Focus on Resolution: Degradations in Image Acquisition

Ken Turkowski
Google, Inc.

22 August 2007
Overview of Talk

- Lens Aberrations
- Diffraction Effects of Apertures
- Image Acquisition Devices
- Resolvability and Sampling Density
- The 70% Rule
- FOV, Focal Length, Pixel Density
The Journey begins here

🌟 93 million miles away
The Journey

- Light interacts with matter
- Light is transported through space and the atmosphere
- Light enters the aperture of the lens
The dual nature of light

- Wave
  - Wavefront propagation analysis
- Particle
  - Geometric optics, ray tracing analysis

Illustrations from Smith, “Modern Optical Engineering”
Lens System

- Compound Lenses
- Point-Spread Function varies
- Aberrations:
  - Spherical aberration, coma, astigmatism, chromatic aberrations
  - Distortion (barrel & pincushion) affects geometry
Spherical Aberration

- Variation of focus with aperture
  - either focus at the center, or the edge, but not both

Figure 3.2  A simple converging lens with undercorrected spherical aberration. The rays farther from the axis are brought to a focus nearer the lens.  
(from Modern Optical Engineering, by Smith 1990)
Coma

- Variation of magnification with aperture
- A point smears into a comet-shaped flare

Figure 3.4 In the presence of coma, the rays through the outer portions of the lens focus at a different height than the rays through the center of the lens. (from Modern Optical Engineering, by Smith, 1990)

Figure 3.5 The coma patch. The image of a point source is spread out into a comet-shaped flare. (from Modern Optical Engineering, by Smith, 1990)
Astigmatism and Field Curvature

- **Non-planar focal surface**

Figure 3.7 Astigmatism.

Figure 3.8 The primary astigmatism of a simple lens. The tangential image is three times as far from the Petzval surface as the sagittal image.

(from Modern Optical Engineering, by Smith, 1990)
Chromatic aberrations

- Variation of aberrations with wavelength
- Magnification aberration is easy to correct

Figure 3.10  The uncorrected longitudinal chromatic aberration of a simple lens is due to the blue rays undergoing a greater refraction than the red rays.
(from Modern Optical Engineering, by Smith, 1990)

Figure 3.11  Lateral color, or chromatic difference of magnification, results in different-sized images for different wavelengths.
(from Modern Optical Engineering, by Smith, 1990)
Geometric distortion

- East to correct

*Figure 3.9* Distortion. (a) Positive, or pincushion, distortion. (b) Negative, or barrel, distortion. The sides of the image are curved because the amount of distortion varies as the cube of the distance from the axis. Thus, in the case of a square, the corners are distorted $2\sqrt{2}$ as much as the center of the sides.

(from *Modern Optical Engineering*, by Smith, 1990)
Wave Optics

- Aperture diffraction
- Worse with smaller aperture
- Airy Disk

\[ I = I_0 \left[ \frac{2J_1(m)}{m} \right]^2 \]

from Smith, "Modern Optical Engineering"
Diffraction-Limited Resolution

Lord Rayleigh’s criterion

\[ Z = \frac{0.61\lambda}{NA} = 1.22\lambda \left(\frac{f}{\#}\right) \]

Figure 6.17  The dashed lines represent the diffraction patterns of two point images at various separations. The solid line indicates the combined diffraction pattern. Case (b) is the Sparrow criterion for resolution. Case (c) is the Rayleigh criterion.
Implications for Cameras

- Visible light ~400-700 nm
- For red light @ f/11
  \[ Z = 1.22 \left( \frac{700 \times 10^{-9}}{11} \right) \approx 9.4 \mu m \]
- For blue light @ f/11
  \[ Z = 1.22 \left( \frac{400 \times 10^{-9}}{11} \right) \approx 5.4 \mu m \]
- Pixel sizes: 6 \mu m (typical DSLR)
  2.2-3.2 \mu m (cells, point&shoot),
  1.75 \mu m (Micron CMOS)
- The optics can’t deliver RGB pixels at f/11!
- The optics can barely deliver Bayer pixels to DSLR at f/11 (with 1.4X pixel size factor)
Image Acquisition Devices

- Film
- CCD sensors
- CMOS sensors
- Splitters / Layers / Bayer
- 2D array / 1D array
- Anatomy of a CCD
Film

- 3 Layers
- Color-sensitive grain in each layer
- Grain size and density determine resolution
Common Digital CCD / CMOS Sensor

- Bayer Sampling Pattern
  - No RGB pixels
  - Only R, G, and B pixels
- Convert to RGB by interpolation
- If 1000 pix/mm, then
  707 G pix/mm and 500 R and B pix/mm, i.e. R and B are sampled every 2 pixels, G is sampled every 1.4 pixels
- 8 Mpix CCD has 4 Mpix G, 2 Mpix R&B, 2 Mpix ≤ RGB ≤ 4 Mpix
3 CCD Sensors

Source: Foveon
Layered CMOS Sensors

- R, G & B pixels at each location!

