Camera Technology at the Dawn of Digital Renascence Era

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DSC camera for mobile applications

Sensor technology

Challenges: optical stack and lens roll-off

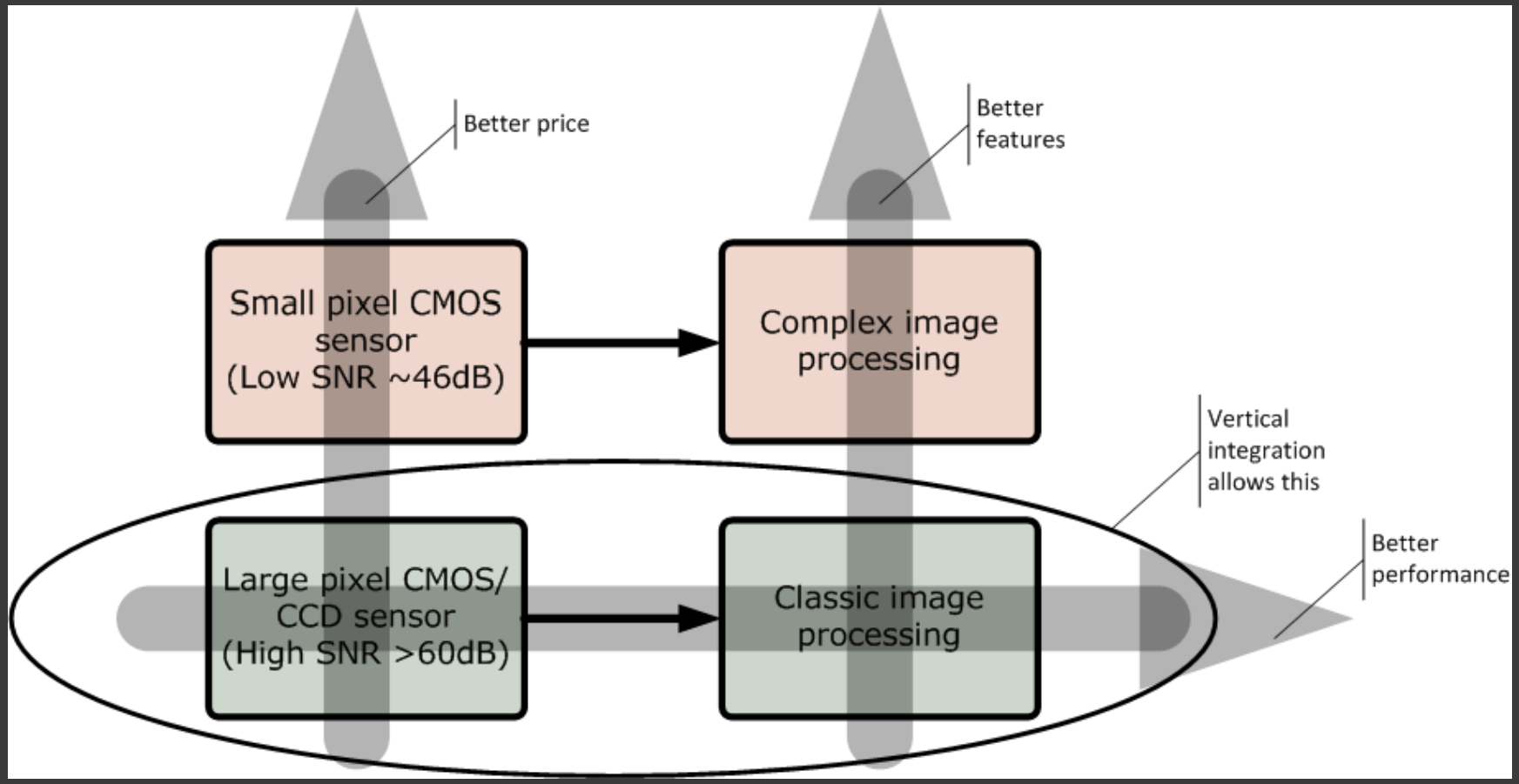
Case studies:

- Bad pixels vs noise reduction
- RAW data and DPCM compression -> MTF integrity curve
- Bayer demosaic evaluation
- Color processing and noise
- EDOF evaluation
- HDR discussion

