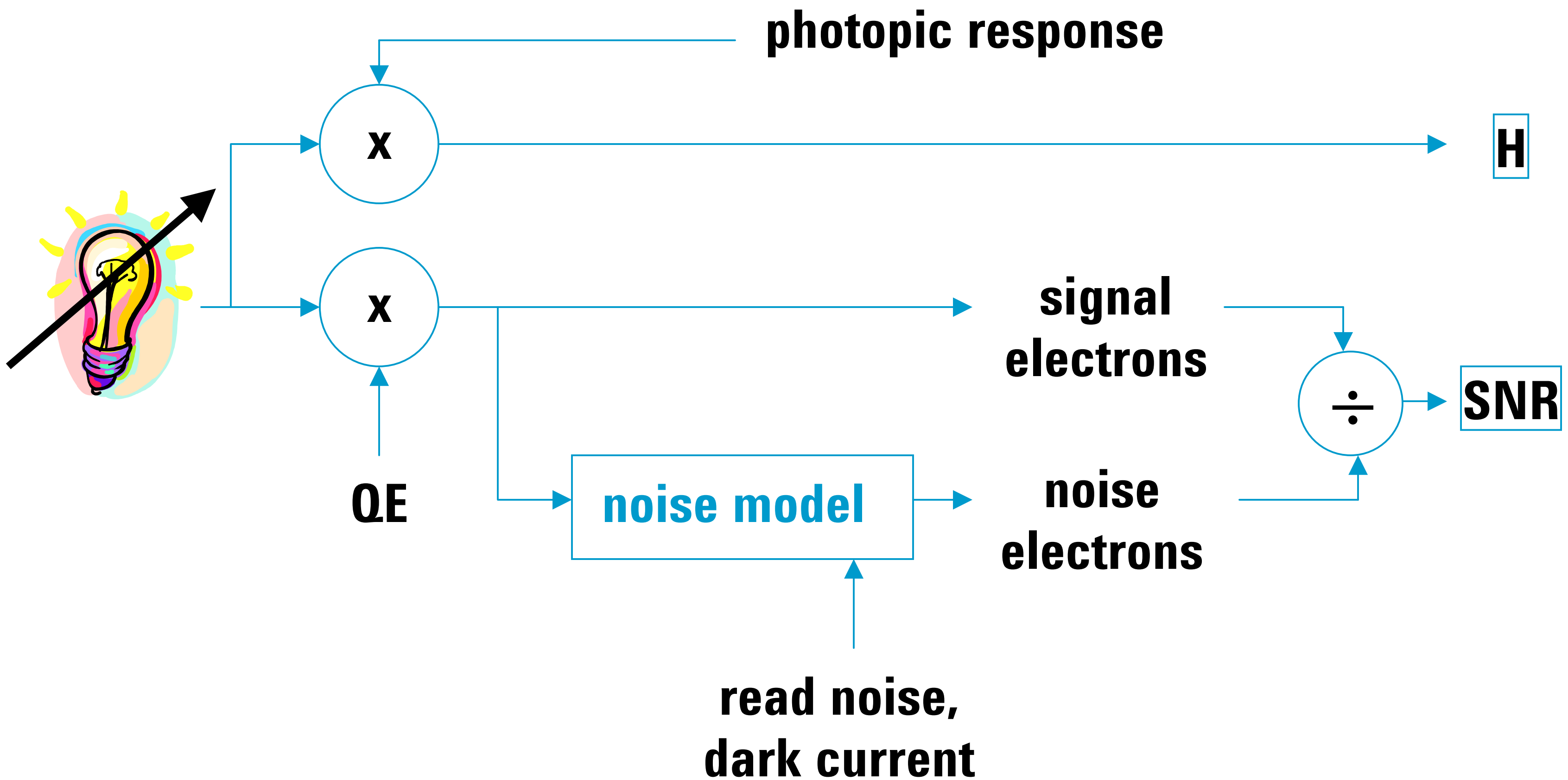


measure SNR of output signal

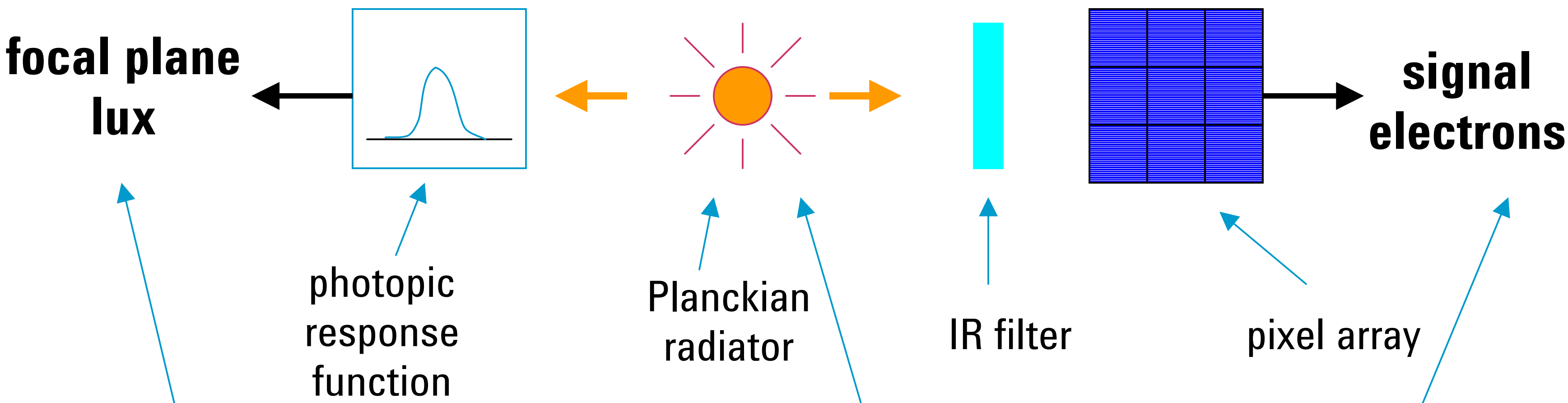

SNR
40
30
20
10
H
H_{10}
H_{40}
H_{sat}
S = 10/H
S = 78/H

ISO speed model for monochrome image sensors

- Determine H required to achieve specified SNR
- ISO speed = 10/ H



Photopic quantum efficiency (photopic electrons per lux)



$$\Phi_e(\lambda) = \frac{\alpha}{\lambda^5}\left(e^{hc/kT\lambda} - 1\right)^{-1}$$

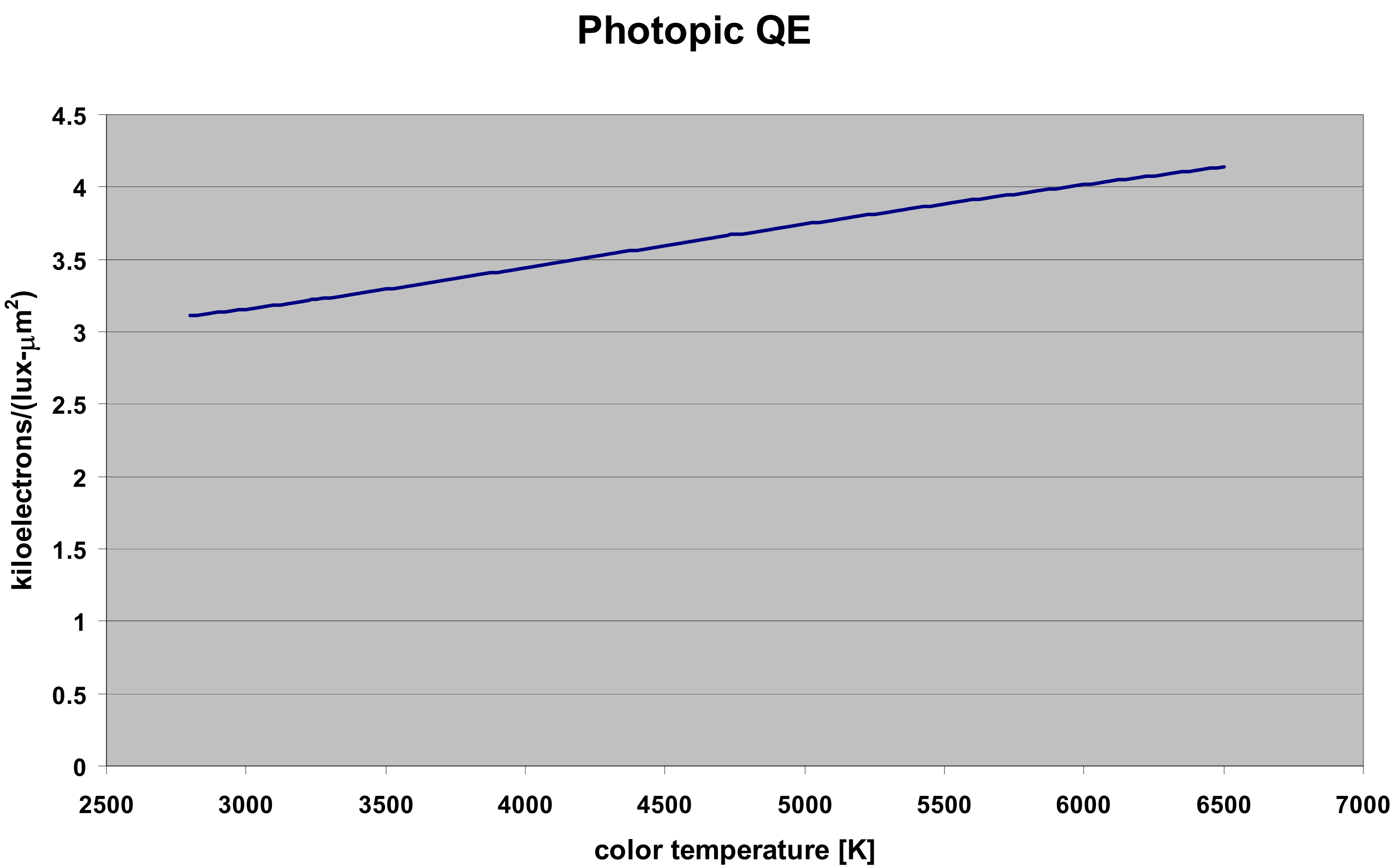
$$\mathrm{H} = 680\int_0^\infty y_\lambda \Phi_e(\lambda)\,d\lambda$$

$$\mathrm{N_e} = \int_0^\infty \frac{\lambda\ \mathrm{IR}(\lambda)\ \mathrm{QE}(\lambda)\ \Phi_e(\lambda)}{h\ c}\,d\lambda$$

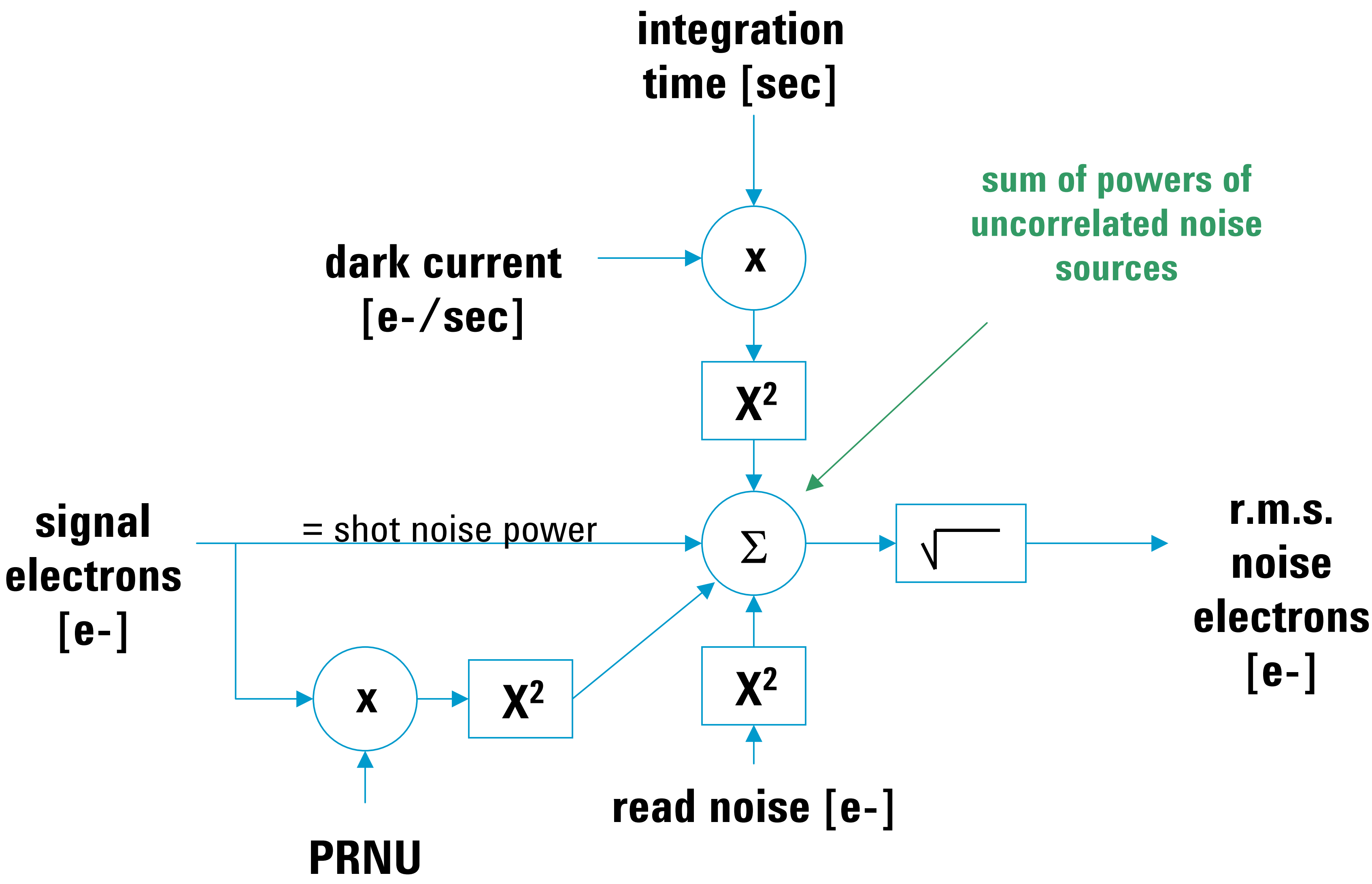
$$\eta_\mathrm{p} = \mathrm{N_e} / \mathrm{H}$$

