ISO Speed

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Outline

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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 $\sim$ number of incident photons

- aperture (f#)
- n.d. filter (density)
- shutter (period)
- sensor
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

\[
\frac{(f\#)^2}{t} = \frac{EI \langle La \rangle}{15.4}
\]
What is the exposure index?

\[
EI = \frac{8}{\langle H_g \rangle} \approx \frac{10}{\langle H_a \rangle}
\]

Where: \( \langle H_g \rangle = \text{geometric mean focal plane exposure} \)

\( \langle H_a \rangle = \text{arithmetic mean focal plane exposure} \)

\[ \langle H_a \rangle = \langle Ef \rangle \cdot T_e \]
Relationship between scene illuminance and focal plane illuminance

\[ E_f = \frac{E_s R}{4 (f\#)^2 (1 + |m|)^2} \]

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

For \( R = 18\% \), \( f\# = 2.8 \), \( m = 0 \)

\[ \frac{E_f}{E_s} \approx 0.006 \]

(1.8 focal-plane lux with office lighting)
Photopic units

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 / m² ~ 10000 photons/sec/um²

(for a spectrally broad illuminant)

Example: office lighting, 10 um² pixel, 1/120 second exposure
→ 1500 photons/pixel
ISO speed and exposure index

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

- 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

- Calibrated light source
- Variable aperture
- IR filter
- Integrating sphere
- Camera body (no lens)
- Shutter speed control
- Processing
- Densitometry
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

Image sensors and digital processing compare with film and developing
ISO 12232 methodology

• Determine focal plane exposure (H) required to obtain a particular SNR value

• Specify ISO speed range:
  
  • $S_{\text{noise}10} = 10/H \ @ \ SNR = 10$ (first acceptable image)
  
  • $S_{\text{noise}40} = 10/H \ @ \ SNR = 40$ (first excellent image)

• Specify ISO speed at saturation
  
  • $S_{\text{sat}} = 78 / H \ @ \ saturation$
vary illumination, shutter speed to control focal plane exposure

measure SNR of output signal

sensor

test camera
The graph shows the relationship between SNR and H, where SNR is defined as $S = \frac{10}{H}$ and $S = \frac{78}{H}$, with H representing a certain parameter. The graph highlights specific values of H, denoted as $H_{10}$, $H_{40}$, and $H_{sat}$, and demonstrates the increase in SNR as H decreases.
ISO speed model for monochrome image sensors

• Determine $H$ required to achieve specified SNR

• ISO speed = $10/ H$

![Diagram of ISO speed model](image-url)
Photopic quantum efficiency (photopic electrons per lux)

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

\[ H = 680 \int_{0}^{\infty} \Phi_e(\lambda) d\lambda \]

\[ N_e = \int_{0}^{\infty} \frac{\lambda \cdot IR(\lambda) \cdot QE(\lambda) \cdot \Phi_e(\lambda)}{hc} d\lambda \]

\[ \eta_p = \frac{N_e}{H} \]
Typical photopic QE for a monochrome image sensor
(Panasonic MN3776; peak QE = 50%)
Noise model

$\text{dark current} \quad [\text{e-}/\text{sec}]$

integration time $[\text{sec}]$

sum of powers of uncorrelated noise sources

$\text{signal electrons} \quad \text{[e-]}$

= shot noise power

$\text{read noise} \quad \text{[e-]}$

$\text{PRNU}$

$\text{r.m.s. noise electrons} \quad \text{[e-]}$
Derivation of ISO speed equation

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

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

```plaintext
S_x = \frac{20 \eta_p A}{(S/N)_x^2} \left( 1 + \sqrt{1 + \frac{4 N r^2}{(S/N)_x^2}} \right)^{-1}
```
SNR curves

SNR vs. charge

Achievable SNR limited by PRNU

Read noise only affects “acceptable” ISO speed
ISO speed curves for a typical sensor

\( \eta_p = 3.7 \text{ ke}, \ N_r = 10 \text{ e}, \ N_{\text{sat}} = 20 \text{ ke} \)

\[ \text{Monochrome ISO speed} \]

\[ \text{ISO speed vs. pixel pitch [um]} \]

(*** neglecting PRNU ***)

\[ \text{acceptable} \quad \text{excellent} \quad \text{saturation} \]
Effect of IR and UV (wavelengths outside photopic response range)

Black body emission

Temperature [K]

Relative photon flux

- far IR
- near IR
- visible
- UV
ISO speed ratio for BB source, w & w/o IR filter

**Photopic response with IRF / photopic response w/o IRF**

![Graph showing photopic response with and without IR filter against color temperature](image-url)
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)

variable aperture

Calibrated light source (fixed color temperature)

