

Sense and sensitivity

2009 International Image Sensor Workshop

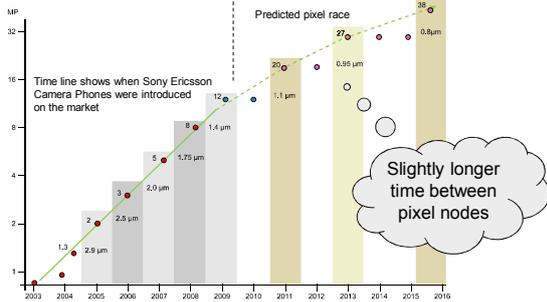
Mats Wernersson and Henrik Eliasson

Pixel race

Not a race for more pixels: it's a race for smaller pixels!
Why do pixels shrink?

- Because we can!
- Easy to sell larger pixel counts
- Demand for smaller cameras

The Pixel Race - Because we can!



How to make sense of the megapixel race

- The maximum useful pixel count is ultimately limited by optical diffraction and photon shot noise.

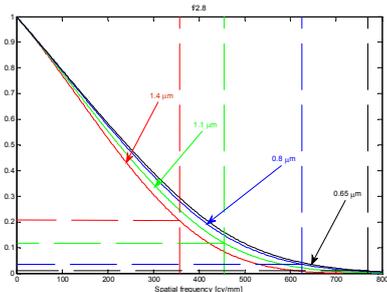
Resolution

• MTF calculated as the product of diffraction limited optical MTF and pixel geometric MTF. The optical MTF is a polychromatic MTF under D65 lighting.

• Dashed lines are the Nyquist frequencies for the respective pixel pitch.

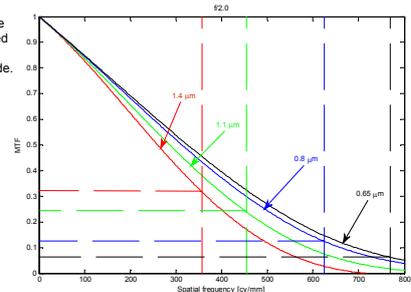
• This sets an absolute limit for the resolution of a certain sensor/lens f-number combination.

• Setting this limit at an MTF of 10% means that f/2.8 should not be used for pixel pitches below 1.1 μm, in order to take advantage of the increased pixel count.



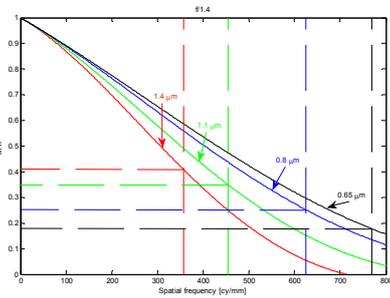
Resolution

• For a 0.8 μm pixel pitch, the f-number needs to be lowered to f/2.0, according to the definition on the previous slide.



Resolution

- Decreasing the pixel pitch even further, the f-number must keep on decreasing.
- Lowering the f-number is very challenging for the optical designer: aberrations increase, especially off-axis, meaning that it might not be possible to maintain diffraction limited optics for smaller f-numbers.



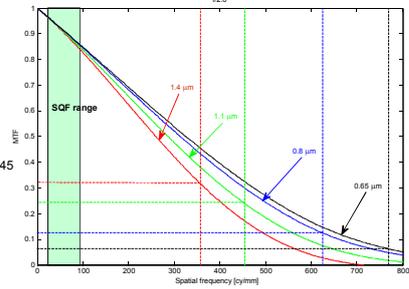
Sharpness

Same optical format, various pixel pitch

- So far we have only discussed the limiting resolution of the camera system. The impression of sharpness is critically dependent on lower spatial frequencies.
- Using SQF (subjective quality factor), we see that there is only a marginal increase in perceived sharpness when the pixel size is decreased.

SQF for 24x32 cm image @ 45 cm viewing distance, 1/2.8" optical format

SQF values
1.4 μm 92%
0.65 μm 93%



Photon shot noise and pixel size – same sensor size

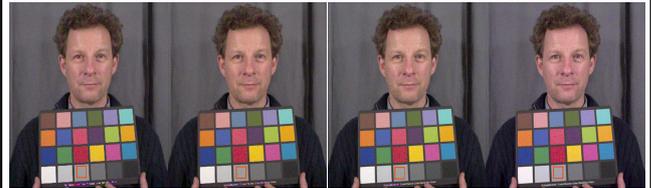
Illuminance: 5000 lux



2.8 μm	2.0 μm	1.4 μm	0.8 μm
t = 1/70 s	t = 1/70 s	t = 1/50 s	t = 1/35 s
Gain: 0 dB	Gain: 0 dB	Gain: 0 dB	Gain: 0 dB
S/N: 90	S/N: 73	S/N: 69	S/N: 56