Typical photopic QE for a monochrome image sensor

(Panasonic MN3776; peak QE = 50%)



Noise model



integration time [sec]
dark current [e-/sec]
x
X^2
sum of powers of uncorrelated noise sources
signal electrons [e-]
= shot noise power
Σ
√
r.m.s. noise electrons [e-]
x
X^2
X^2
PRNU
read noise [e-]

Derivation of ISO speed equation

(*** neglecting PRNU ***)

Photopic QE

pixel area

focal plane exposure

$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)_x = \frac{\eta_p \ \mathrm{A} \ \mathrm{H}}{\sqrt{\eta_p \ \mathrm{A} \ \mathrm{H} + \mathrm{N}r^2}}$$

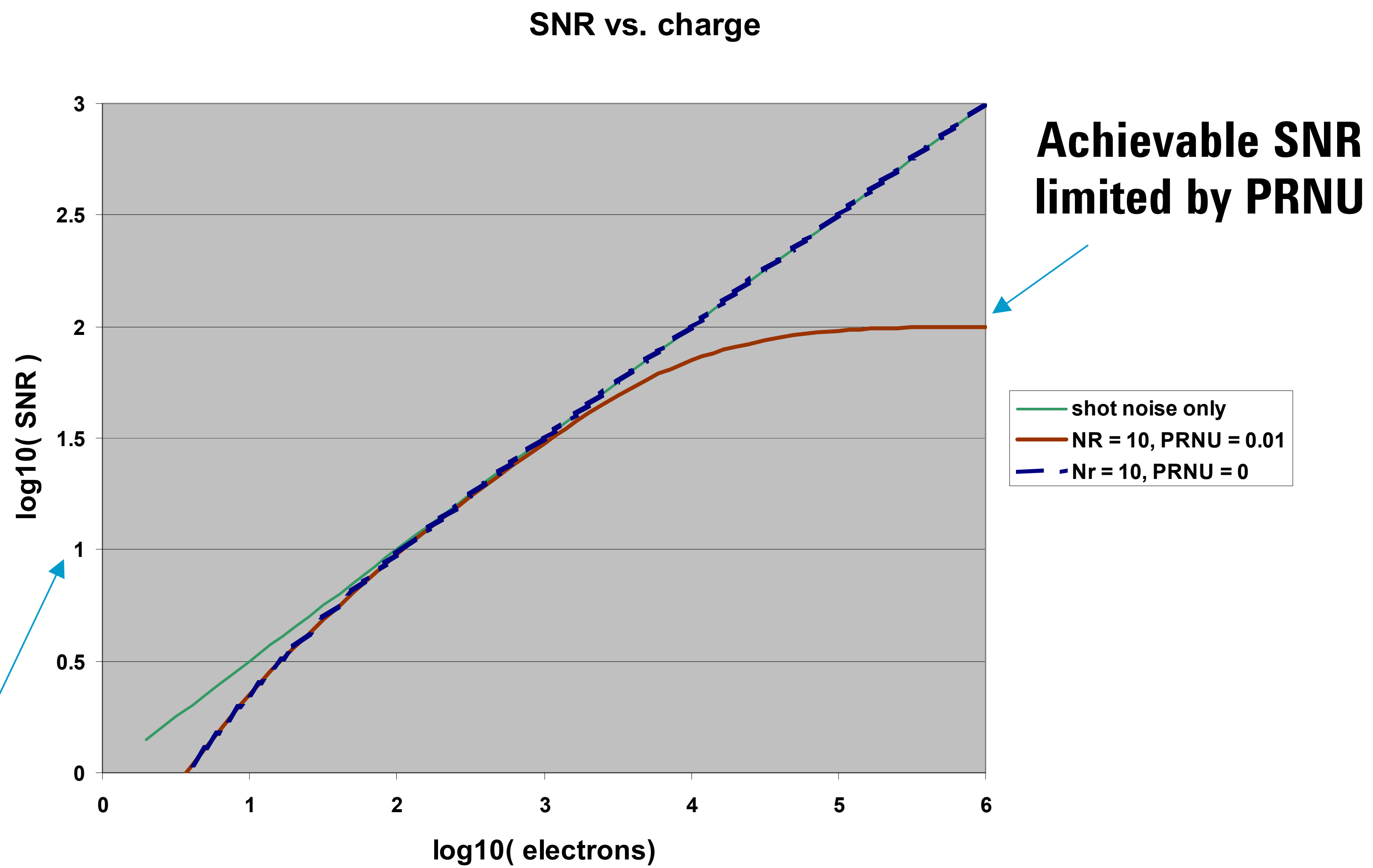
read noise

shot noise

$$S_x = \frac{20 \ \eta_p \ \mathrm{A}}{(\mathrm{S}/\mathrm{N})_x^{\ 2}} \left(1 + \sqrt{1 + \frac{4 \ Nr^2}{(\mathrm{S}/\mathrm{N})_x^{\ 2}}} \right)^{-1}$$

- **ISO noise speed increases linearly with QE and pixel area**
- **"Acceptable" noise speed (SNR=10) depends on electronic noise**