IR (& UV) filter

integrating sphere

Calibrated lux meter

shutter speed control

camera body (no lens)

baffle

Measure SNR versus focal plane exposure
Illumination control

\[ f\# = \frac{d}{z} \]

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

Sony ICX252 angular response

Incidence Angle [deg.]
Response [rel.]

without baffle

F3.5 f2.8 f2.0 f1.4 f0.6
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)

SNR vs. focal plane exposure

Focal plane exposure (lux-sec)

SNR
ISO speed from SNR curve

\[ S_{10} = \frac{10}{0.0044} = 2300 \]

\[ S_{40} = \frac{10}{0.046} = 218 \]
Measurement apparatus (indirect scene luminance: reflection)

- lux meter
- color meter
- shutter speed control
- camera
- light source
- luminance meter
- variac
- diffuse reflection target
- baffle
- variac
- raw digital output

Measure SNR versus (scene luminance $\cdot$ exposure time)
Measurement apparatus (indirect scene luminance: transmission)
Equation relating focal plane exposure to target luminance

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

Calculate speed as \(10 / H_a\) @ 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)

spectral measurements

QE(λ)  →  photopicQE calculation

IR(λ)  →  ISO speed equation

noise parameters

noise model

ηₚ  →  ISO speed range

operating parameters (gain, temp., etc.)

noise measurements

ηᵣ
ISO speed calculation from QE and noise (color case)

- QE(λ)
- IR(λ)
- ηp
- Nr
- operating parameters (gain, temp., etc.)

spectral measurements
noise parameters
noise measurements

photopic QE calculation
ISO speed model

color correction matrix calculation

ISO speed range
Measure QE versus $\lambda$
CC matrix determination

From QE curve

From Macbeth chart
Noise measurement

- collect a set of images
- compute the average image
- determine FPN from average image
- subtract average to create difference images
- determine temporal noise from differences
- correct FPN for temporal contribution
- FPN variances
- temporal variances

compute average of all columns (row noise)
compute average of all rows (column noise)
correct image for row noise by subtracting row noise from each column
correct image for column noise by subtracting column noise from each row
correct random noise from corrected image
correct row noise for random contribution
correct column noise for random contribution
row, random, column

(see ISO 15739 standard)
Example: CCD for a typical consumer digital camera

Sony ICX202

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

The five “R’s” of image quality

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

- **Reproduction**
- **DNR**
- **SNR (ISO speed)**
- **Resolution**
- **ARTifacts**
Coupling between ISO speed and other IQ dimensions

- Reproduction
- DNR
- Artifacts
- Resolution
- SNR (ISO speed)
Demosaic

Bayer mosaic pattern

bilinear reconstruction

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

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: \( (\text{ISO speed}) \times \text{resolution} \) \{also true for DNR\}
\[\propto \text{QE} \times (\text{sensor area})\]

Size matters!
Acknowledgements

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• Jack Holm
References

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

- QE vector
- photopic response
- white balance
- color correction
- RGB to Y
- SNR
- RGB to Y-cb-cr
- Y-cb-cr to perceived noise
- read noise, dark current
- R,G,B signal electrons
- R,G,B noise electrons
- x
- H
- ÷
Spectral response => photopic QE vector

\[ \overline{N}_e = \int_0^\infty \frac{\lambda \cdot IR(\lambda) \cdot QE(\lambda) \cdot \Phi_e(\lambda)}{hc} \, d\lambda \]

\[ \overline{\eta}_p = \frac{\overline{N}_e}{H} \quad [\text{electrons/lux-second}] \]
White balance

Calculate coefficients from photopic QE vector

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} =
\begin{bmatrix}
G/R & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & G/B
\end{bmatrix}
\cdot
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

Apply to noise vector
Color correction and spectral response

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

\[
\begin{align*}
R & = \begin{pmatrix} a_{11} & a_{12} & a_{13} \end{pmatrix} \cdot R \\
G & = \begin{pmatrix} a_{21} & a_{22} & a_{23} \end{pmatrix} \cdot G \\
B & = \begin{pmatrix} a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot B
\end{align*}
\]
Color noise

\[ Y = 0.2125 \, R + 0.7154 \, G + 0.0721 \, B \]  
\[ \sigma(D) = \sqrt{\sigma^2_Y + 0.279 \, \sigma^2_{R-Y} + 0.088 \, \sigma^2_{B-Y}} \]  

luminance noise  
chrominance noise  
luminance equation  
total noise
Color versus monochrome sensitivity

Monochrome compared to color:

• Higher peak QE
• Broader spectral response

→ ISO speed ~ 10 times greater