Interleaved Imaging: Rod-Cone Vision Based Imaging System

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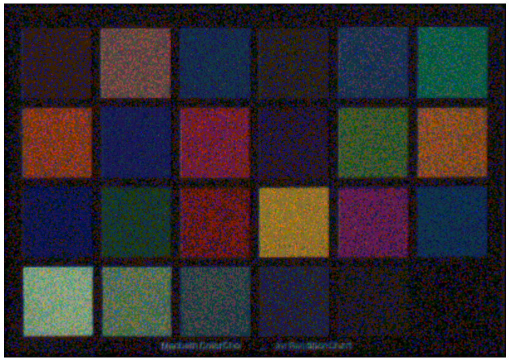
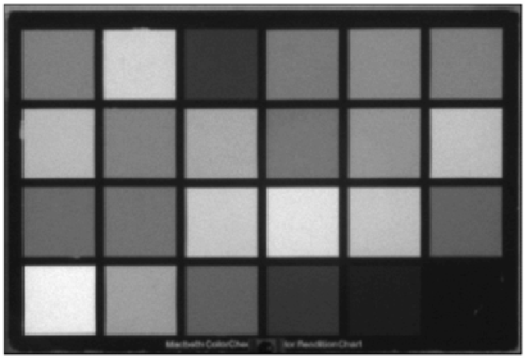
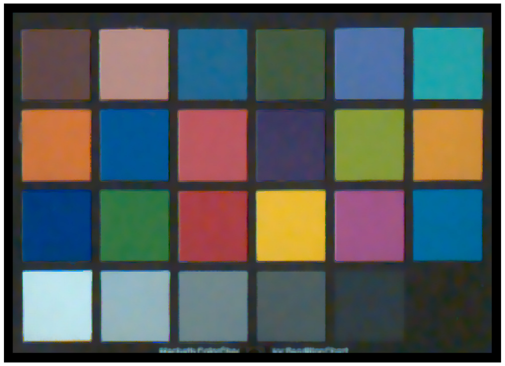
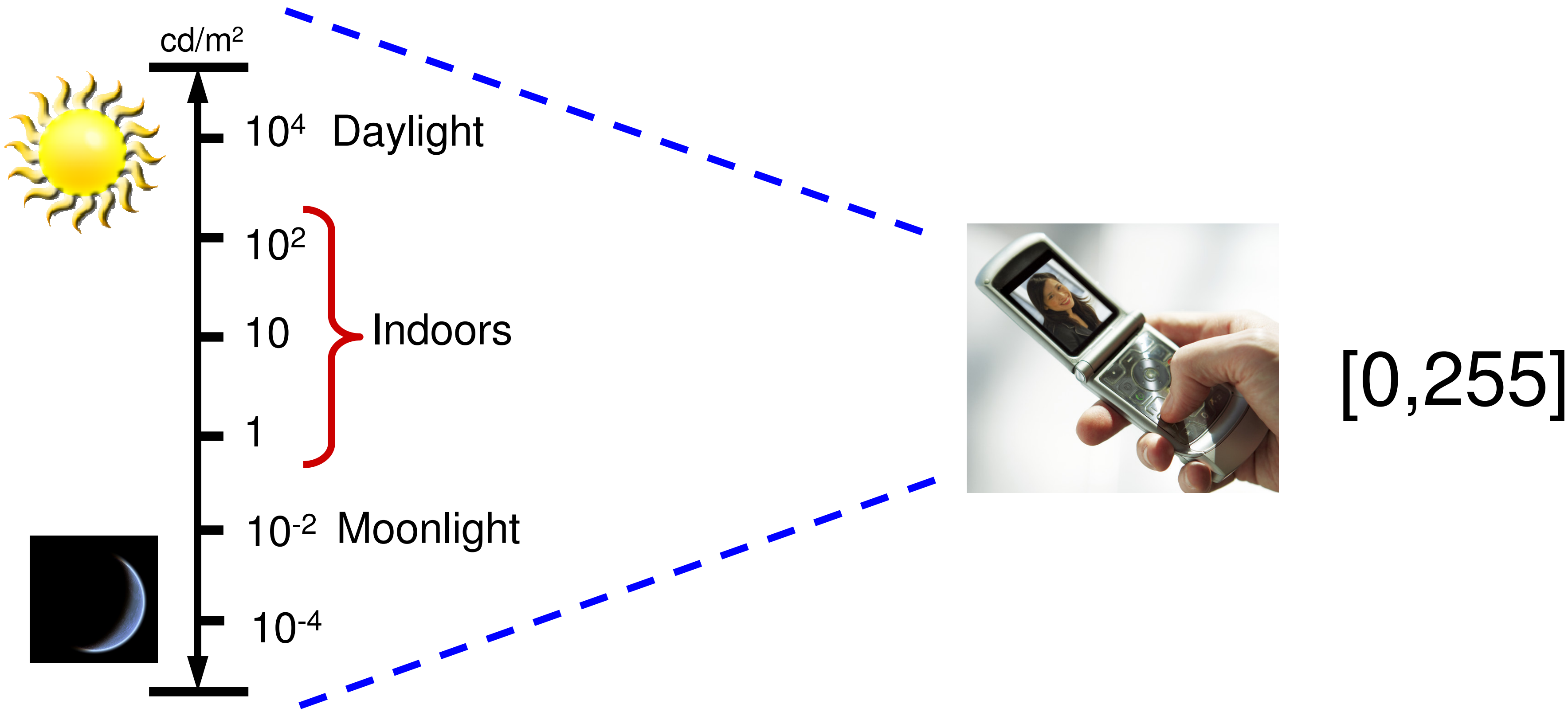