**Foveon X3 Capture**

- A Foveon X3 image sensor features three separate layers of photodetectors embedded in silicon.
- Since silicon absorbs different wavelengths of light at different depths, each layer captures a different color.
- As a result, only Foveon X3 image sensors capture red, green and blue light at every pixel location.

**Mosaic Capture**

- In conventional systems, color filters are applied to a single layer of photodetectors in a tilted mosaic pattern.
- The filters let only one wavelength of light—red, green or blue—pass through to any given pixel, allowing it to record only one color.
- As a result, typical mosaic sensors capture 50% of the green and only 25% of the red and blue light.
Panoramic (cylindrical-scan) cameras

- Rotate a linear (1D, not 2D) CCD imaging array
- Rotate too fast ==> aliasing
- Rotate too slow => blurring because CCD cell overlaps
Anatomy of an interline CCD (plan view)

- Active area is a small part of the total cell
- E.g. 8x4 μm in 9x9 μm cell
- Warning: 2X faster aliasing potential!
- Warning: Tossing half the light!

![Diagram showing Anatomy of an interline CCD](image)

- Top View
- Direction of Charge Transfer
- Photodiode
- Transfer Gate
- V1
- V2
- True Two Phase Burried Channel VCCD Lightshield over VCCD not shown

From Kodak KAI-1102 spec
Anatomy of a CCD (cross section)

- Pixel takes cover under light shield for readout

Cross Section Through Photodiode and VCCD Phase 2 at Transfer Gate

From Kodak KAI-11002 spec
Recovering the light

- Lenslets redirect light into the photodiode well (horizontally)
Recover Light

★ 3X more light with lenslets!

Quantum Efficiency

Color with Microlens Quantum Efficiency

Figure 10: Color with Microlens Quantum Efficiency Using AR Glass

Color without Microlens Quantum Efficiency

Figure 11: Color without Microlens Quantum Efficiency Using AR Glass
Color Pollution

* Rays from adjacent color cells enter obliquely

Diagram:
- Lenslet
- Red Color Filter
- Photodiode
Resolution

- The difference between resolution and pixel sampling density
- Determining resolution
- Intimate relationship between resolution and focal length
What is the resolution?

- Both images have the same number of pixels (360x270).
Determining Resolution with the Fourier Transform

- Bright ==> high energy
- Horizontal & vertical frequency (detail) increases to the right and up
The Empirical 70% Rule

- Negligible loss of quality when shrunk by 70%
- Half the pixels
Determining Resolution by Resizing

» Shrink, expand, subtract, amplify:
  » Reduce size
  » Increase back to original size
  » Apply Image > Difference
  » Enhance contrast
Resolution in Photoshop

- 50% reduction
  20X gain

- 60% reduction
  20X gain

- 70% reduction
  20X gain

- 80% reduction
  20X gain

- 90% reduction
  20X gain
Units of Panorama Resolution

- How do you compare the resolution of a cylindrical, cubic, and spherical panorama?
- Pixels?
- Pixels / inch?
- Pixels / degree!
Panorama resolution (pix/°)

- Cylindrical or spherical circumference / 360
- Round 180° fisheye \((\text{diameter} - 1) / 180\)
- Cubic \((\text{faceWidth} - 1) \times \pi / 360\)
- E.g. 2496 pixel cylindrical circumference = 1249 pixel 180° fisheye diameter
  795 pixel cube face = 6.9 pixels / degree
Definitions: panoramic resolution and focal length

- Panoramic resolution: the angular pixel density as determined by the focal length.
- The focal length: the distance to the imaging surface at the center of projection.
Focal Length & Resolution

- Intimate relationship between the focal length and panoramic resolution in pixels per degree.
- Lens focal length in mm (per radian)
- Sensor: pixels / mm

\[(\text{pix/mm}) \times (\text{mm/rad}) \times (\text{rad/deg}) = \text{pix/deg}\]

sensor    focal length    unit conversion
Why is focal length mm/radian?

- From elementary trigonometry:
  \[
  \tan(\phi/2) = \frac{h}{2f}
  \]
- With small \( \phi \), expressed in radians,
  \[
  \frac{\phi}{2} \approx \frac{h}{2f}
  \]
- Or
  \[
  f \approx \frac{h}{\phi}
  \]
  \( \text{(mm/rad)} \)
Conclusion

- Know where your pixels have been
- Pixel sampling density ≠ resolution
- Don’t use more pixels than you need
- Apply the 70% rule
- Focal length = pixel sampling density (resolution)