Noise at the System Level

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Introduction
The systems view

Noise sources

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

Noise modifiers

- output
- color space
- compress
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

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output
Simplified noise / exposure control model

signal → + → X → + → X → + → ADC

- Dark current noise
- Read noise (N1)
- ADC input, quantization noise (N2)

+ Texp
+ Analog gain

Exposure controls
SNR variation

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

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

\[ DR = \frac{255}{k} \sqrt{G^2 \sigma_{N_1}^2 + \sigma_{N_2}^2} \]

The dynamic range decreases with gain.
Exposure

Short exposure (noise, quantization)

Long exposure (clipping)

Ideal exposure
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

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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

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

average of 40 columns
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

Pixel circuit

Optical black

Average

Column buffer
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

ADC/PGA gain (four blocks)

Column gain

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

Data in $\times$ Data out

Inverse flat-field image

Data in $\times$ Data out

$1/(\text{column gain})$

Data in $\rightarrow$ Data out

AWB

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 $\rightarrow$ spatial correlation)
Defect correction

Data in -> Row buffers -> interpolator -> Data out

bypass / interpolate

address

Defect location table

Static defect correction

Data in -> Row buffers -> exception detector -> interpolator -> Data out

Dynamic 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

![Graph showing count vs. dark current for white defects](image1)

![Graph showing count vs. dark current for black defects](image2)
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)

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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

0% flare

-10% 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

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Output
Vignetting and color shading

Sources of shading
• Lens vignetting
• IR filter CRA dependence
• Pixel angular response / asymmetry

Lens vignetting: color planes share a common center

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

shading correction parameters (from camera characterization)

Uncorrected image

Corrected image

Approximate inverse flat-field

Shading model
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

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Pixel reconstruction

• Undersampling results in artifacts
• Demosaic uses interpolation $\rightarrow$ results in spatial correlation of noise.
Color artifacts caused by undersampling
Noise correlation

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

- red stats
- green stats
- blue stats

Scene rule base (e.g. gray world)
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

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Color Processing Decreases the SNR

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

Consider a two-color world:

\[
\begin{align*}
R & = \frac{C_1 - \alpha C_2}{1 - \alpha^2} \\
B & = \frac{C_2 - \alpha C_1}{1 - \alpha^2} \\
(S/N)^r & = \frac{S_1 - \alpha S_2}{\sqrt{N_1^2 + \alpha^2 N_2^2}}
\end{align*}
\]

\[
\begin{align*}
C_1 & = R + \alpha B \\
C_2 & = \alpha R + B
\end{align*}
\]

\[\alpha = \text{pixel crosstalk factor}\]

\[
\begin{align*}
x & = \frac{1}{2} (C_1 + C_2) \\
(S/N)^x & = \frac{S_1 + S_2}{\sqrt{N_1^2 + N_2^2}}
\end{align*}
\]

- 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

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output
Sharpening filters amplify 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

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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

- Exposure control
- Scene intelligence
  - Pixel array
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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

The tone correction function must be reversed to make meaningful noise measurements.
Color space conversion

2 pixels

\[ R G B R G B \]

conversion

2 pixels

\[ Y u Y v Y u Y u \]
Chrominance filtering

luminance

chrominance → LPF

Chrominance filtering involves separating the luminance and chrominance components of an image. The chrominance component is then filtered by a Low Pass Filter (LPF) to reduce high-frequency noise.
Effects of color space conversion

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

- Pixel array
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Compression

- Noise reduced
- Severe block artifacts

JPEG compression
27x

- Noise significantly reduced
- Loss of texture

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 & Fairchild 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

Extended source

OECF test chart

Diffusing screen

System under test

Required to un-map gamma & tone correction functions
ISO 9358:1994 veiling glare measurement

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

  ![Integral method diagram](image)

  - Extended source
  - Diffusing screen
  - Black area
  - System under test

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

  ![Analytical method diagram](image)

  - Source
  - Collimator
  - System under test
ISO 15739 noise measurement

- Extended source
- Diffusing screen
- OECF test chart
- System under test
- High frequency measurement patches
- OECF measurement patches
- Noise measurement patches
ISO 15739 noise component analysis (1)

>= 8 images

<average> + -

FPN image (+ σ_temporal)

Temporal noise images
ISO 15739 noise component analysis (2)

- <average columns>
- FPN or temporal noise image
- <average rows>
- Spatially-random noise image

Row noise vector
(+ $\sigma_{\text{random}}$)

Column noise vector
(+ $\sigma_{\text{random}}$)
Utility of noise decomposition

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<th></th>
<th>Random</th>
<th>Patterned</th>
<th>Constant</th>
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<tr>
<td>Constant</td>
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</tbody>
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**Spatial**

- **Random**: kT/C, Shot noise
- **Patterned**: Row reference kT/C, Power supply, Flicker, PRNU shading, Row reference dark current
- **Constant**: ADC offset, Column offset, Flare, Dark current

+= additive  × = multiplicative
Quantization limits

Noise below $\frac{1}{2}$ LSB can't be measured
Conclusions
Image processing modifies noise ...

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Cancels / reduces noise

Generally increases noise

Increases 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