Light intensities in the natural world

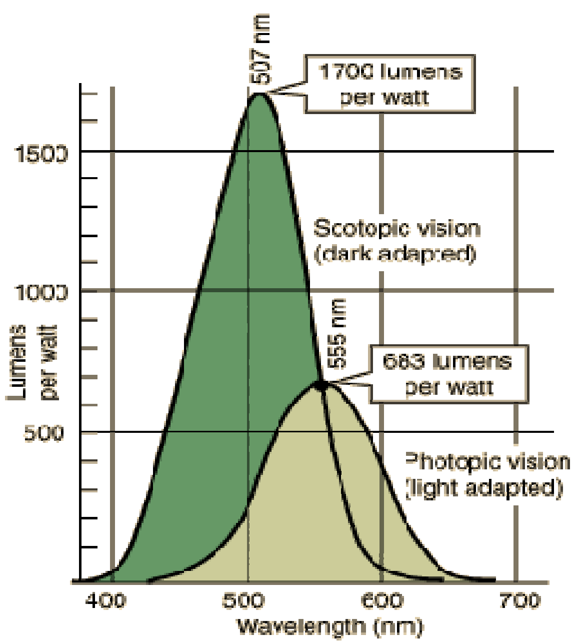
- Large range of light intensities in the environment



- HVS operates in a range of ~10^8 units
  - We'd like cameras to have similar capability

Light adaptation, HVS vs. camera

- •HVS, pupil diameter – Camera, lens aperture
- •HVS, integration time – Camera, exposure duration
- •HVS, rod-cone vision -- ?



- •Rods – high sensitivity, achromatic, low spatial and temporal resolution
- •Cones – low sensitivity, high spatial and temporal resolution, chromatic

Figure courtesy: http://hyperphysics.phy-astr.gsu.edu/hbase/vision/bright.html#c4

Industry challenge: Better Low light imaging

- Small number of photons in low-light.
  - In moonlight, a 2 μm pixel can expect to see 1 photon in a 25 ms exposure
- Photon noise visible for < 1000 photons on a uniform background [Xiao, 2005]

Simulation of images – 100 cd/m^2

6 μm pixels

2 μm pixels

Industry roadmap

- More pixels: sensor size stays same, each pixel gets smaller
  - Pixel sizes have shrunk from 2.2 um to 1 um (going lower)
- Each pixel gathers fewer photons, reducing SNR

Peter B. Catrysse and Brian A. Wandell (2005).
***In Proceedings of the SPIE Electronic Imaging '2005 Conference*, vol. 5678, p. 1-13, Digital Photography,**
Eds. Sampat, DiCarlo and Motta San Jose, CA.