Photon shot noise and pixel size – same sensor size

Illuminance: 100 lux



2.8 μm	2.0 μm	1.4 μm	0.8 μm
t = 1/5 s			
Gain: 10 dB	Gain: 10 dB	Gain: 14 dB	Gain: 18 dB
S/N: 68	S/N: 55	S/N: 39	S/N: 24

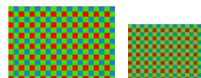
How to make sense of the megapixel race

- The maximum useful pixel count is ultimately limited by optical diffraction and photon shot noise.
- However, there is a fair chance to maintain a reasonable image quality between pixel generations *if the optical format is kept* (and disregarding other implications arising from smaller pixels)¹.

¹G. Agranov et al., 2007 International Image Sensor Workshop, pp 307-310, Ogunquit USA.

The dark side

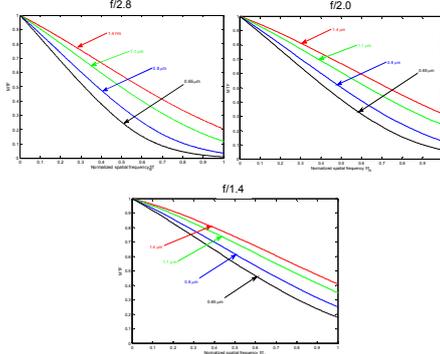
Smaller cameras: Keeping the pixel count means smaller sensor (optical format) => image quality for a given megapixel count will decrease with newer pixel generations.



Aberration and process technology limitations are being replaced by physical limitations (diffraction, photon shot noise). So far, technology has been limiting the image quality.

Resolution

If the pixel count is maintained, but the sensor size is decreasing, because of a smaller pixel pitch, the resolution will quickly become optics-limited for a diffraction-limited, ideal, system. To keep the same resolution and sharpness, the f-number must be decreased. If it is not possible to do this, the image quality of cameras with the same pixel number will decrease with new sensor generations.



Rev

13

Sharpness

Same pixel count – decreasing optical format with smaller pixel pitch

$$Q = K \int_0^{\infty} M(u) d(\log u)$$

$u_1 = 3$ cycles/deg

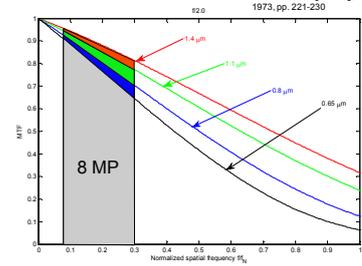
$u_2 = 12$ cycles/deg

$K =$ normalizing constant

Granger & Cupery, *Photographic Science and Engineering*, Vol. 16, 1973, pp. 221-230

SQF for 24x32 cm image @ 45 cm viewing distance

0.65 μm 82% Very good
0.8 μm 85% V.g. – Ex
1.1 μm 89% Excellent
1.4 μm 91% Excellent



Rev

14

Sharpness

Same pixel count – decreasing optical format with smaller pixel pitch

$$Q = K \int_0^{\infty} M(u) d(\log u)$$

$u_1 = 3$ cycles/deg

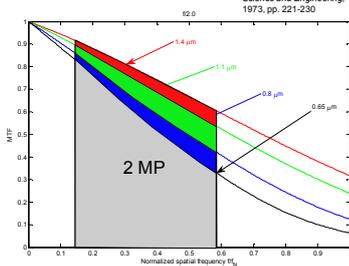
$u_2 = 12$ cycles/deg

$K =$ normalizing constant

Granger & Cupery, *Photographic Science and Engineering*, Vol. 16, 1973, pp. 221-230

SQF for 24x32 cm image @ 45 cm viewing distance

0.65 μm 63% Fair – Good
0.8 μm 69% Good
1.1 μm 76% Good – V.g.
1.4 μm 80% Very good