SNR curves

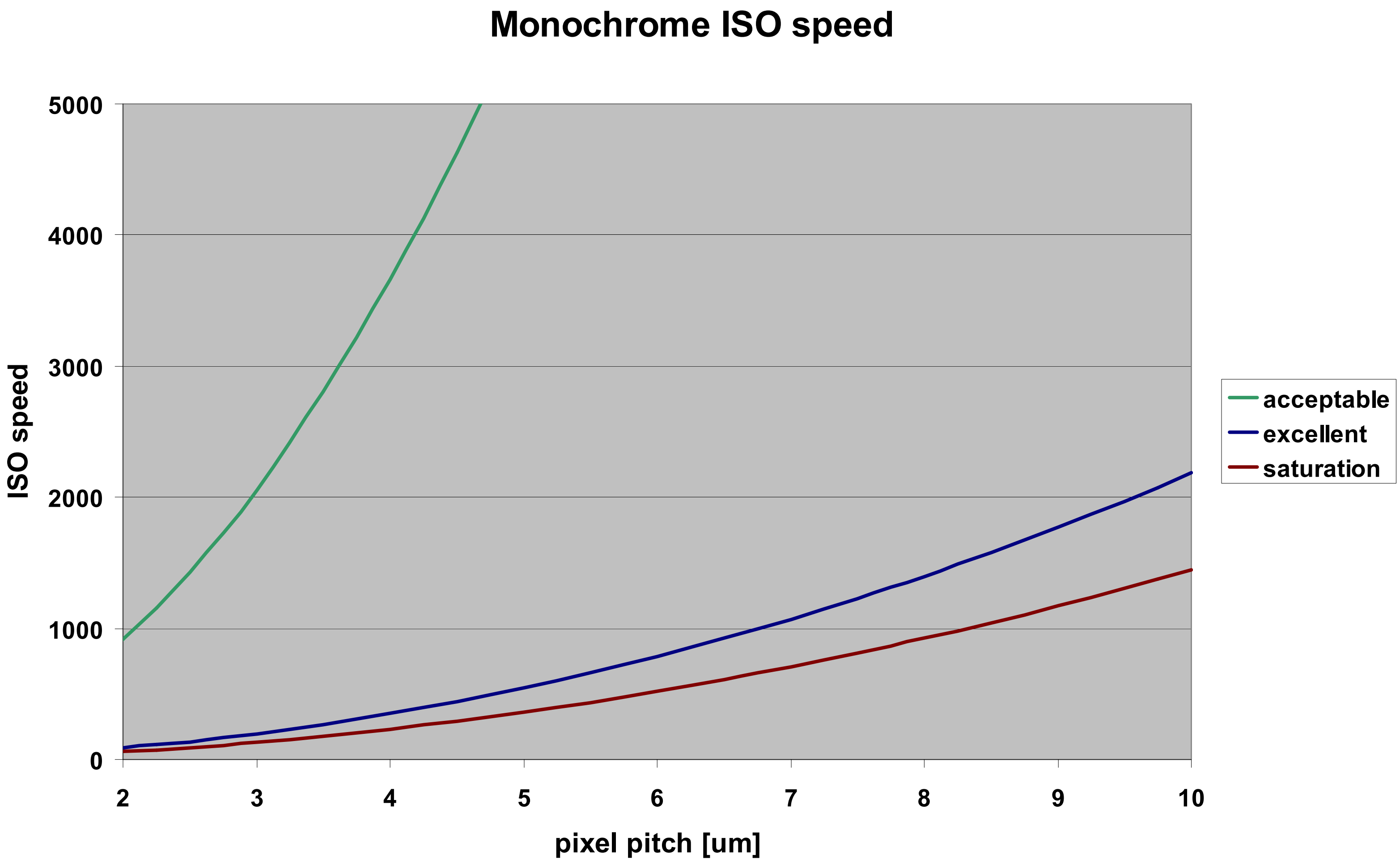


Read noise only affects "acceptable" ISO speed

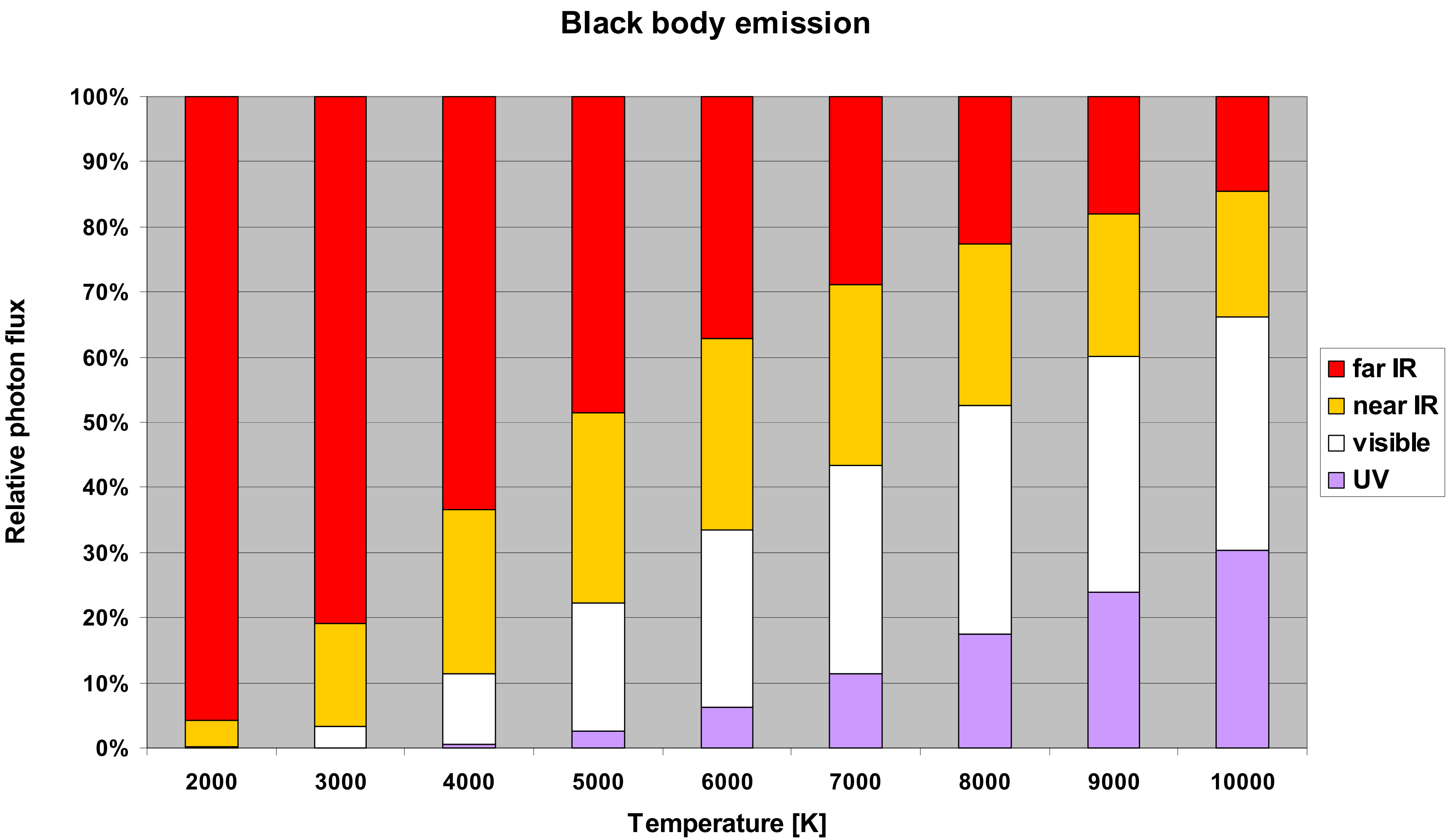
ISO speed curves for a typical sensor

(* neglecting PRNU ***)**

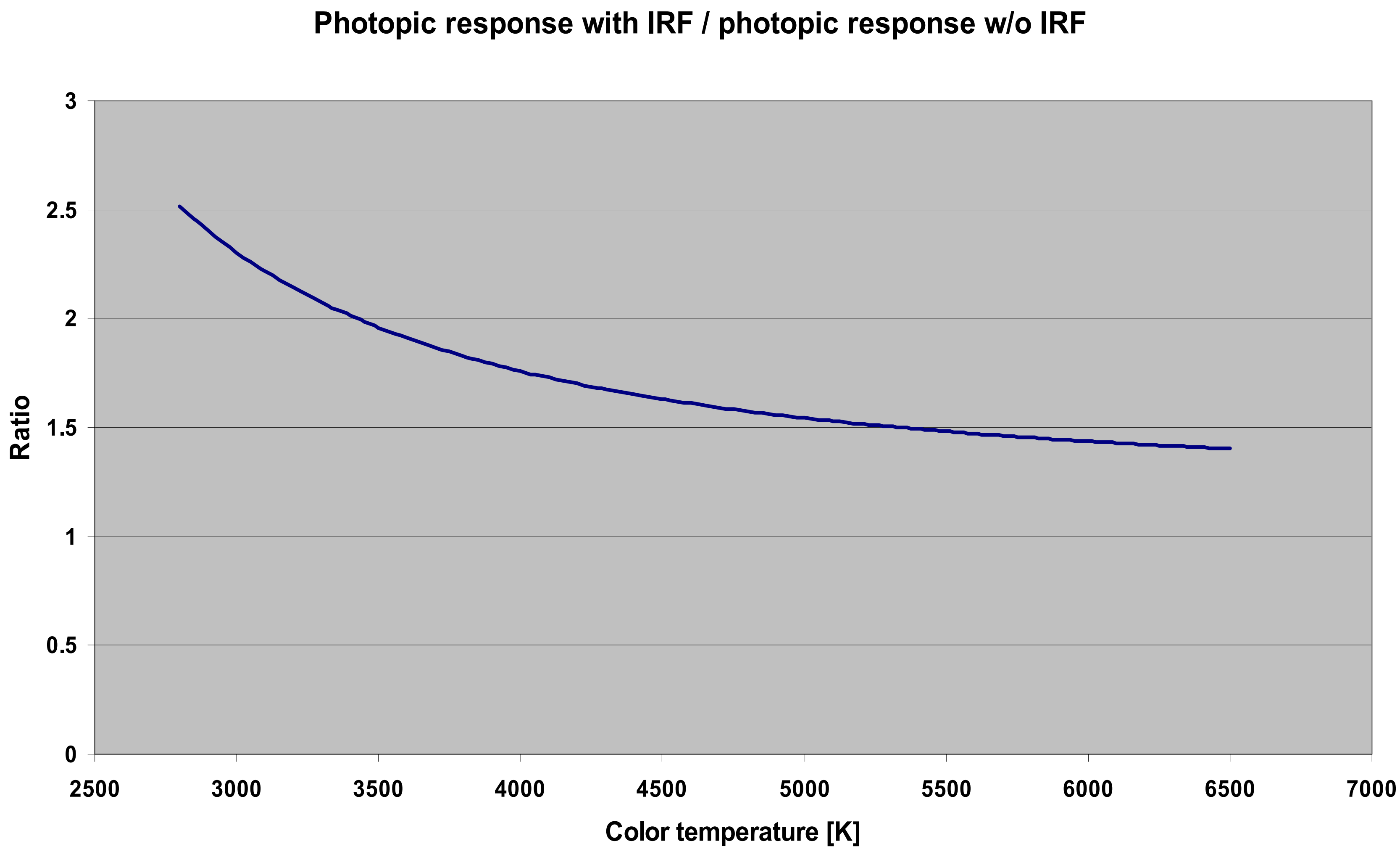
η_P = 3.7 ke, Nr =10 e, N_{sat} = 20 ke



Effect of IR and UV (wavelengths outside photopic response range)



ISO speed ratio for BB source, w & w/o IR filter



Effect of dark current

In the low-SNR, high noise limit:

$$S_a \approx \frac{10\ \eta_p\ A}{Nd\ Te}$$

ISO “acceptable” speed

dark current [e/sec]

exposure period

ISO speed varies inversely with exposure period: longer integration times don’t help!

The high ISO speeds of solid-state image sensors (compared to film) are a consequence of the higher QE of silicon.

ISO speed characterization

Camera characterization: ISO 12232

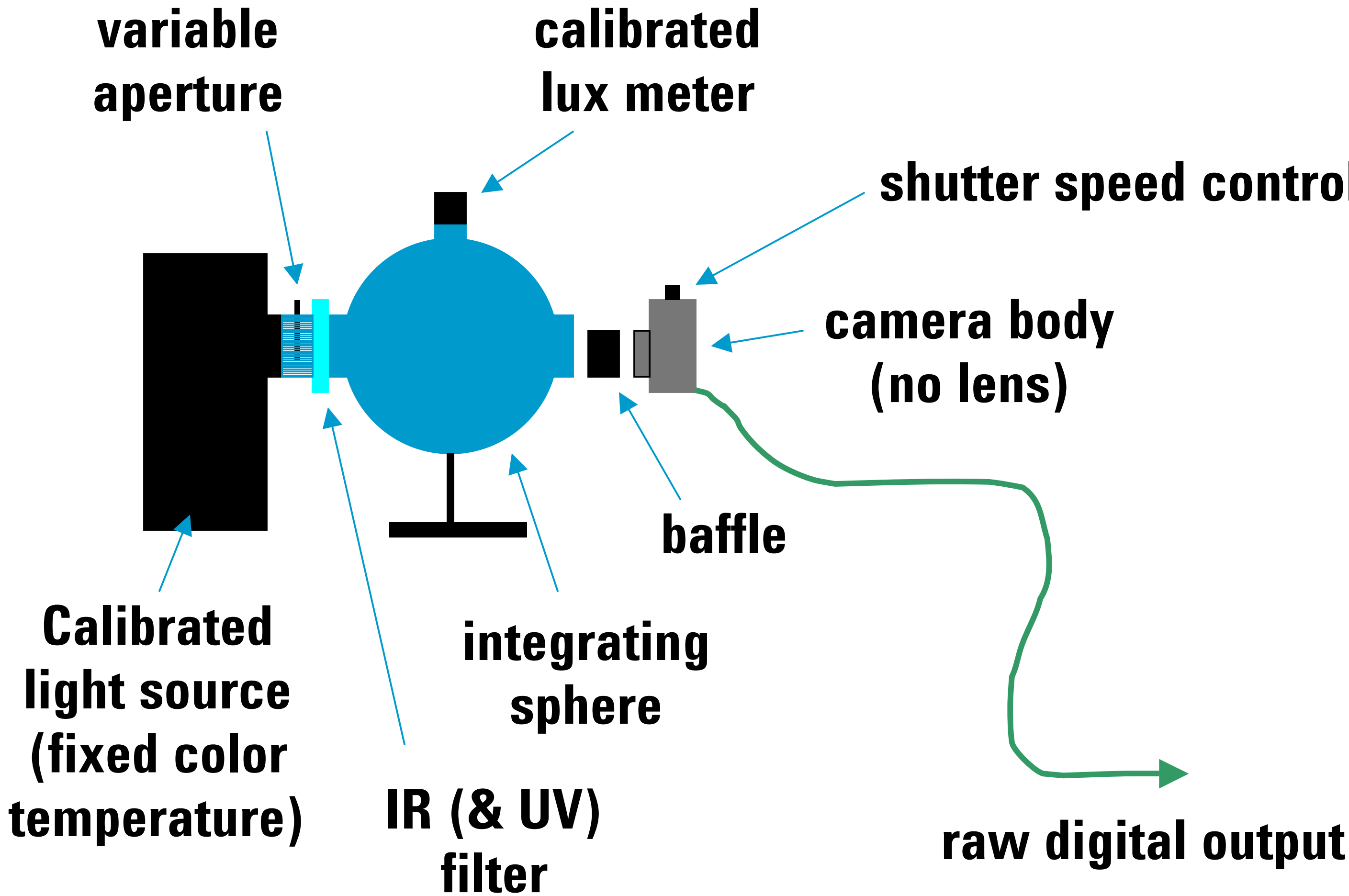
Sensor characterization: QE and noise

ISO 12232 procedures for determining speed

Direct focal plane exposure method

Indirect scene luminance method

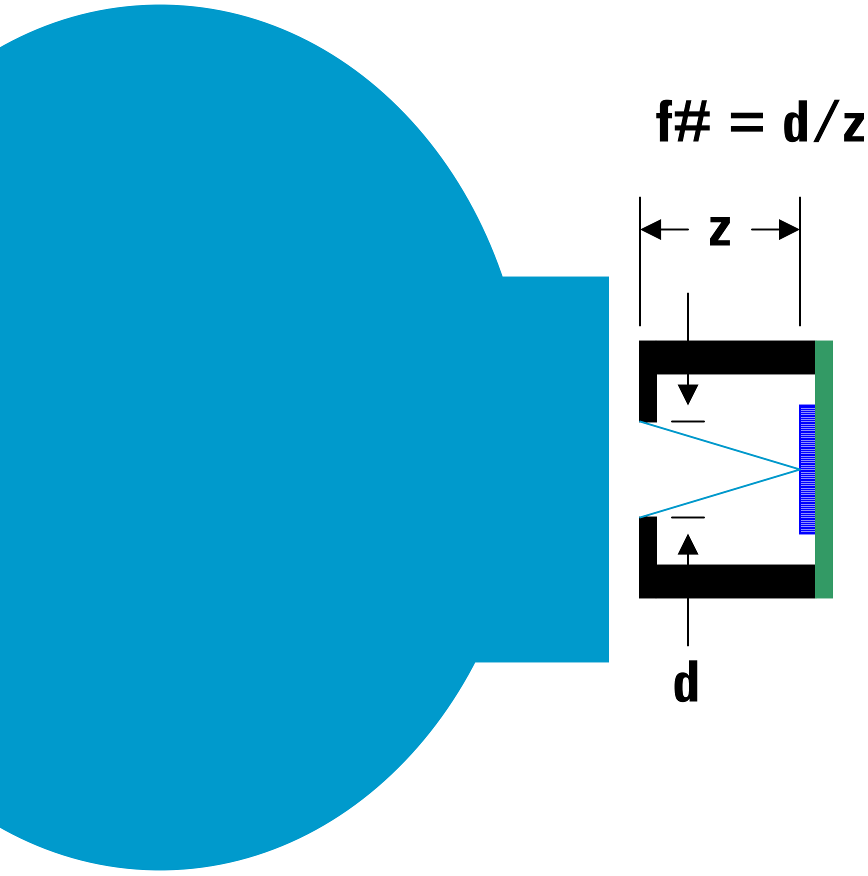
Measurement apparatus (direct focal plane exposure)

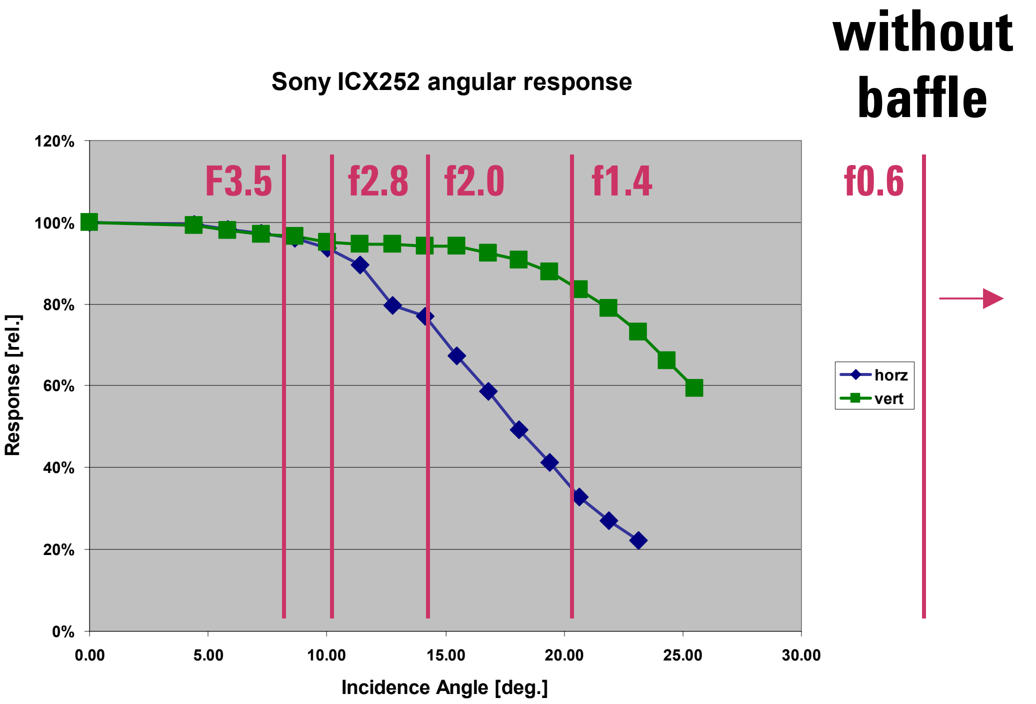


Measure SNR versus focal plane exposure

Illumination control

The angular spread of illumination must match the lens f#.