Roadmap for CMOS image sensors: Moore meets Planck and Sommerfeld

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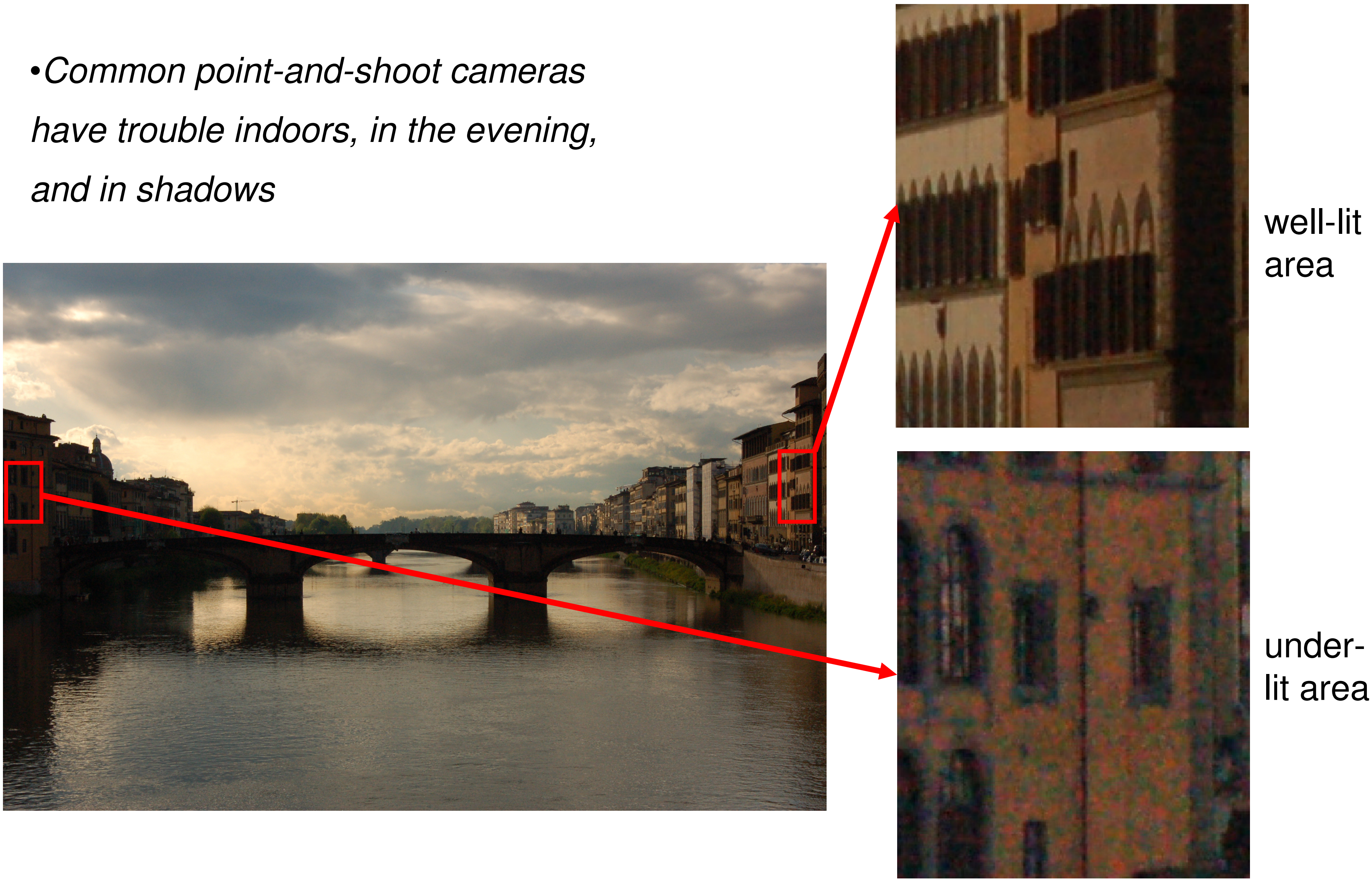
The steady increase in CMOS imager pixel count is built on the technology advances summarized as Moore's law. Because imagers must interact with light, Moore's Law impact differs from its impact on other integrated circuit applications. In this paper, we investigate how the trend towards smaller pixels interacts with two fundamental properties of light: photon noise and diffraction. Using simulations, we investigate three consequences of decreasing pixel size on image quality. First, we quantify the likelihood that photon noise will become visible and derive a noise-visibility contour map based on photometric exposure and pixel size. Second, we illustrate the consequence of diffraction and optical imperfections on image quality and analyze the implications of decreasing pixel size for aliasing in monochrome and color sensors. Third, we calculate how decreasing pixel size impacts the effective use of microlens arrays and derive curves for the concentration and redirection of light within the pixel.

Industry challenge: Better Low light imaging

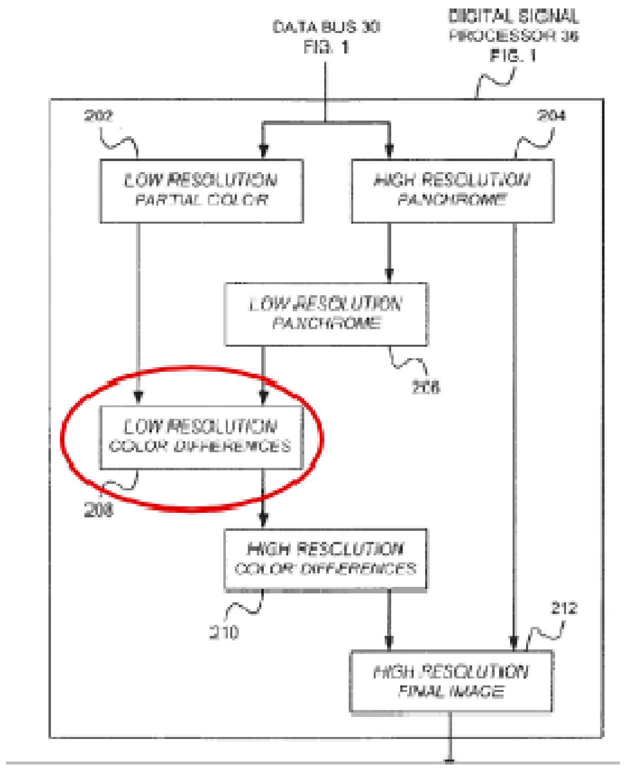
•*Common point-and-shoot cameras have trouble indoors, in the evening, and in shadows*