Innovative thinking example: open loop AF

Conclusions: use-cases and system level

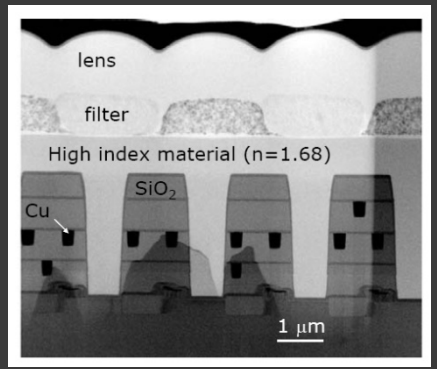
Why? – Because…

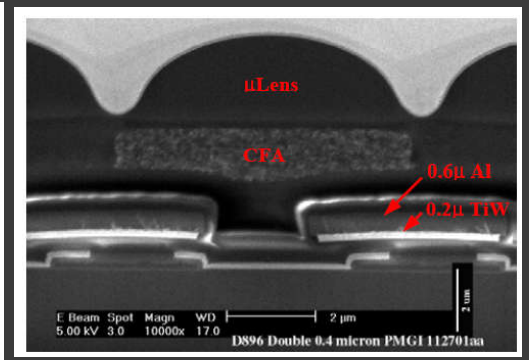

Better price
Better features
Small pixel CMOS sensor (Low SNR ~46dB)
Complex image processing
Vertical integration allows this
Large pixel CMOS/ CCD sensor (High SNR >60dB)
Classic image processing
Better performance

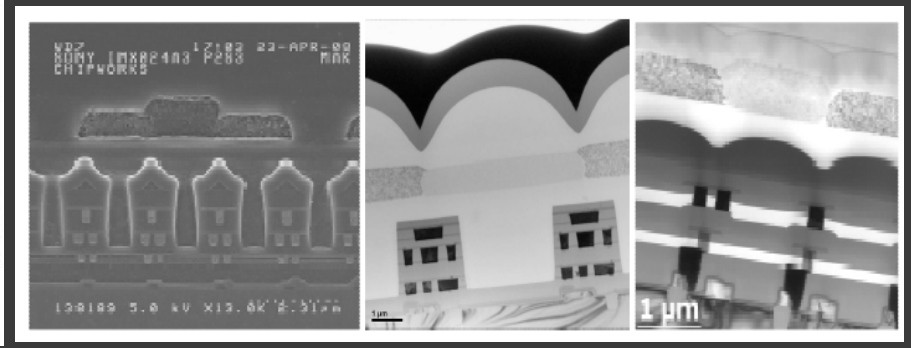
CMOS sensors with small pixels

CMOS fundamental issues (current technology?):

- require several metal layers to interconnect -> optical-tunnel problem -> microlens -> undesired optical effects : low f-number optical systems, vignetting, pixel crosstalk, light scattering, and diffraction (strong sensitivity dependence on incident photon wavelength and angle).
- lower clock voltages lead to smaller well capacity -> lower dynamic range.
- standard foundry processes use low resistivity silicon and require low voltage drive -> weak electric field (~1-2um) -> diffusion problem -> forced CMOS groups to work with foundries that provide custom fabrication processes -> critical for backside illuminated devices because thinning is limited to a dimension no thinner than approximately 8 um (Janesick)