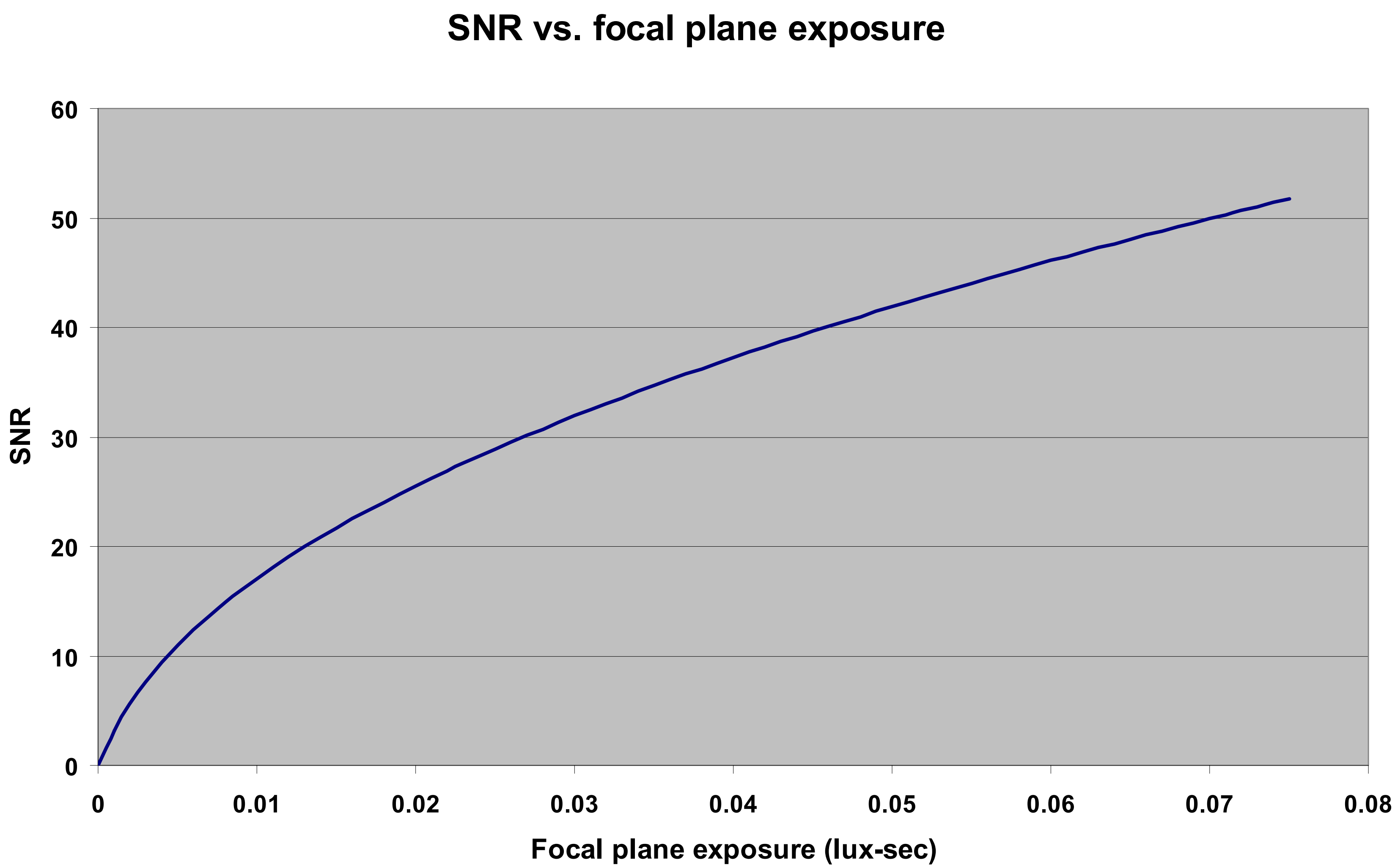




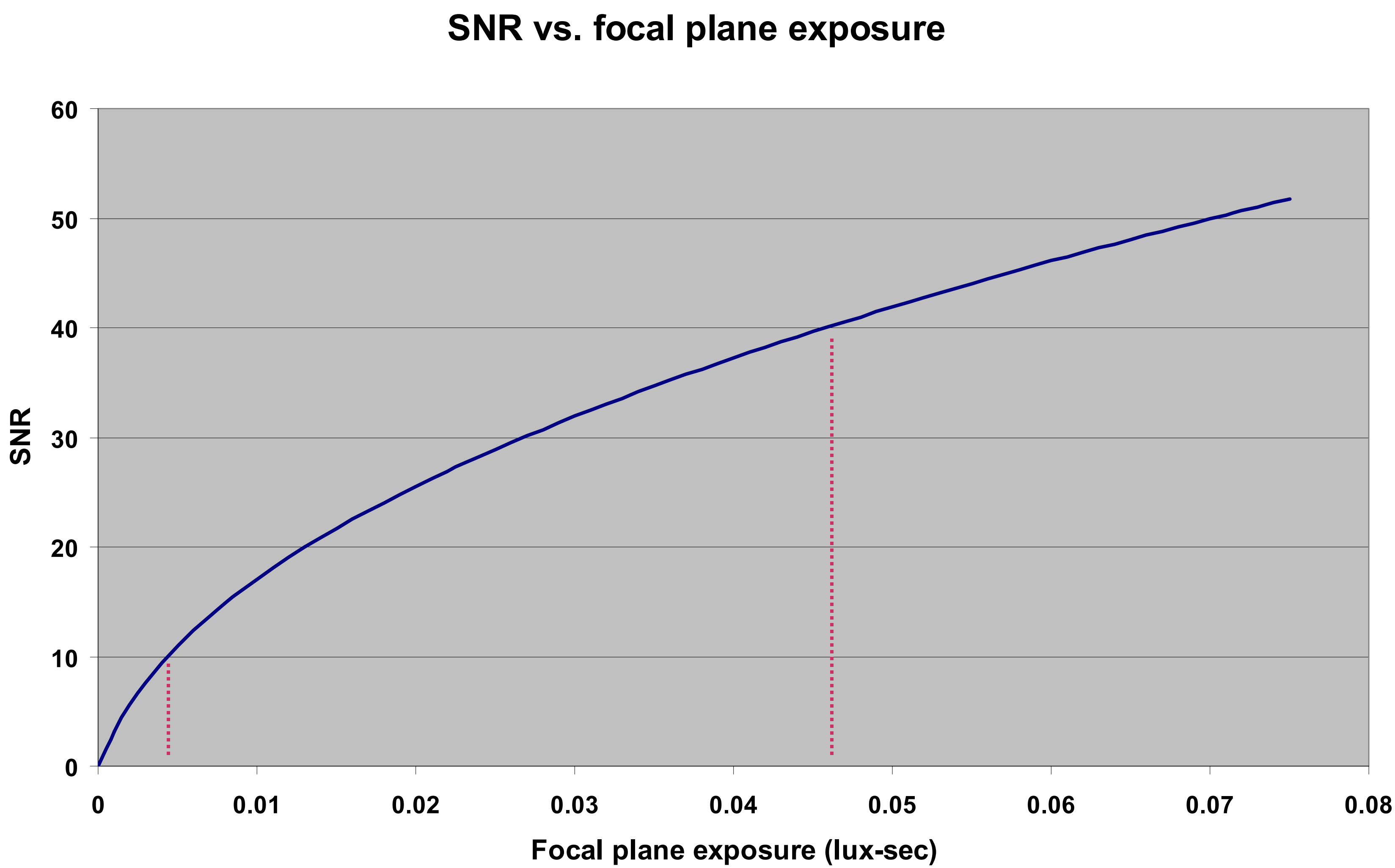
Other requirements

- Linear data (raw data or linearized)
- No lossy compression
- Proper white balance
- Integration period < 1/30 s (may need aperture control)
- Consider only central pixels when sensors include microlenses

SNR curve (monochrome CCD)