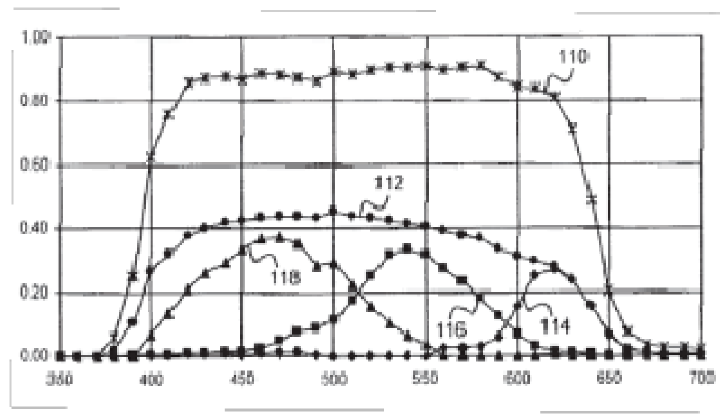
Improving low-light performance

- Increase amount of light incident on sensor
  - Lens apertures are limited
  - Increasing exposure times causes shake in still cameras, limited by frame-rate in video cameras
- Improve color filter efficiency
  - Broad-band color filter sensitivities
    - Amplifies noise during color correction, issues with attaining saturated colors [Baer 1999, Barnhoefer 2003]
  - Higher peak efficiency
    - Channel sensitivity mismatch

Previous attempts



(a)



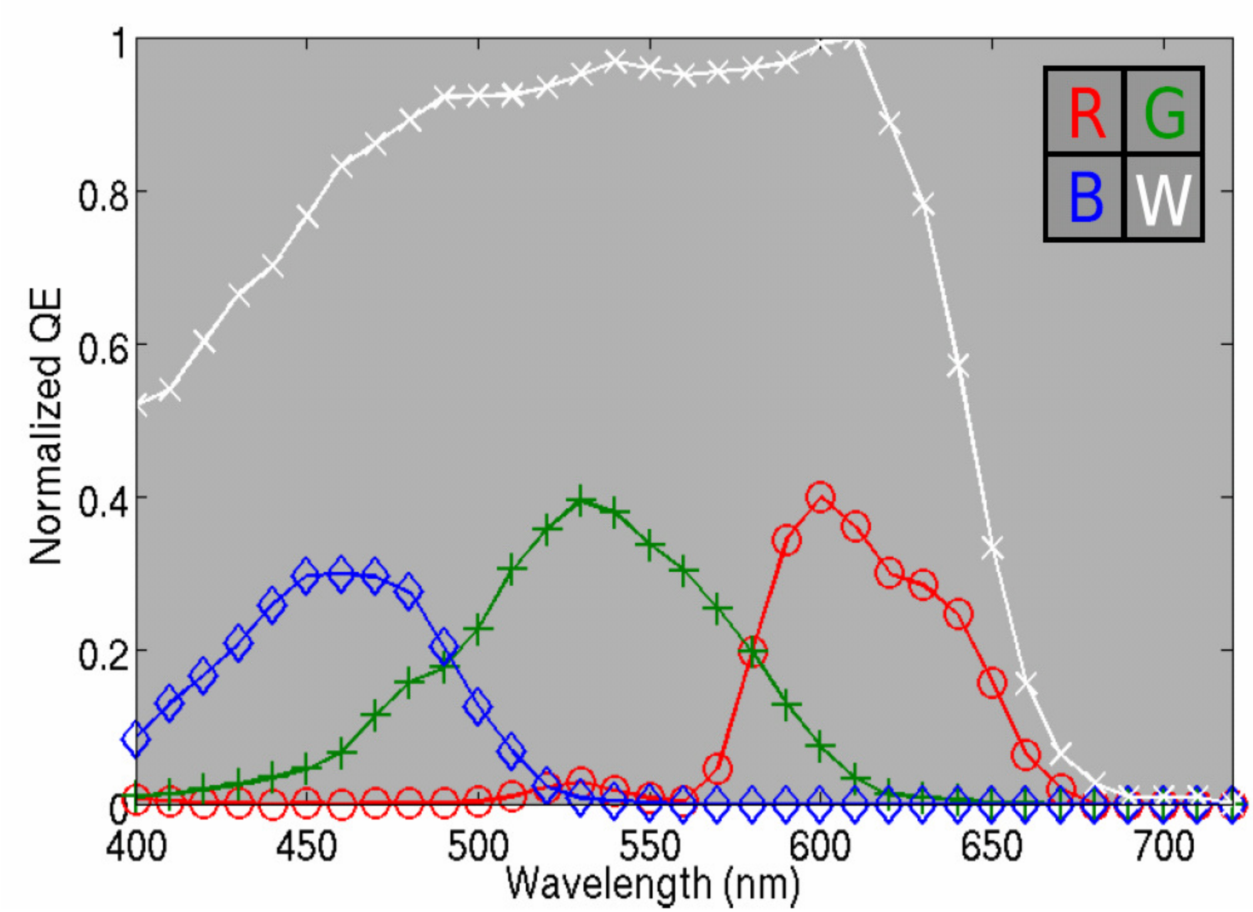
(b)

Kijima et al., 2007, page 5, column 2, par 57

"the color filter pixels will be significantly less sensitive than the panchromatic pixels" it is "advantageous to adjust the sensitivity of the color filter pixels so that they have roughly the same sensitivity as the panchromatic pixels"