[12]Chipworks-Sony/Samsung/Canon

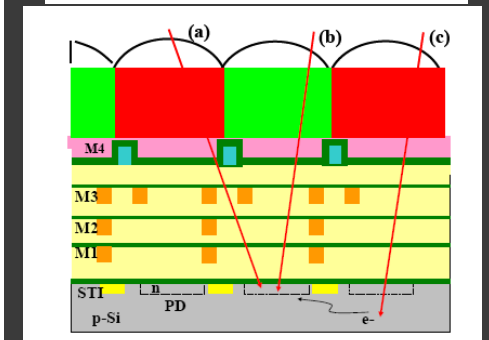
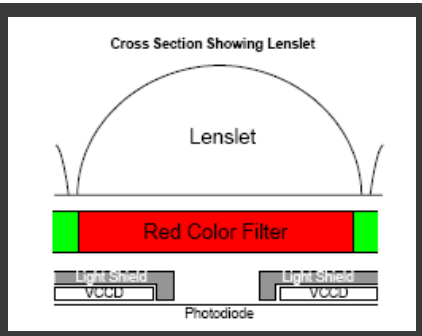
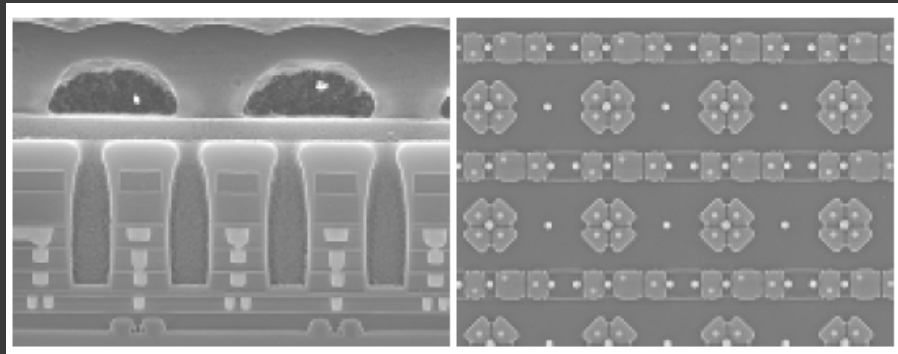


Fig. 11. Schematic of contributions to color cross-talk; (a) optical cross-talk, (b) color-filter cross-talk, (c) electrical cross-talk.

[1]IBM



[4]Kodak



[12]Chipworks-Sony

Sensor technology - BSI

CCD FSI – BSI motivation (CCD BSI has no microlens):

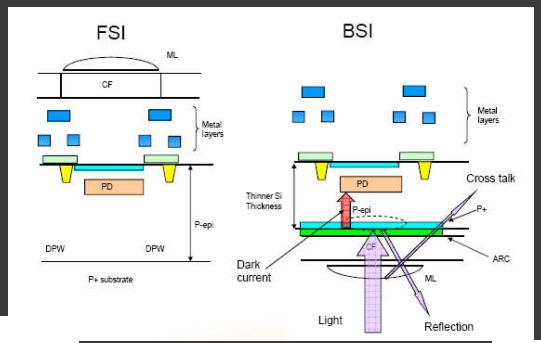
- QE increase for FSI with no microlens (full-frame CCDs)
- Fill factor increase / microlens removal (interline CCDs)

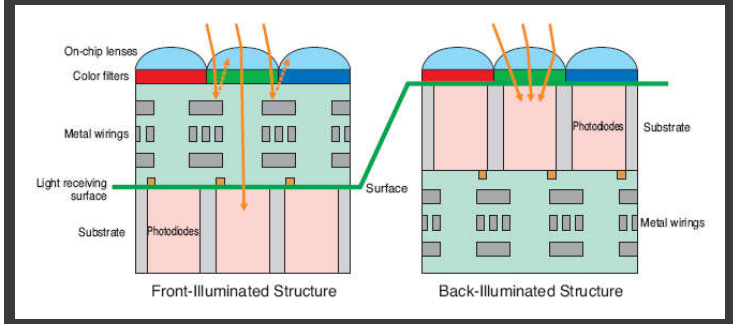
CMOS FSI-BSI motivation (CMOS BSI has microlens to reduce electrical crosstalk):

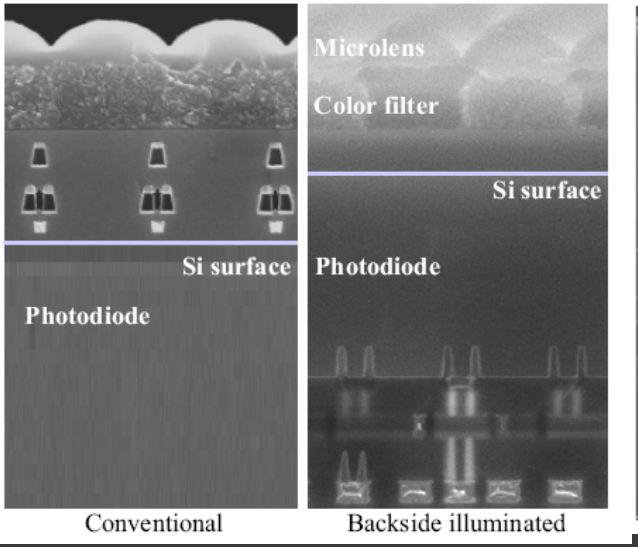
- optical stack height
- Fill factor increase