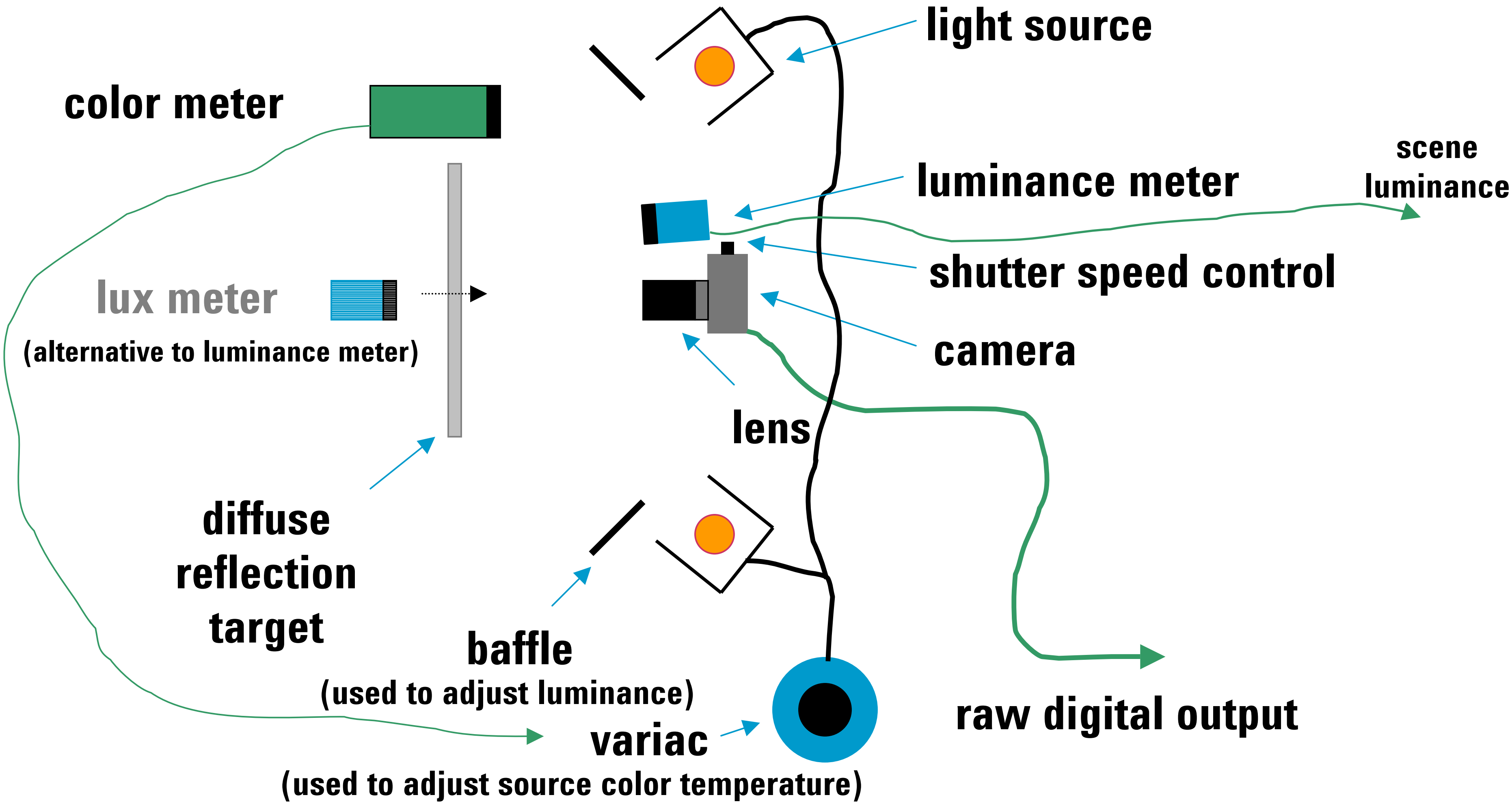


ISO speed from SNR curve



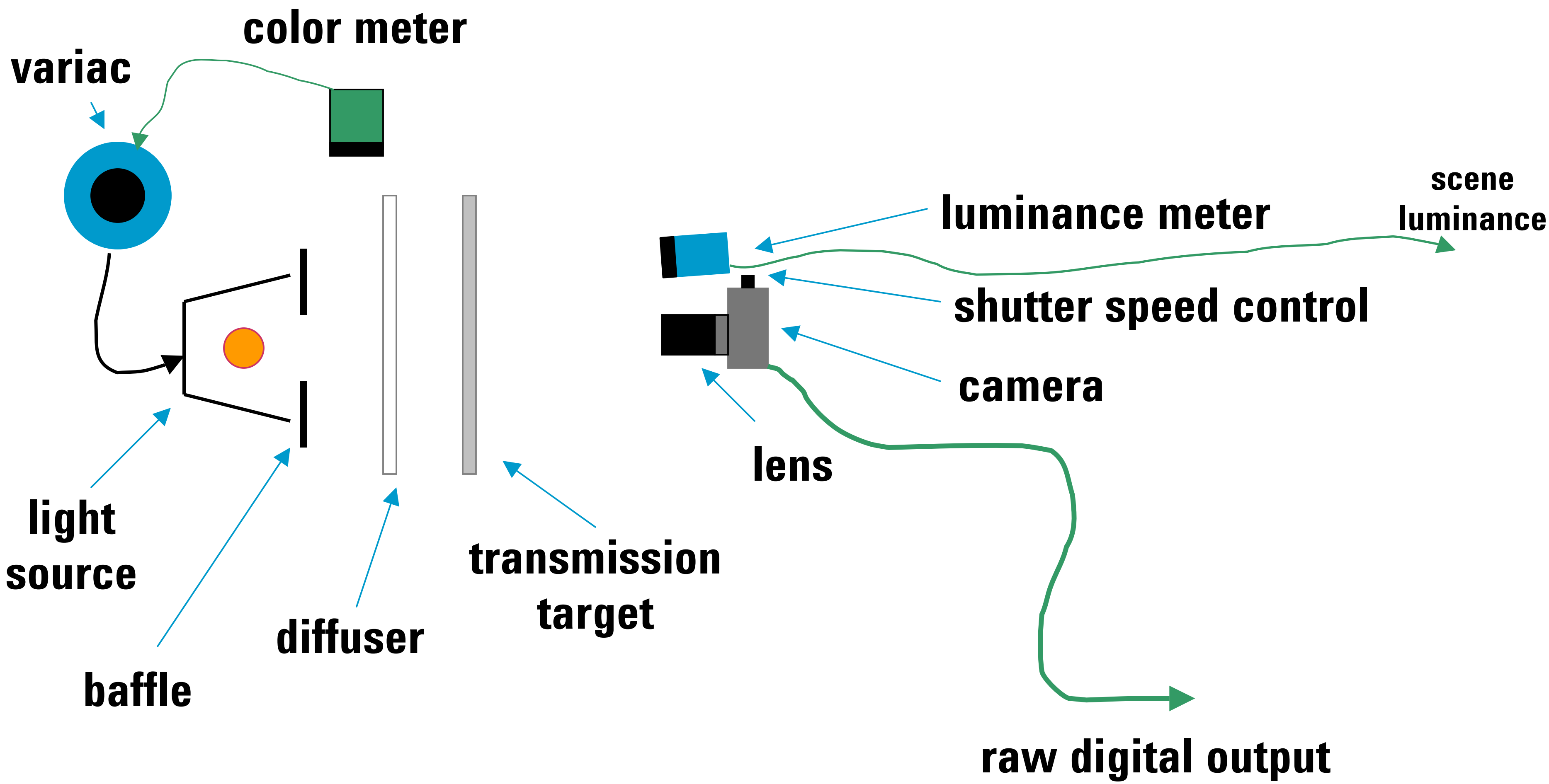
$S_{10} = 10/0.0044 = 2300$ $S_{40} = 10/0.046 = 218$

Measurement apparatus (indirect scene luminance: reflection)



Measure SNR versus (scene luminance · exposure time)

Measurement apparatus (indirect scene luminance: transmission)



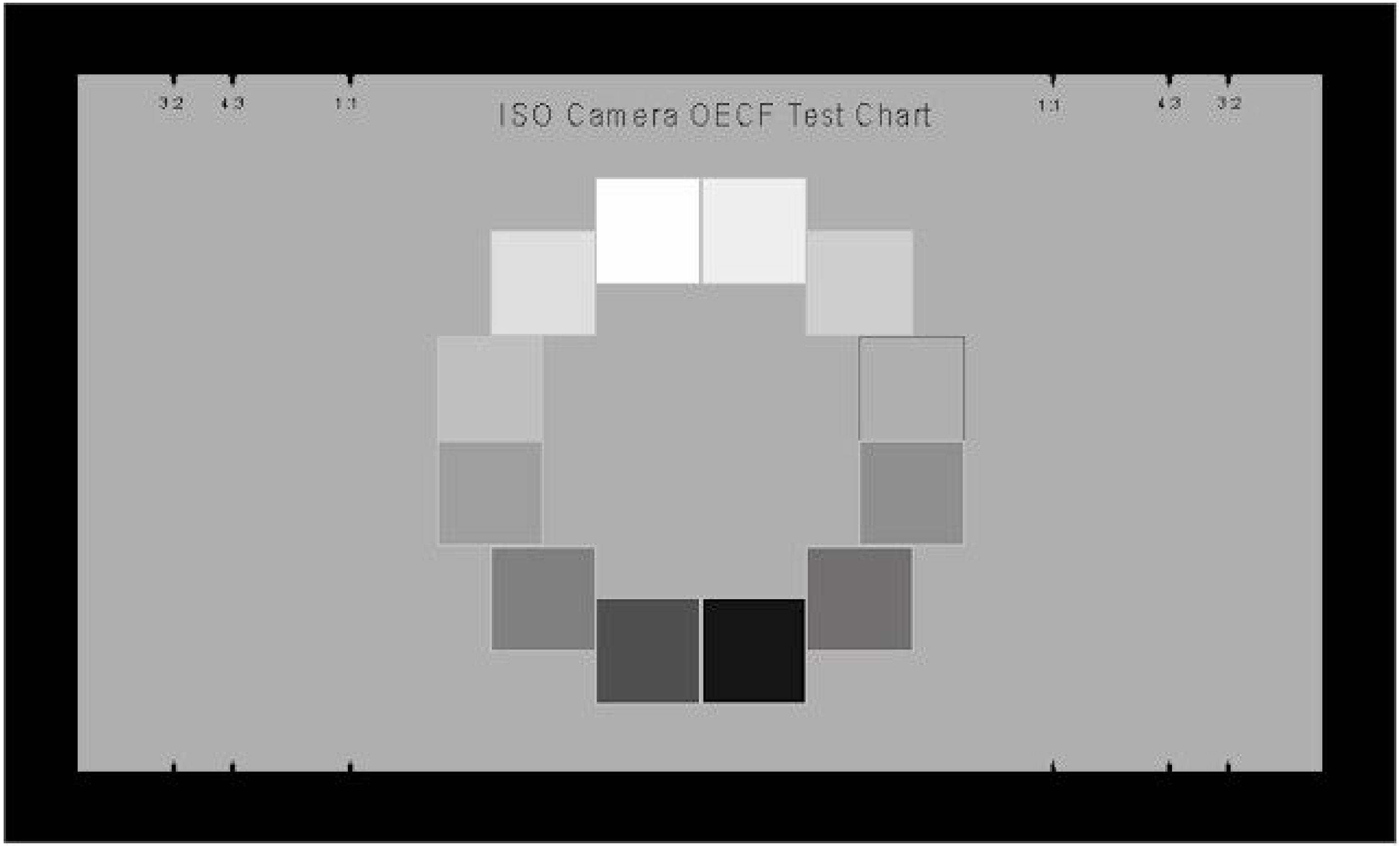
Equation relating focal plane exposure to target luminance

luminance **Integration time**

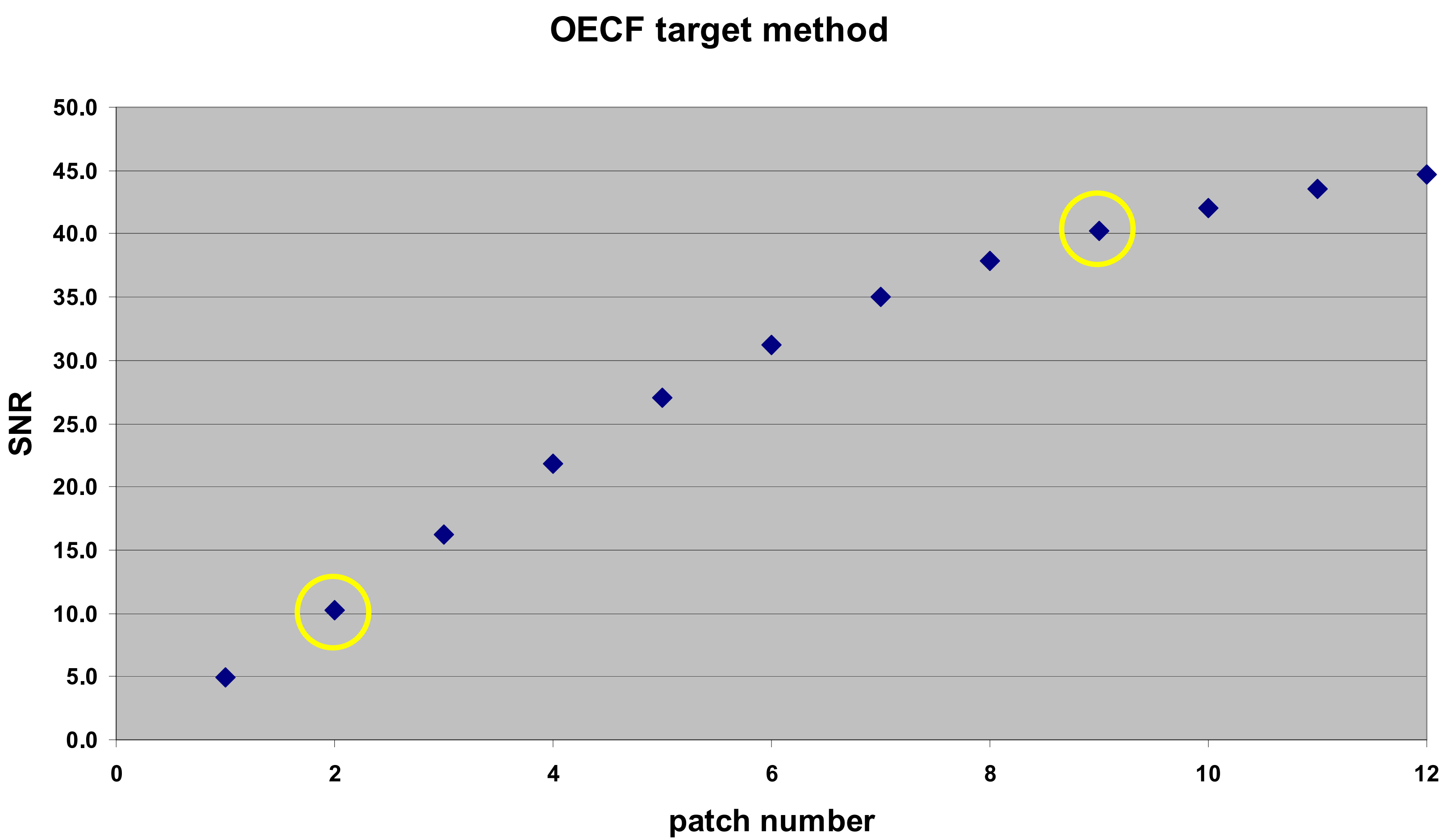
$$H_a = \frac{65\ L_a\ t}{100\ (f\#)^2 (1+|m|)^2}$$

Calculate speed as 10/Ha @ SNR = x (as before)