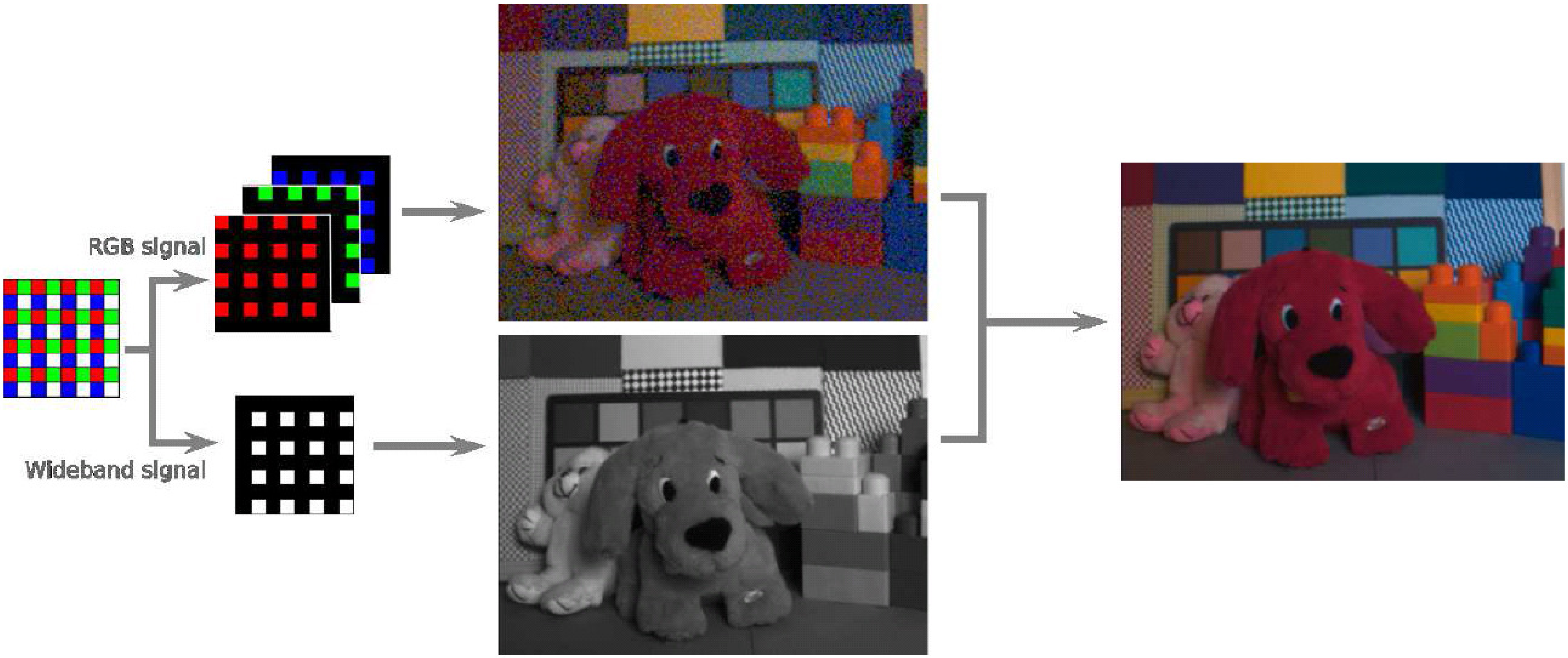
Figures from Kijima et al. 2007, US Patent Application no. 20070268533

Interleaved imaging color filter array



- RGB color filters optimized for color reproduction
- Wideband filter optimized for sensitivity

Interleaved Imaging



A single acquisition provides two interleaved images

- RGB image encodes color information
- wideband image encodes an achromatic high SNR scene representation.