Current issues:

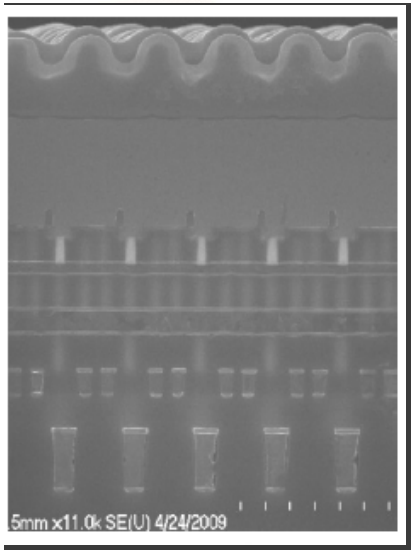
- crosstalk
- low red response
- Low electrical-field



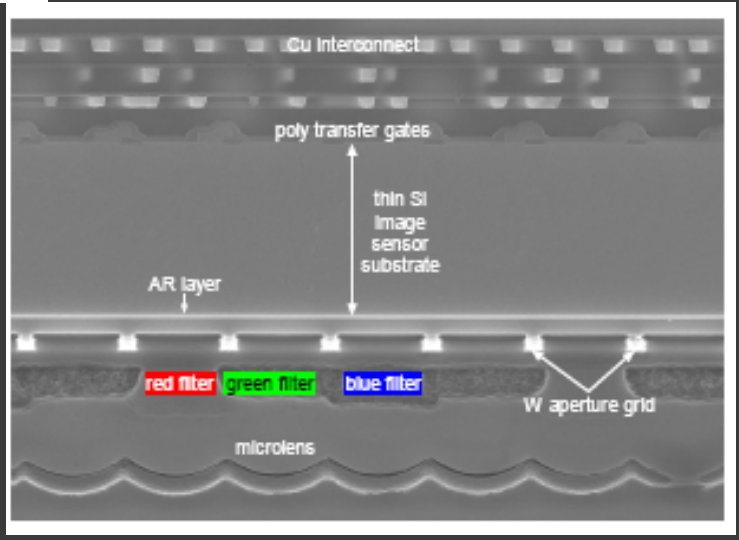




[11]Samsung



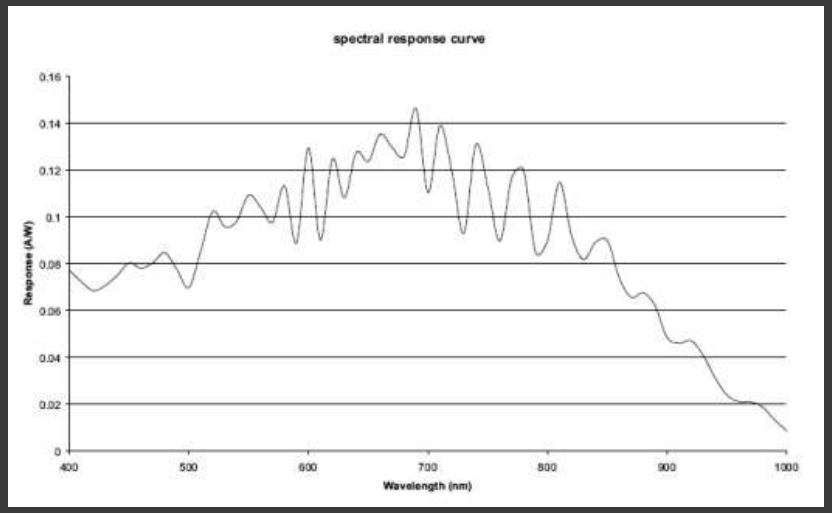
[10]Omnivision



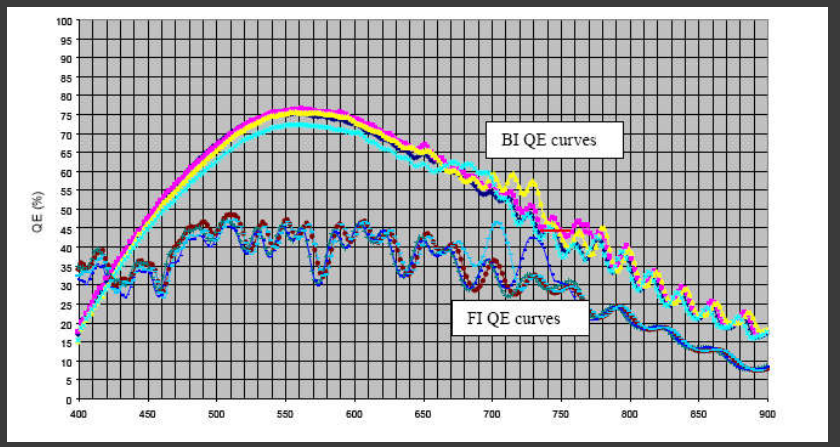
[12]Chipworks-Sony

CMOS sensor technology - artifacts