Need for OECF characterization: perform analysis on OECF target



SNR curve from OECF target

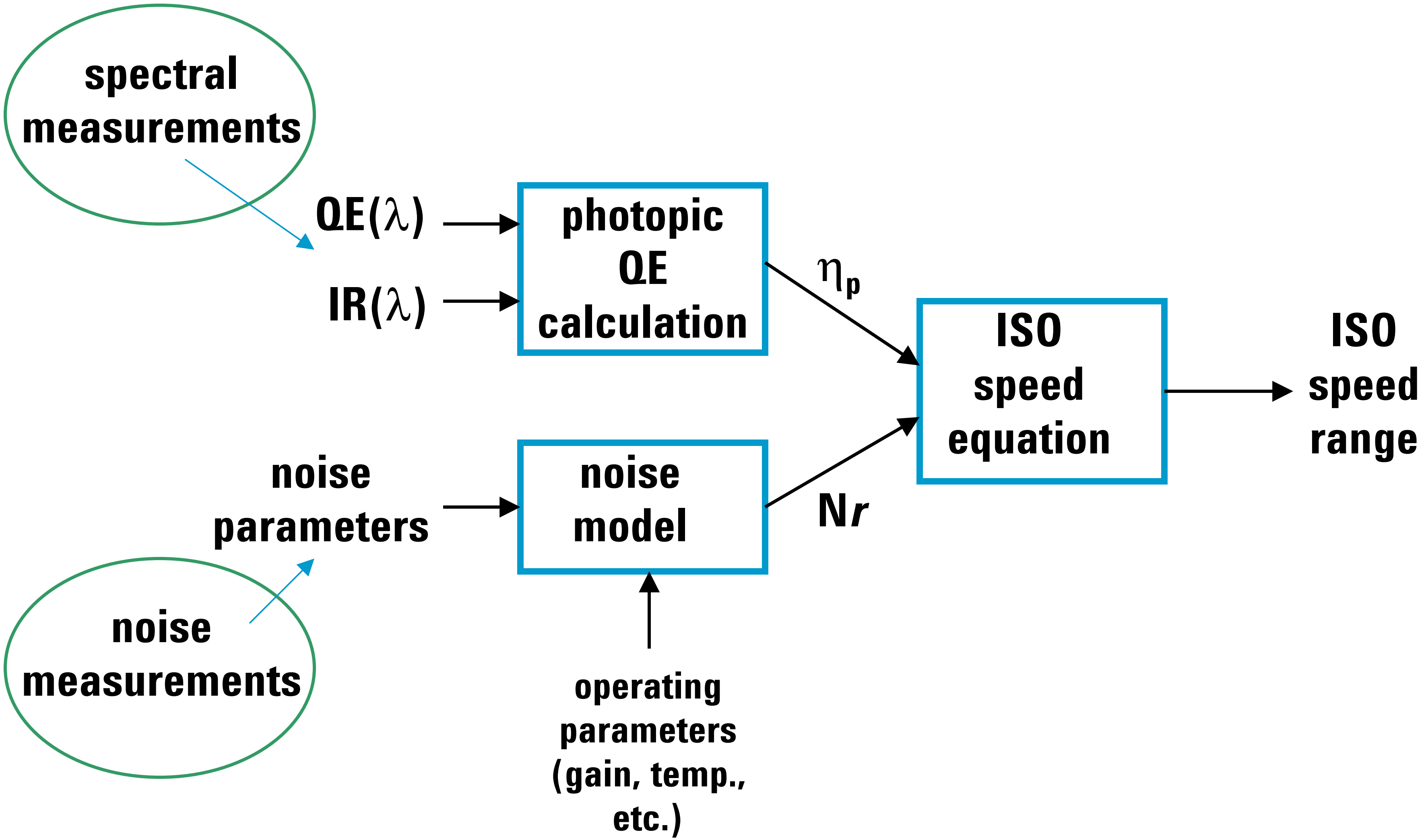


Sensor characterization: QE and noise

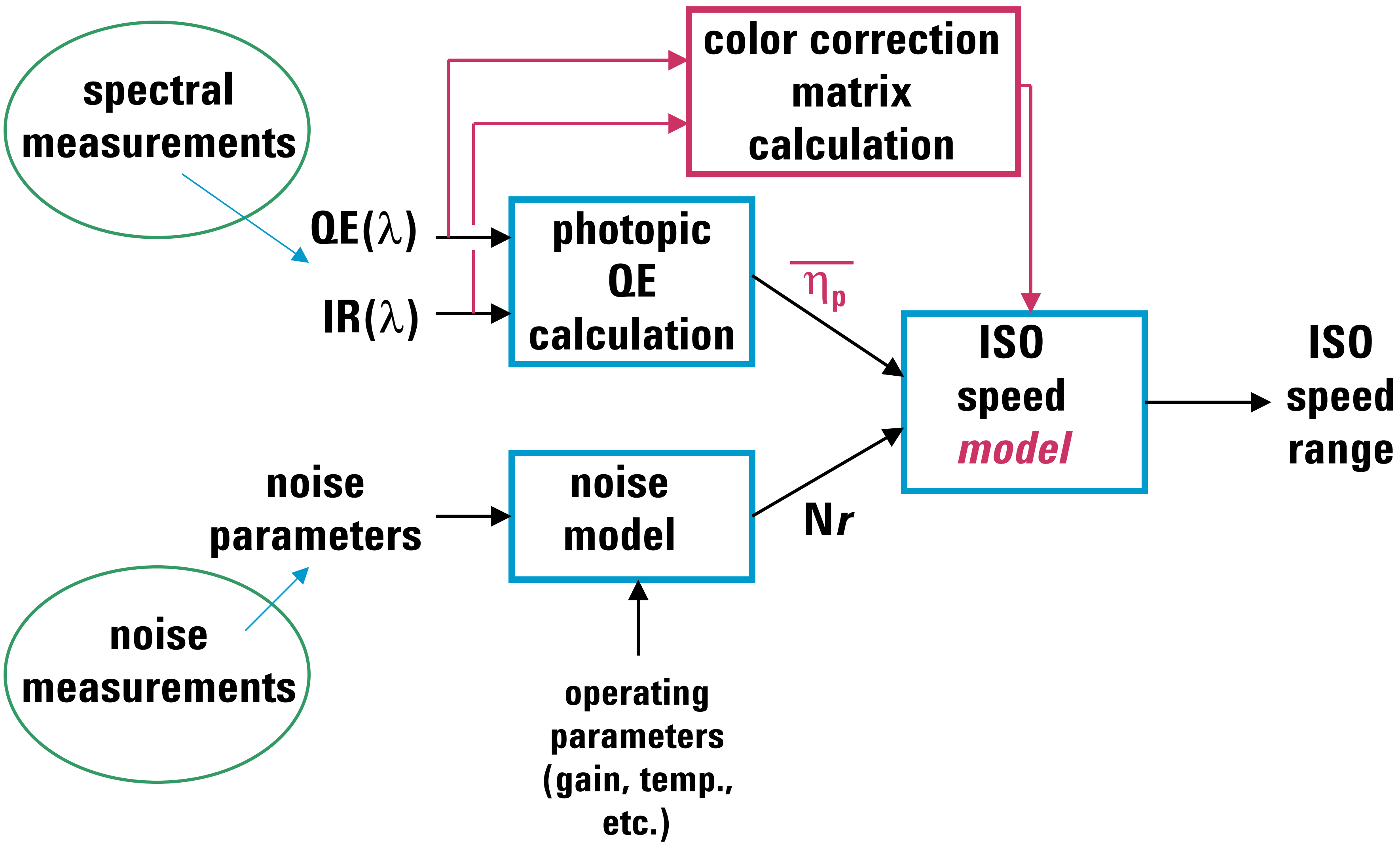
QE measurement

Noise characterization

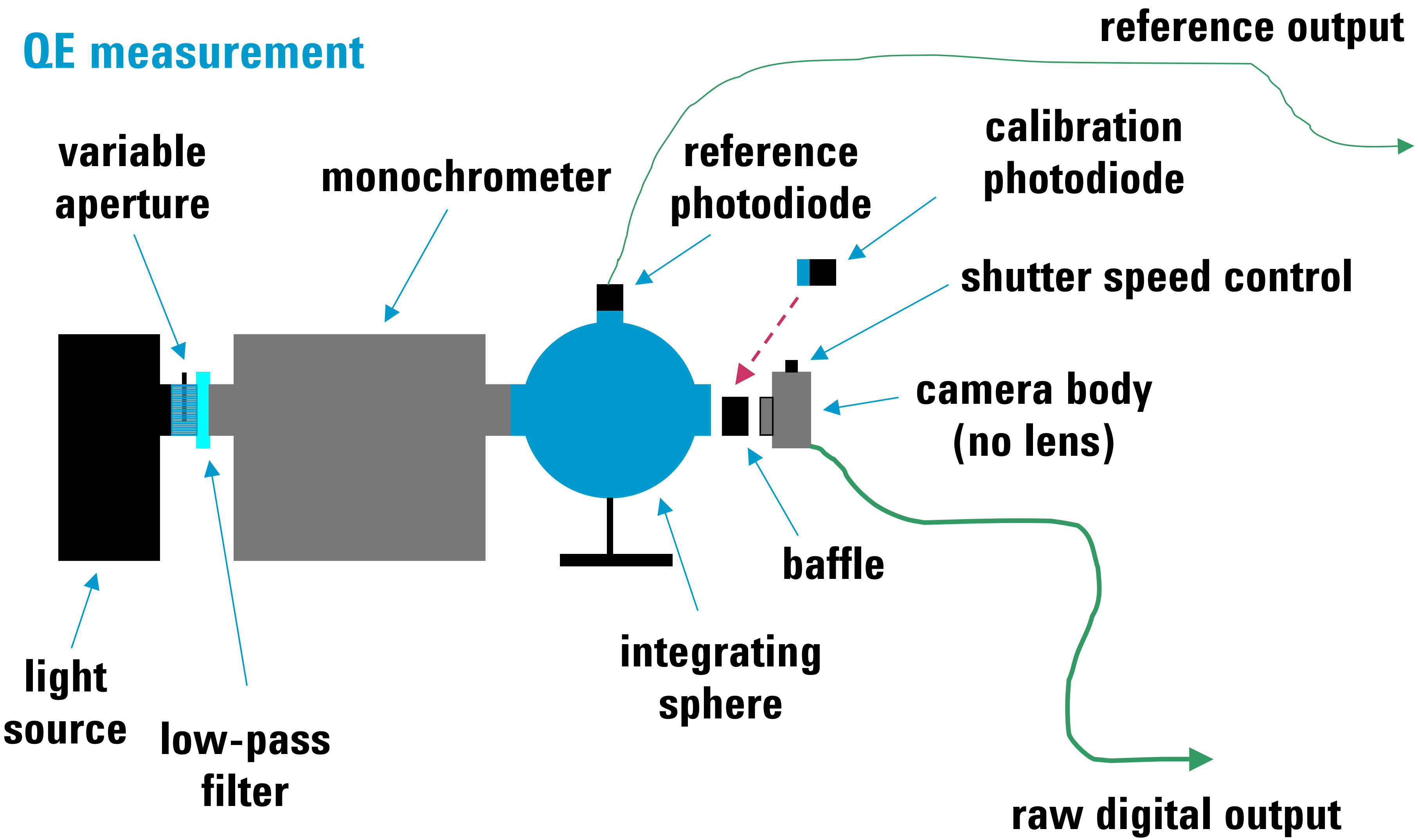
ISO speed calculation from QE and noise (monochrome case)



ISO speed calculation from QE and noise (color case)