Reconstruction filter

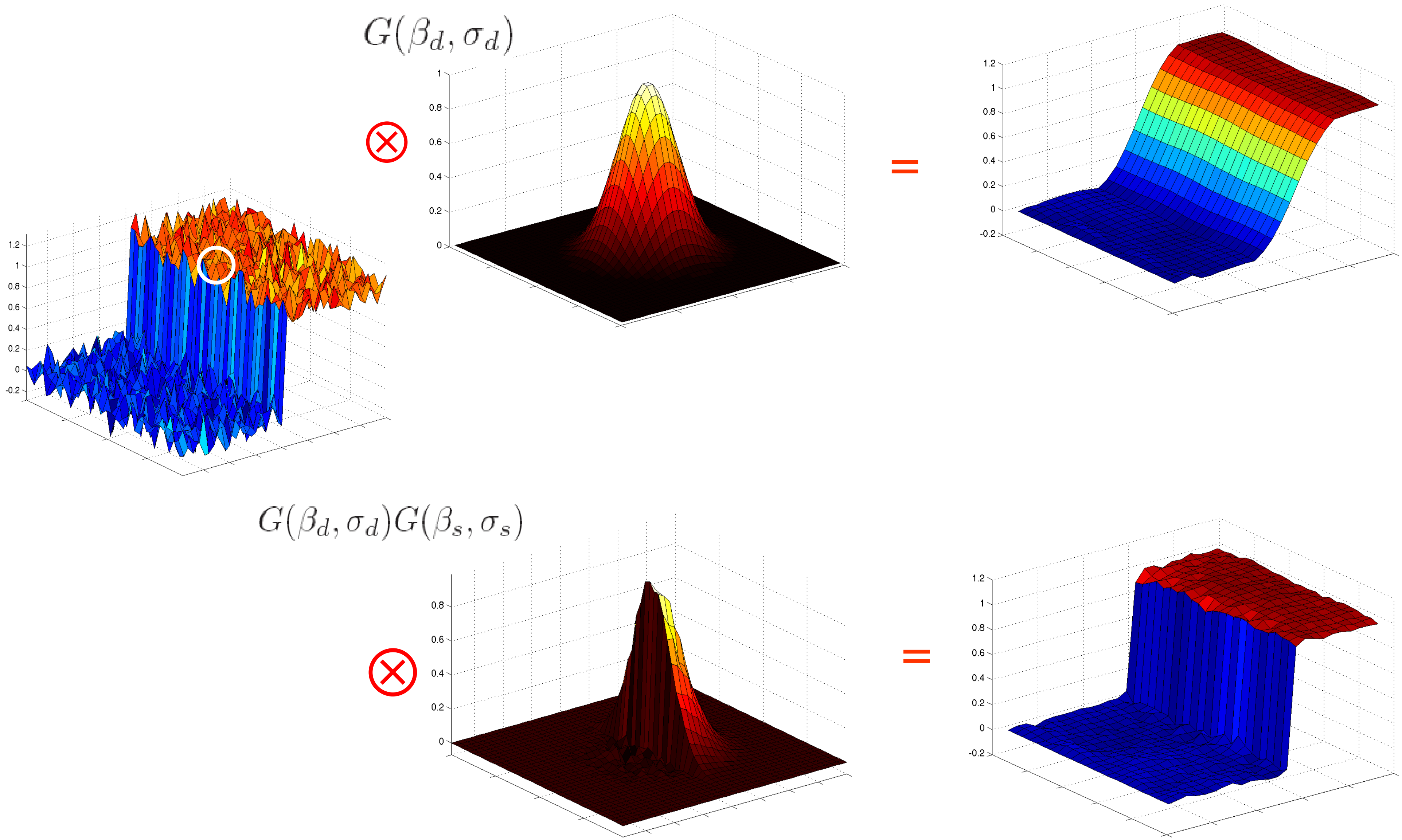
•Based on bilateral filter [Tomasi and Manduchi 1998] and nonlinear means filter [Buades et al. 2005]

•Filter coefficients depend on both pixel-distance *and* pixel-similarity

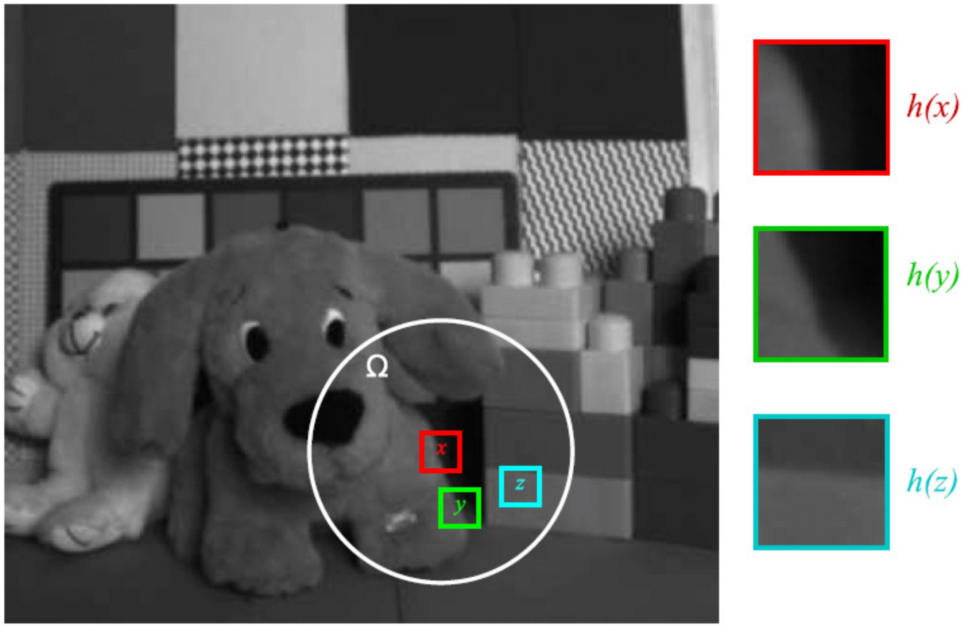
Updated intensity $$f_i(x) = \frac{1}{W_y}\sum_{y\in\Omega} G(\beta_d, \sigma_d)\, G(\beta_s, \sigma_s)\, S_i^{\Omega}\, g_i(y)$$ Measured intensity

Must define pertinent pixel-distance, pixel-similarity measures

Adaptive smoothing



Pixel-similarity



- Each pixel is associated with a small surrounding patch

- Pixel-similarity is determined by similarity of associated patches.