CMOS QE response due to metal interconnects – fringes in the QE curve



[5]CYPRESS



[6]E2V

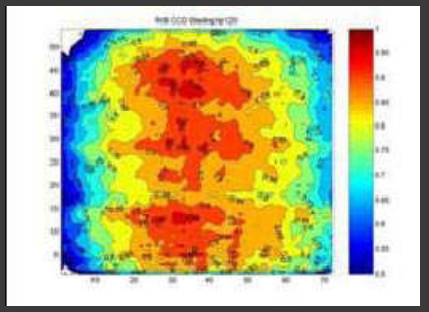
Optical Stack and Corrections

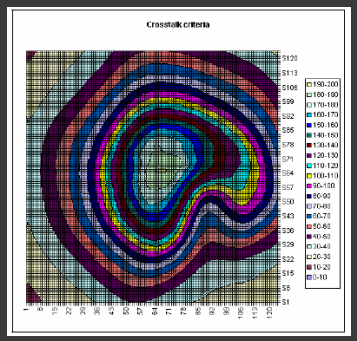
Pixel MTF (electrical)

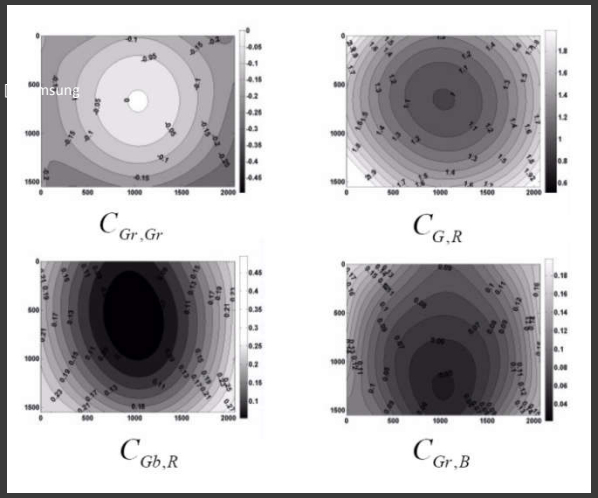
Pixel crosstalk (electrical)

