Resolution Limits in Digital Photography

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IMPA

Motivation

• Longstanding Interest in Photography
  – Photo Gallery
• Current Work on Panoramic Images
  – Visorama
  – N-Pan Project
• Recent Collaboration
  – Diego Nehab
  – Pedro Sander
Breaking the Record

- **Corcovado 67 GP**

- **Sugar Loaf (153 GP)**

  *work in progress*
Concepts

- Resolution
  - Representation
- Frequency
  - Contents
- Scale
  - Waves

MTF

- Modulation Transfer Function
Understanding MFT

- Modulation
  - Contrast Attenuation
- Spatial Frequencies
  - Patterns

Measuring a System

- MTF Curve
Continuous Image

- Frequency Content...

\[ \hat{f}(\xi) = \int_{-\infty}^{\infty} f(x) e^{-2\pi i x \xi} dx, \]

\[ \text{Fourier Theory} \]

Discrete Image

- **Shannon-Whittaker Theorem**

\[ f(t) = \sum_{k=-\infty}^{+\infty} 2\Omega \Delta t \ f(k\Delta t) \ \text{sinc}(2\pi \Omega (t - k\Delta t)) \]
**Ideal Optical Image**

Real Image \[\rightarrow\] **Perfect Lens** \[\rightarrow\] Projected Image

- **Diffraction Limit!!!**
  - Abbe Theorem

\[
\frac{d}{\lambda} = \frac{2n \sin \alpha}{\text{numerical aperture}}
\]

- **Resolution**
- **Wavelength**
- **Lens Index of Refraction**
- **Lens Aperture Angle**

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**Diffraction (Circular Aperture)**

- **Large Aperture**

- **Small Aperture**

**Monday, August 23, 2010**
Resolvable Detail

- Airy Disk (Rayleigh Criterium)

![Image of Airy Disk and Diffraction Pattern](cambridgeincolor.com)

Diffraction Limited System

- Resolution matches Theoretical Limit

- smallest feature ~ size of Airy disk

![Image of Diffraction Patterns](agunterphotography.com)

More on that later...
Gigapixel Image

- OBS: Only a single image ...

The Gigapixl Project

- Big Camera ;-)  
  - Large Format - Film (45 kg)

- Portrait of America
Gigapixel Mosaic

- OBS: Many individual images ….

Gigapan Project

- Gigapan Imager
  - Robotic Head + Digital Camera

- gigapan.org
  - Worldwide Community

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Our Problem

The Real Scenario

- Complete Pipeline

(from Joshi-Cohen 2010, edited)
Back to MTF

- System MTF
  - Lens + Sensor + etc.. + (Human Eye)

Atmospheric Limitations

- Turbulence  (Heat)

- Aerosols (Distance)
Sensor Formats

- FX - Full Frame
- DX - Digital Camera

Lens MTF Parameters

- Sagital / Meridional Patterns
- Distance from Image Center
Lens Performance

- the good and the bad ;-) 

MTF-50
- sharpness perception

Lens MTF Chart

- Manufacturer's Data
Aperture x Pixel Size

• Optimal Aperture

The Sweet Spot

• Why ?
  - Large Apertures (light aberrations)
  - Small Apertures (diffraction effect)
Sensor Resolution

- **Bayer Pattern**
- **Demosaicing**
- **Moire Artifacts**

Lens Vignetting

- **Radial Falloff**
- 4 types:
  - Natural
  - Pixel
  - Optical
  - Mechanical
Natural

- Due to:
  - Area of exit pupil: $\cos(b)$
  - Change in effective area: $\cos(b)$
  - Larger distance to corner: $\cos^2(b)$

- Law: $\cos^4(b)$

Pixel

- Angular Sensitivity of Sensor
  - Finite depth of photon wells
Optical

• Entrance Pupil shaded by lens barrel

• Depends on Aperture

Mechanical

• Light blocked by lens hood
Vignetting Correction

- Venice panorama

Motion Blur

- Object Movement
- Camera Motion

De-blurring...
The Camera Sensor

- Noise
- Quantization

Sensor Noise

- ISO / Sensor Size

<table>
<thead>
<tr>
<th>Camera-Grade</th>
<th>Prosumer</th>
<th>Prosumer</th>
<th>Professional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Type</td>
<td>Compact</td>
<td>Compact</td>
<td>SLR</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>Small</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>ISO</td>
<td>100</td>
<td>200</td>
<td>100, 200</td>
</tr>
</tbody>
</table>

Canon EOS-1D Mark IV

- ISO 6,400
- ISO 25,600
- ISO 102,400

- Long Exposure
- Other Factors
  - Noise Reduction...

(dpreview.com)
Sensor Quantization

- Response Curve

- Analog - Digital (8 to 14 bits)

Camera Processing

- Photosites (photons to electrons)
- ISO (amplification)
- A/D (quantization)
- Demosaicing
- [denoising]
- [color conversion]
- Response Curve
- Gamma Encoding
- JPEG
Stitching

- Alignment
  - Projective Transformation

- Blending
  - Linear
  - Multiband
  - GraphCut
  - Poisson

The Future

- Terapixel Imaging Systems
- Metalens
- Super-resolution
Terapixel Imaging

Dr. David Brady
Professor of Electrical and Computer Engineering
Duke University

The diffraction limited space-bandwidth product for reasonable camera apertures sizes may easily exceed 10 gigapixels. In concert with spectral and temporal degrees of freedom, information capacities in excess of a terapixel/second are within reach. Construction of cameras approaching this limit requires (1) optoelectronic focal planes with terapixel/second capacity, (2) information systems capable of communicating and exploiting terapixel datacubes and (3) diffraction limited optical systems with gigapixel to terapixel capacity. Rapid decline in focal plane cost per pixel and dramatic demonstrations of real time large image processing suggest that challenges (1) and (2) may be surmounted. This talk reviews the challenges and limits of terapixel system design, presents scaling laws for system aperture, volume and power as a function of pixel count and describes recent optical design efforts that address challenge (3) for incoherent and coherent terapixel imagers.

Invited Talk
• ICCP 2010

Metalens

• Breaking the Diffraction Limit

capture details of 1/80 the wavelength of light
Super Resolution

Slide Credits

- Fredo Durand
- Neel Joshi and Michael Cohen
- Pablo d'Angelo

- http://dpreview.com
- http://www.wikipedia.org/
- http://www.cambridgeincolour.com
- http://www.aguntherphotography.com
- http://www.normankoren.com/