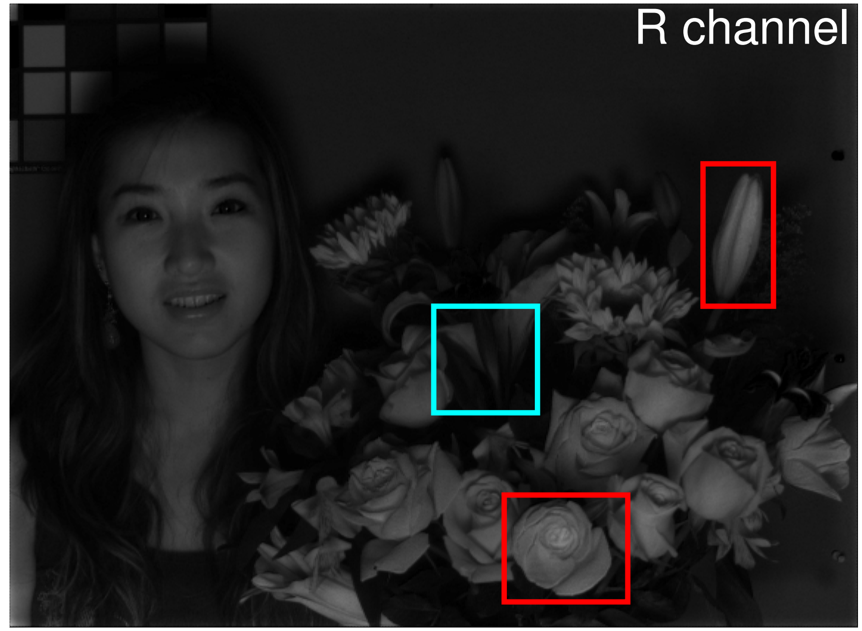
- The pixel-similarity between x and y is higher than the pixel-similarity between x and z

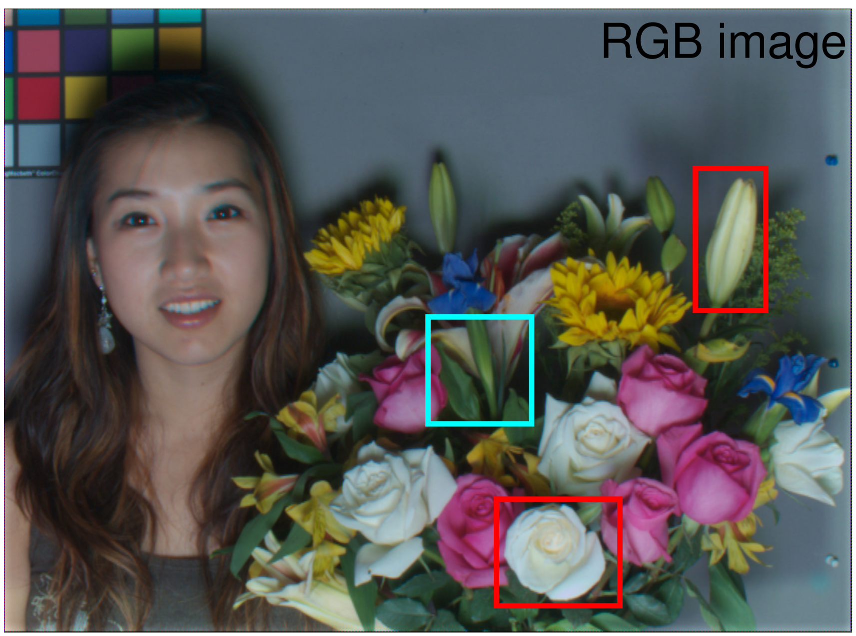
Combined color-wideband pixel-similarity

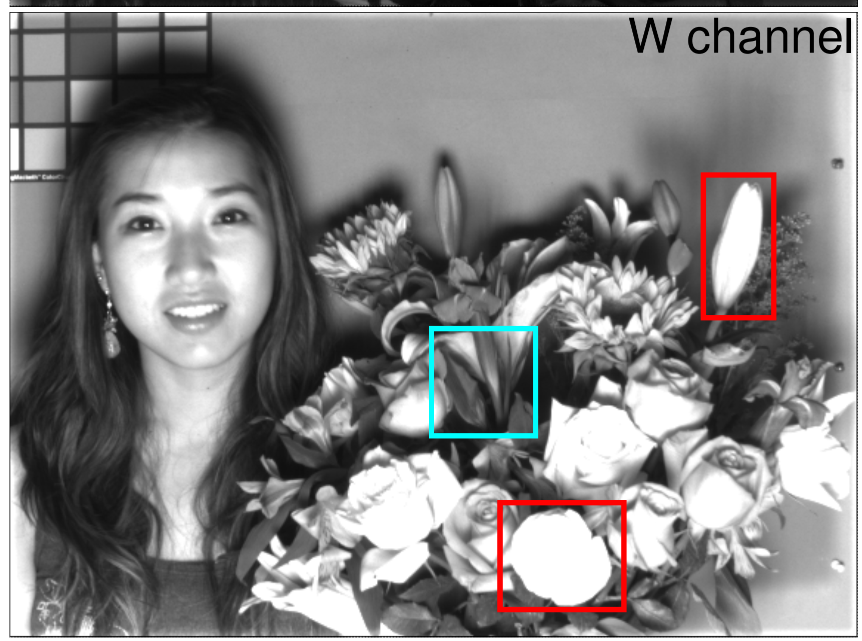
$G(\beta_s, \sigma_s)$ weights based on pixel-similarity in both color *and* wideband channels

$$\beta_s = \alpha(y)\|h_i(x) - h_i(y)\|_2 + (1 - \alpha(y))\|h_W(x) - h_W(y)\|_2,$$