Lens shading – microlens impact – fill factor-apochromatic

Snr degradation due to lens correction – error propagation







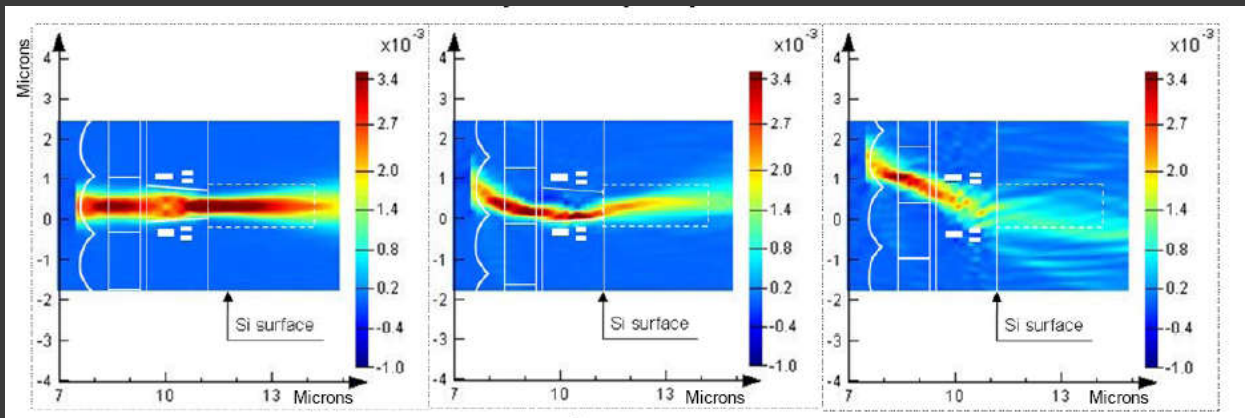


Figure 3. Examples of light propagation FDTD simulation for 1.4um pixel for 600nm wavelength, F number 1.4, and different CRA of incident light.
a. – pixel with light guide, CRA of incident light is equal to zero;
b. – pixel with light guide and shifted ulens/CF, large CRA of incident light;
c. – pixel with shifted ulens/CF and no light guide, large CRA of incident light.

[2]Aptina

Lens roll-off fallacies

Assumptions usually not true (CMOS cameraphone sensors):

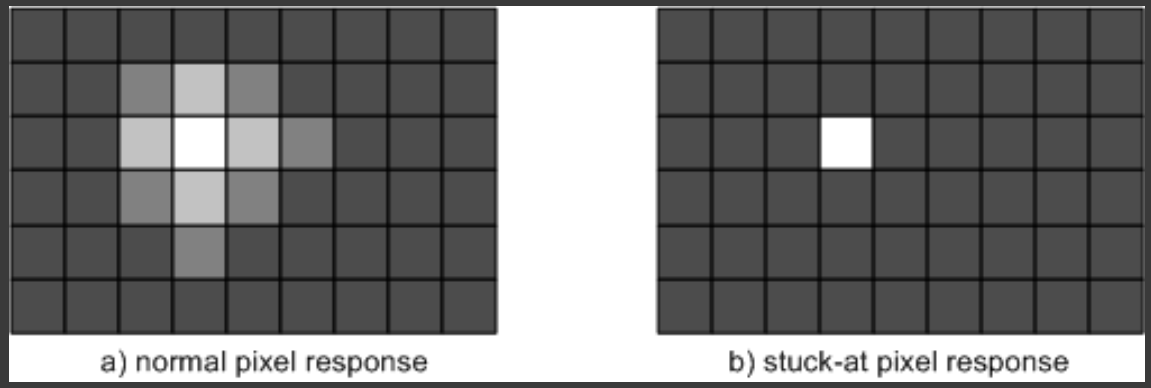
- It is radial – it's not
- It is only on luminance (ie. affects all colors the same) – it's not
- It is not illuminant dependant – it is
- It can be ignored because it is low (<5%) – it is >30%, some times 70%
- Both greens have the same roll-off – not true

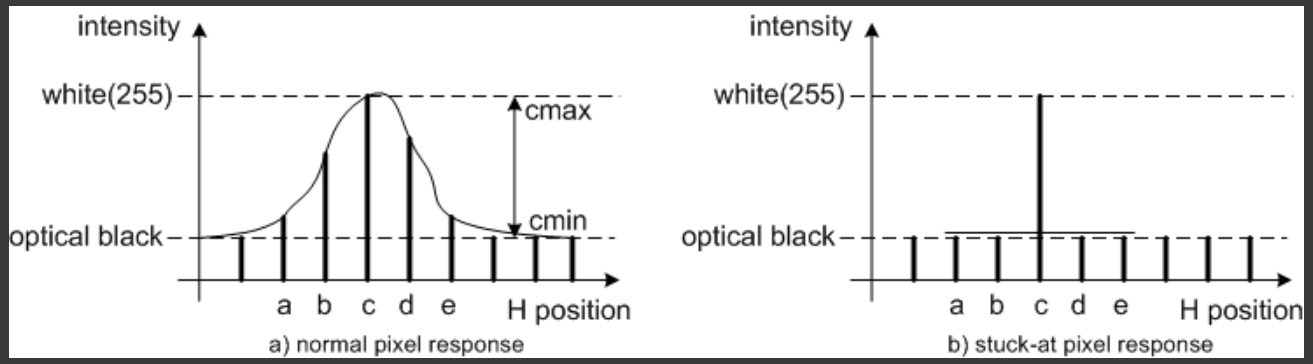
Additional issues:

- As the correction is anisotropic, per channel and per module, the error propagation implications are degrading accordingly any pixel based noise model.
- To be efficient, it is done in RAW domain, usually before most processing.