QE measurement



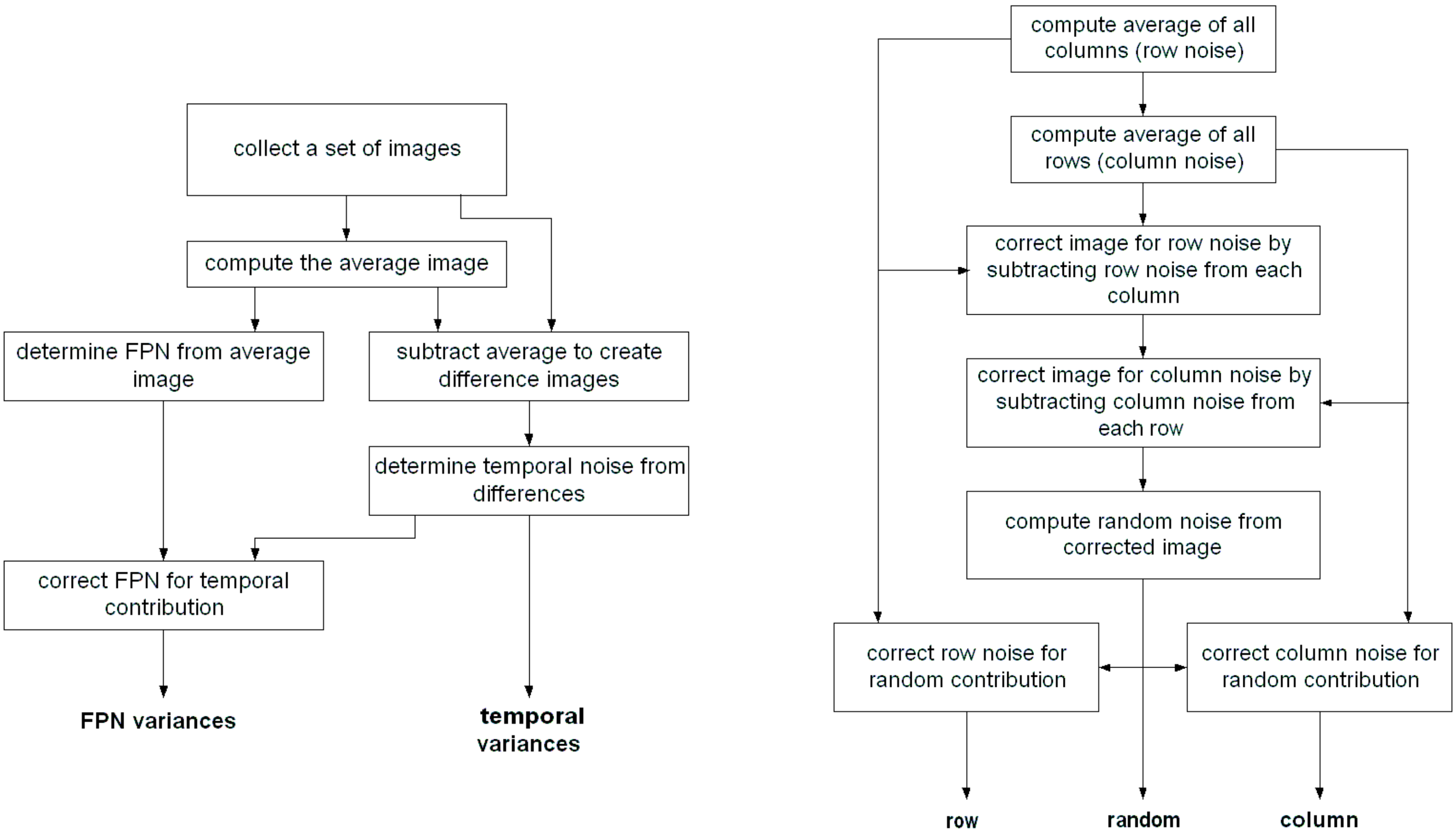
Measure QE versus λ

CC matrix determination

From QE curve

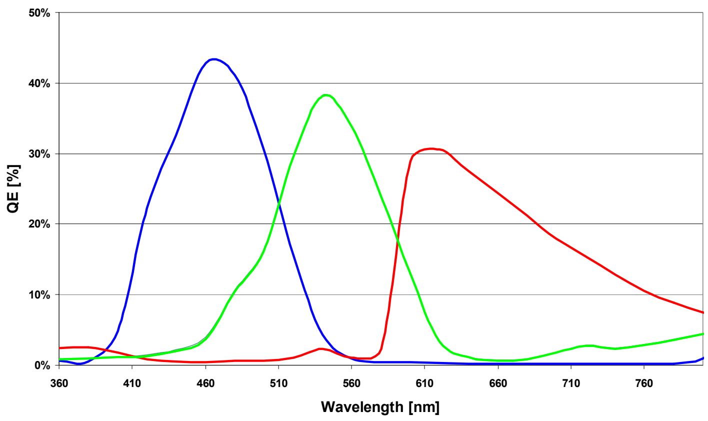
From Macbeth chart

Noise measurement



(see ISO 15739 standard)

Example: CCD for a typical consumer digital camera



Sony ICX202

Nr = 8 e

Nsat = 10 ke

PRNU = 1%

For 3 um pixel pitch:

Acceptable quality speed:

$S_A = 285$

Excellent quality speed:

~~$S_E = 23$~~

Saturation speed:

$S_{sat} = 72$

Speed range: ~ 50 - 400

Effect of signal processing on ISO speed

- Five (coupled) dimensions of image quality
- Effects of common image processing functions
  - Demosaic
  - Vignetting correction
  - Sharpening
  - Tone mapping
  - Color space conversion
  - Compression

Five (coupled) dimensions of image quality

<u>The five "R's" of image quality</u>

Resolution (pixel count, MTF)

snR (ISO noise speed)

dnR (ISO saturation speed)

Reproduction (exposure control, color and tone reproduction)

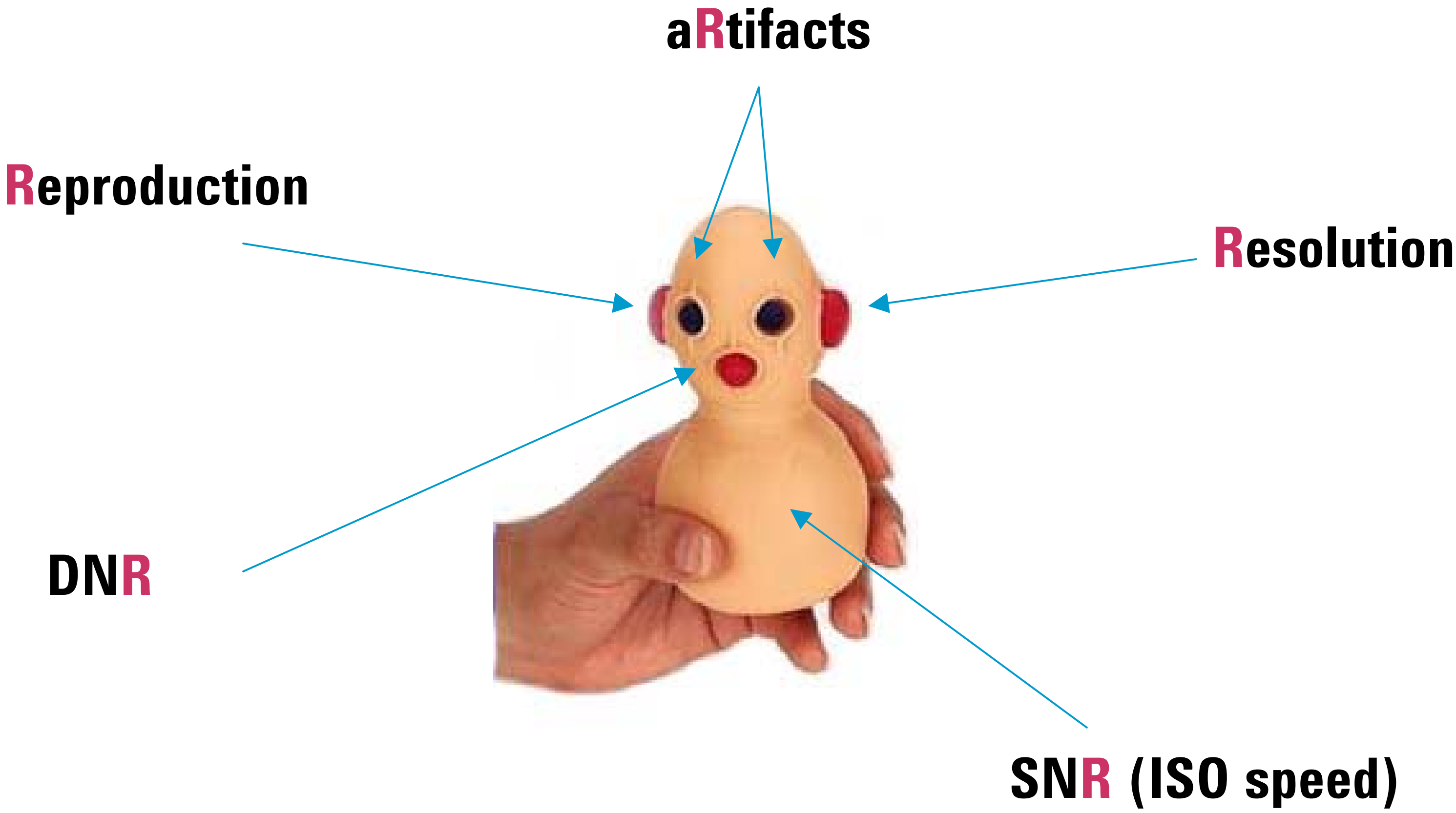
aRtifacts (demosaic and sampling artifacts, flare)

Coupling between image quality dimensions

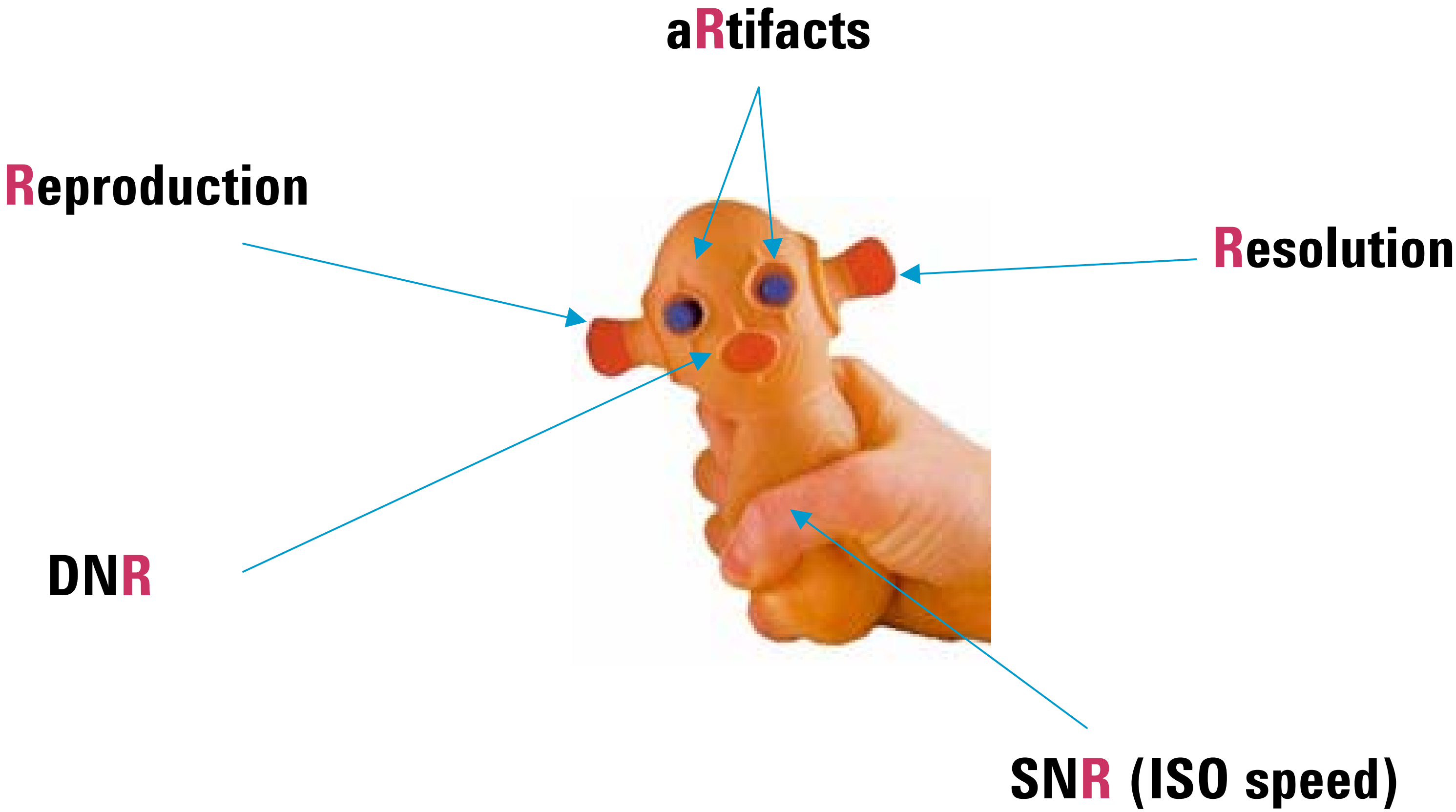
(high resolution, high-noise)

(low resolution, low-noise)

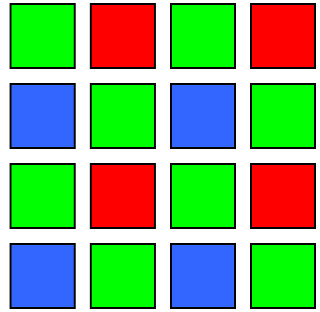
Coupling between ISO speed and other IQ dimensions



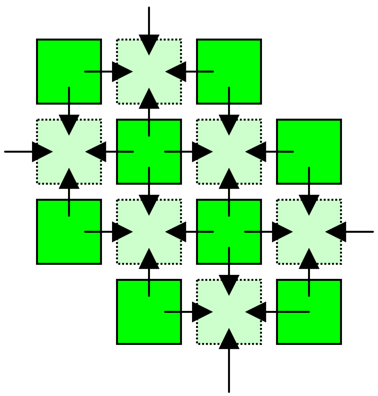
Coupling between ISO speed and other IQ dimensions