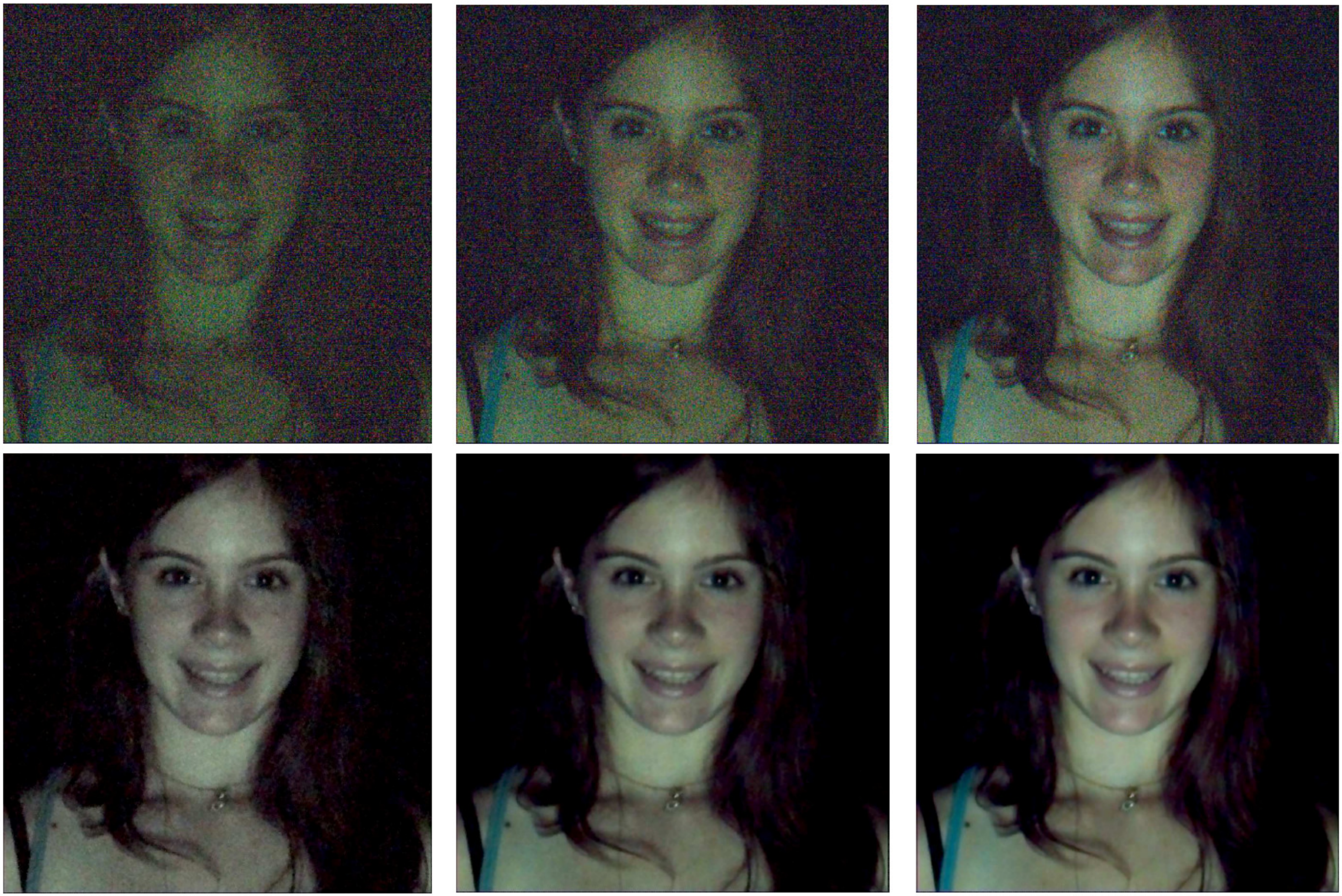
$$\alpha(v) = \frac{N_{\text{saturated}}(h_W(y))}{N_{\text{total}}(h_W(y))}.$$







Simulations – Bayer (top) vs. interleaved (bottom)– 5 cd/m^2 illumination, 2.2 µm pixel



(a) 5 ms (b) 10 ms (c) 20 ms

Bayer vs. Interleaved, exposure = 0.010 sec

Bayer vs. Interleaved, exposure = 0.013 sec

Bayer vs. Interleaved, exposure = 0.019 sec

Bayer vs. Interleaved, exposure = 0.026 sec

Bayer vs. Interleaved, exposure = 0.037 sec

Bayer vs. Interleaved, exposure = 0.051 sec

Bayer vs. Interleaved, exposure = 0.071 sec

Future work

- Understand resolution-loss when the W-channel is saturated
- Study effect of filter transmittances
- Develop improved demosaicking algorithms for interleaved imaging architecture