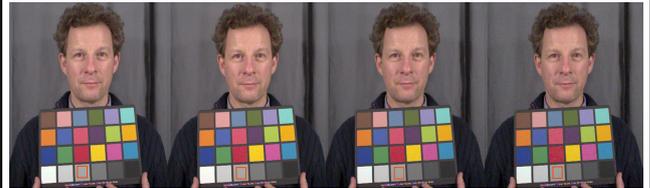


Rev

15

Photon shot noise and pixel size – same pixel count, different sensor size

Illuminance: 5000 lux



2.8 μm

$t = 1/70$ s

Gain: 0 dB

S/N: 90

2.0 μm

$t = 1/70$ s

Gain: 0 dB

S/N: 73

1.4 μm

$t = 1/50$ s

Gain: 0 dB

S/N: 69

0.8 μm

$t = 1/35$ s

Gain: 0 dB

S/N: 56

Rev

16

Photon shot noise and pixel size – same pixel count, different sensor size

Illuminance: 100 lux



2.8 μm

$t = 1/5$ s

Gain: 10 dB

S/N: 68

2.0 μm

$t = 1/5$ s

Gain: 10 dB

S/N: 55

1.4 μm

$t = 1/5$ s

Gain: 14 dB

S/N: 39

0.8 μm

$t = 1/5$ s

Gain: 18 dB

S/N: 24

Rev

17

How to make sense of the megapixel race

- The maximum useful pixel count is ultimately limited by optical diffraction and photon shot noise.
- However, there is a fair chance to maintain a reasonable image quality between pixel generations *if the optical format is kept* (and disregarding other implications arising from smaller pixels).
- But if the pixel count is kept constant while pixel size is decreased, *image quality will suffer!*

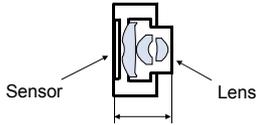
Rev

18

The best compromise between physical size and image quality



- How large sensor can we use?
A mobile phone must be slim
- The camera thickness depends on the sensor format
The sensor format dictates the focal length of the lens



Thickness ~ Sensor format

The best compromise between physical size and image quality

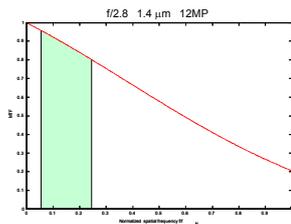
- The maximum sensor format that can be used ~1/2.8 inch
- 1/2.8 = .357 inch = **Magnum**

Digital zoom

There are some claims that digital zoom will become more usable with an increasing pixel resolution. More pixels should automatically lead to a larger zoom range.

1x

SQF for 24x32 cm image @ 45 cm viewing distance:
90% ~ Excellent



$$Q = K \int_{u_1}^{u_2} M(u) d(\log u)$$

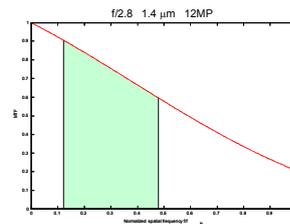
$u_1 = 3 \text{ cycles/deg}$
 $u_2 = 12 \text{ cycles/deg}$
 $K = \text{normalizing constant}$

Digital zoom

There are some claims that digital zoom will become more usable with an increasing pixel resolution. More pixels should automatically lead to a larger zoom range.

2x

SQF for 24x32 cm image @ 45 cm viewing distance:
79% ~ Very Good



$$Q = K \int_{u_1}^{u_2} M(u) d(\log u)$$

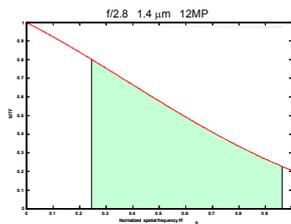
$u_1 = 3 \text{ cycles/deg}$
 $u_2 = 12 \text{ cycles/deg}$
 $K = \text{normalizing constant}$

Digital zoom

There are some claims that digital zoom will become more usable with an increasing pixel resolution. More pixels should automatically lead to a larger zoom range.

4x

SQF for 24x32 cm image @ 45 cm viewing distance:
57% ~ Fair



$$Q = K \int_{u_1}^{u_2} M(u) d(\log u)$$

$u_1 = 3 \text{ cycles/deg}$
 $u_2 = 12 \text{ cycles/deg}$
 $K = \text{normalizing constant}$

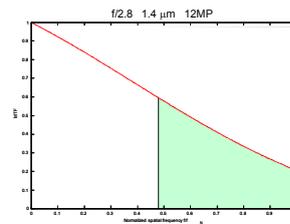
Conclusion: Decent performance with perhaps 2x digital zoom for a good system (not confirmed).

Digital zoom

There are some claims that digital zoom will become more usable with an increasing pixel resolution. More pixels should automatically lead to a larger zoom range.

8x

SQF for 24x32 cm image @ 45 cm viewing distance:
22% - Off scale -



$$Q = K \int_{u_1}^{u_2} M(u) d(\log u)$$

$u_1 = 3 \text{ cycles/deg}$
 $u_2 = 12 \text{ cycles/deg}$
 $K = \text{normalizing constant}$

Conclusion: Decent performance with perhaps 2x digital zoom for a good system (not confirmed).