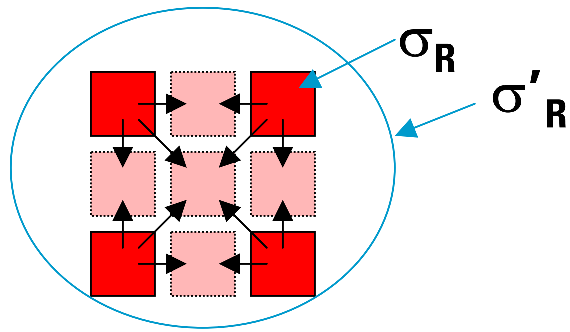


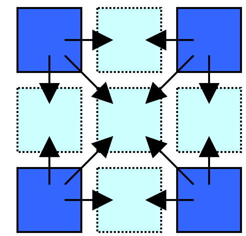
Demosaic



Bayer mosaic pattern





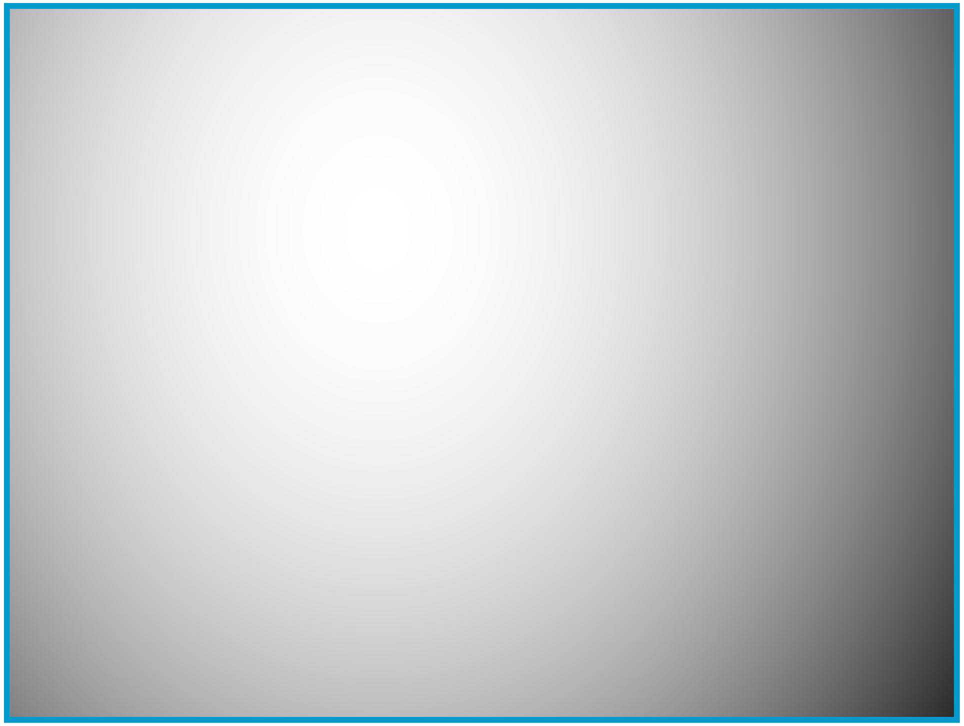


bilinear reconstruction

$$\sigma'_G = \sqrt{9/16}\ \sigma_G \qquad \sigma'_R = \sqrt{5/8}\ \sigma_R \qquad \sigma'_B = \sqrt{5/8}\ \sigma_B$$

Bilinear reconstruction reduces noise (at the expense of resolution)

Vignetting correction



Sharpening

~ 30% noise increase

Tone mapping

Color space conversion

RGB 888 →

YUV 422, YUV 411 ...

Chrominance down-sampling reduces color noise

Compression

original image

JPEG compressed

Summary

ISO speed is a valuable quality metric for the solid-state sensors used in (visible) photography.

Different combinations of measurement and analysis can be used to obtain the ISO speed.

Digital processing can improve one dimension of image quality at the expense of others. All dimensions of IQ must be considered together in sensor comparisons.

Total IQ: (ISO speed) $\times$ resolution {also true for DNR}

$\propto$ QE $\times$ (sensor area)

Size matters!

Acknowledgements

• Albert Theuwissen and the organizers of this forum

• Jack Holm

References

1. **ISO 12232: Photography – *Electronic still-picture cameras – Determination of ISO speed* (1998)**
2. **M. Kriss, "A model for equivalent ISO CCD camera speeds", SPIE Vol. 3302, pg. 56-67 (1998)**
3. **J. Holm, "The photographic sensitivity of electronic still cameras", J. Soc. Photogr. Sci. Tech. Japan, Vol. 59, No. 1, pg. 117-131 (1996).**
4. **R. Baer & J. Holm, "A model for calculating the potential ISO speeds of digital still cameras based upon CCD characteristics", IS&T PICS Conference, pg. 35-38 (1999).**
5. **R. Palum, "How many photons are there?", IS&T PICS Conference, pg. 203-206 (2002).**
6. **J. Holm, "Challenges and progress in digital photography standards", SPIE Vol. 5294 (2004).**

Appendices

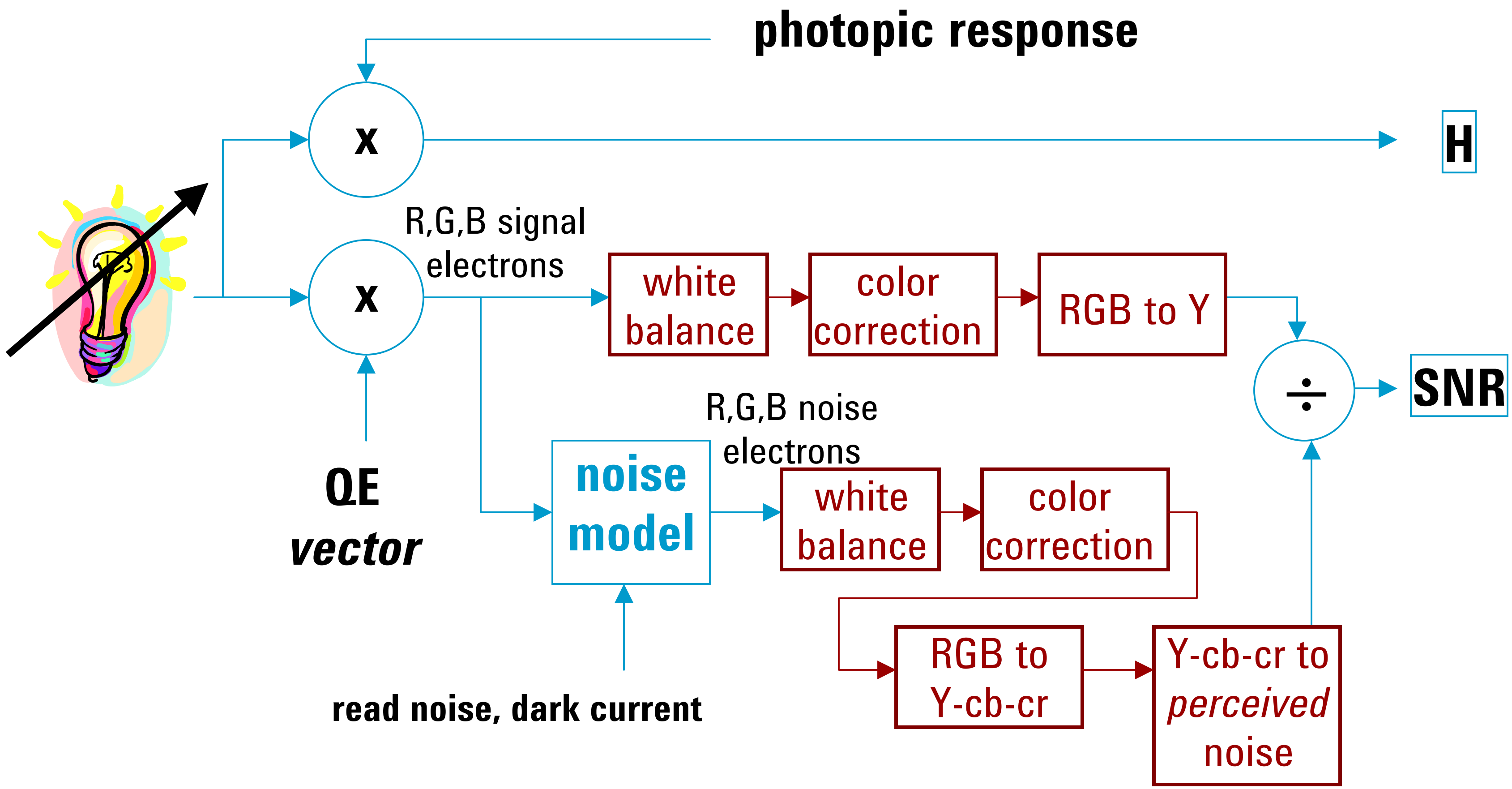
- **ISO speed model for color image sensors**

ISO speed model for color image sensors

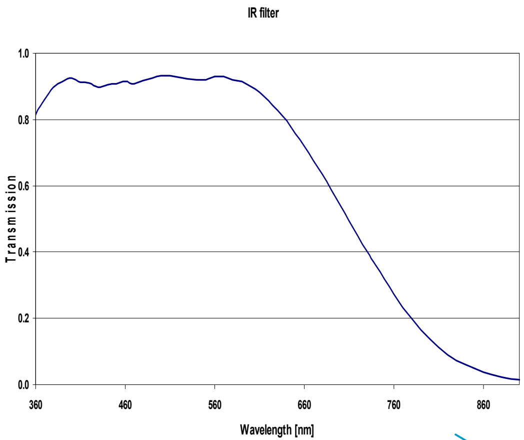
Assumptions:

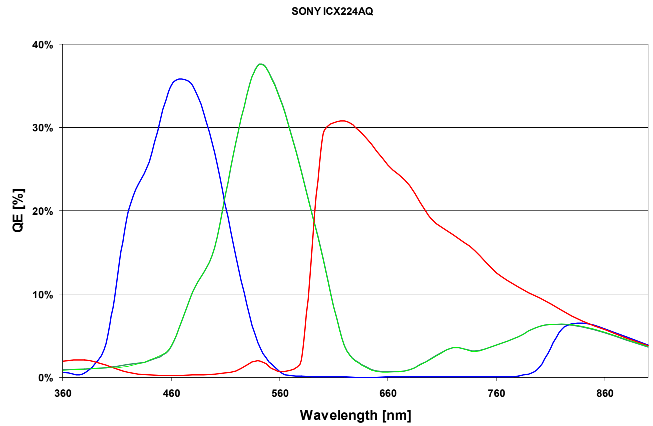
1. **Independent RGB color samples at every pixel location**
2. **No image processing other than white balance and color correction (e.g. no tone correction, sharpening, compression)**

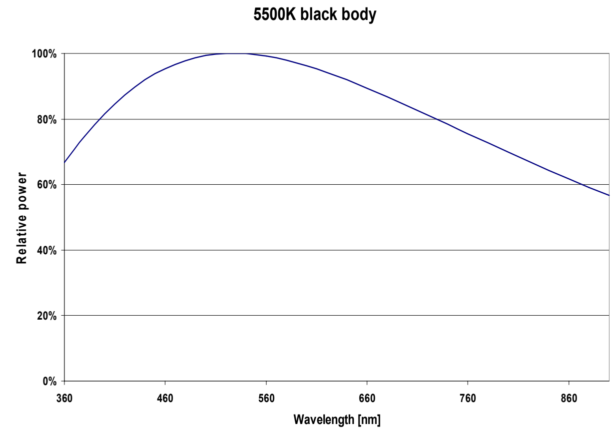
Extension of monochrome model to color



Spectral response => photopic QE vector







$$\overline{\mathrm{N}}_{\mathrm{e}} = \int_0^{\infty} \frac{\lambda \ \mathrm{IR}(\lambda)\ \mathrm{QE}(\lambda)\ \Phi_e(\lambda)}{h\ c} d\lambda$$

$$\overline{\eta}_{\mathrm{p}} = \overline{\mathrm{N}}_{\mathrm{e}} \,/\, \mathrm{H}$$ **[electrons/lux-second]**

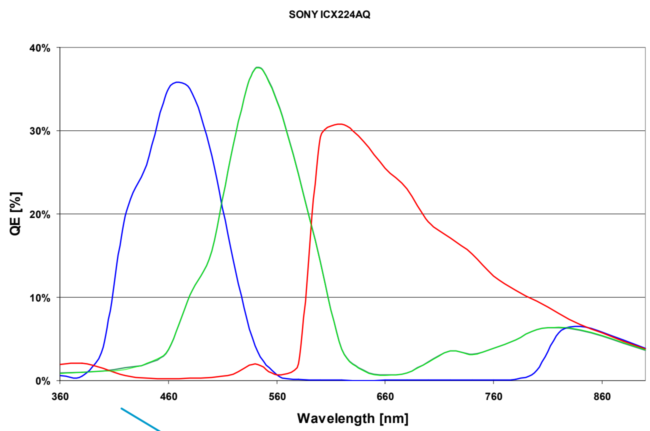
White balance

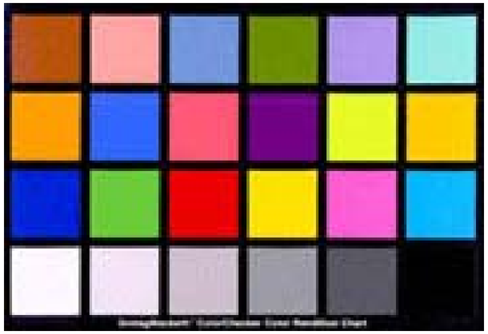
Calculate coefficients from photopic QE vector

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} \mathrm{G/R} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \mathrm{G/B} \end{vmatrix} \cdot \begin{vmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{vmatrix}$$

Apply to noise vector

Color correction and spectral response





Compute color correction matrix from spectral response, or Macbeth chart image

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix} = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \cdot \begin{vmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{vmatrix}$$

Color noise

luminance noise

chrominance noise

$$Y = 0.2125\ R + 0.7154\ G + 0.0721\ B$$

luminance equation

$$\sigma(D) = \sqrt{\sigma^2{}_{Y} + 0.279\ \sigma^2{}_{R-Y} + 0.088\ \sigma^2{}_{B-Y}}$$

total noise

Color versus monochrome sensitivity

Monochrome compared to color:

•Higher peak QE

•Broader spectral response

→ ISO speed ~ 10 times greater