Field of view vs CRA

In pursuit of smaller cameras, especially the height is important. A consequence of decreasing the height is a shorter focal length. Not only does this have a bad effect on image quality (shading), but also the user experience is negatively affected, leading to perspective distortion (e.g., close distance portraits).



F = 150 mm @ 2.4 m



F = 36 mm @ 0.4 m

Can image processing help?

- Distortion correction
- Noise reduction
- Sharpening

Distortion correction

Impossible to fix perspective distortion.

Neglectable distortion



Perspective distortion



Optical distortion



Noise reduction – problem solved?



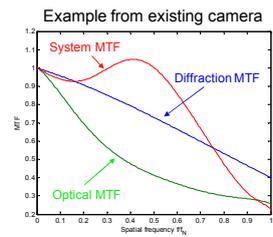
Images copyright ISA – the International Imaging Industry Association

While adaptive noise reduction algorithms in general do a good job at preserving sharp edges, the effect on low contrast detail can be horrible.

Digital sharpening

- Introduces artefacts and amplifies noise
- EDOF? Same problem.

Effect of digital sharpening



Digital sharpening can increase perceived sharpness substantially, but at the expense of noise amplification and introduction of artefacts.

Digital processing

The impact on image quality due to the ISP is increasing. This leads to improvements but also artefacts that are difficult to quantify.



Two different cameras: same sensor, different optics and ISP.

CPIQ

Since the megapixel race seems out of control, and no-one (except marketing people...) really wants it, an industry-wide effort needs to be made in order to move the focus away from pixel count to image quality.

The Camera Phone Image Quality (CPIQ) initiative was started by the I3A in 2006.

Currently developing image quality measurement methods for:

- Sharpness
- Color shading
- Distortion
- Lateral chromatic aberration
- Texture sharpness
- Subjective image quality assessment

CPIQ

Phase 2 finished April 2009.
Phase 3 started autumn 2009. Open enrollment is taking place at this moment.

Phase 3 will continue to develop metrics for:

- Spatial acutance
- Color consistency and white balance
- Luminance shading
- Straylight
- Signal to noise ratio

A method for combining all metrics into a single consumer-oriented rating system is the ultimate goal.

Participating companies in Phase 2:	
AMD	Omnivision Technologies, Inc.
Actina	Palm, Inc.
CDM Optics	Philips Lumileds Lighting Co.
Eastman Kodak Co.	Sensata Technologies
Foveon, Inc.	Sony Ericsson Mobile Communications
Freescale Semiconductor, Inc.	Sprint
FUJIFILM Corporation	STMicroelectronics
Hewlett-Packard	Teves Instruments, Inc.
Image Engineering	Tessera
Motorola, Inc.	Verizon Wireless
Nethra Imaging	Vieta Print Technologies
Nokia Corporation	Zoran Corporation

Hot Topics

Wafer Level Cameras

- Important for cost and size reduction
- Concerns about optical performance and yield

High Dynamic Range

- May be the next big step in image quality improvement
- True HDR requires proper infra structure (not just sensor)
 - Adaptive tone mapping for pleasant representation
- Challenging for small pixels?

HD Video

- A new "pixelrace" – adding one dimension
- High data rates put high demands on infra structure

Appendix

Original scene radiance image



Rendered into sRGB by calculating the CIEXYZ values from the spectral data at each sample followed by a chromatic adaptation to D65 and conversion to sRGB according to IEC 61966-2-1.

cont. →

The images were simulated under the following conditions:

The scene was captured using a Nikon D700 camera with a 28 mm^{2.8} Nikkor lens. The relative spectral sensitivity of this camera was previously measured. From the camera spectral data, a radiance scene was calculated such that each pixel contains the radiance spectrum from 400 up to 700 nm. Using only 3 color channels, the spectral accuracy is still reasonably good.

The sensor images were calculated from the same spectral QE in all cases. All noise sources except photon shot noise were set to zero. The raw images were processed by a very simple image pipe: white balance, color correction and gamma correction. The color matrix was calculated using a white-point preserving least squares method.

The sensor parameters that were varied were:

- Pixel size
- Full well capacity
- Conversion gain
- ADC voltage swing

For the 0.8 μ m pixel, a full well capacity of 2000 electrons was assumed, together with a conversion gain of 160 μ V/e⁻ and an ADC swing of 400 mV. We are thus assuming that the full well capacity is considerably better than estimated from a simple scaling of full well vs pixel area.

The signal to noise ratio was calculated on the rendered images using the Photoshop histogram for the luminosity channel.