Bad pixel correction vs. noise reduction

Reasonable assumptions: PSF is 3-5 pixels, bad pixel=double edge but opposite sign, hard to align a continuous vertical edge for a lot of pixels

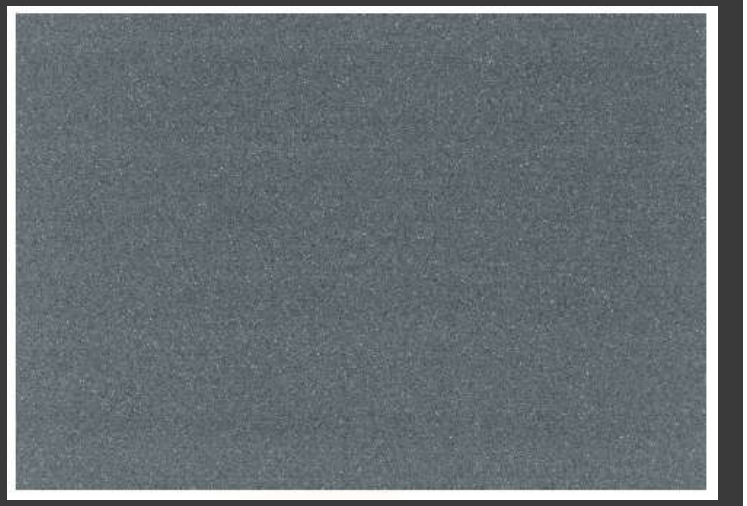




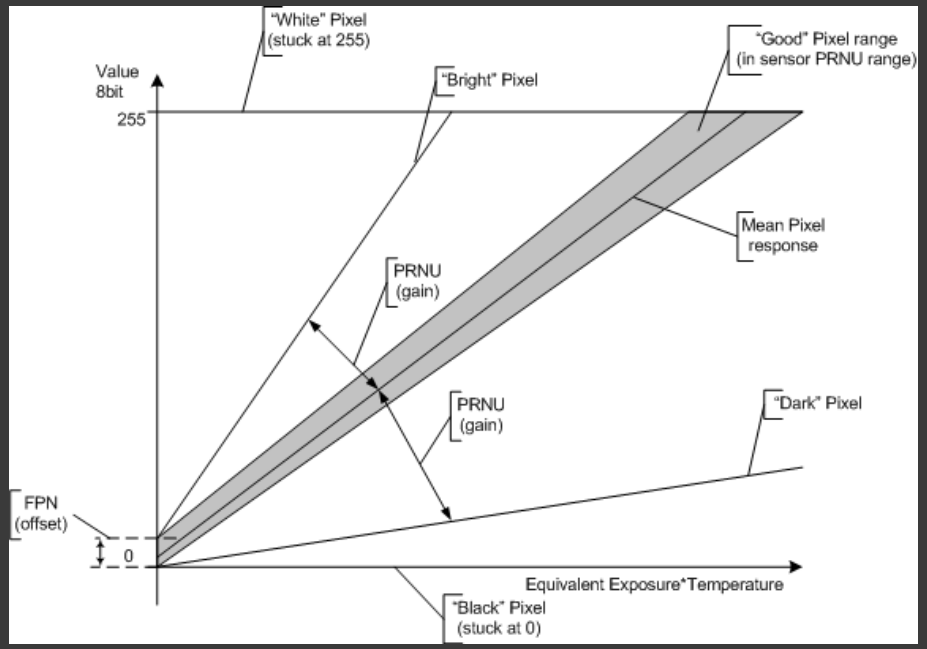
Bad pixel correction vs. noise reduction

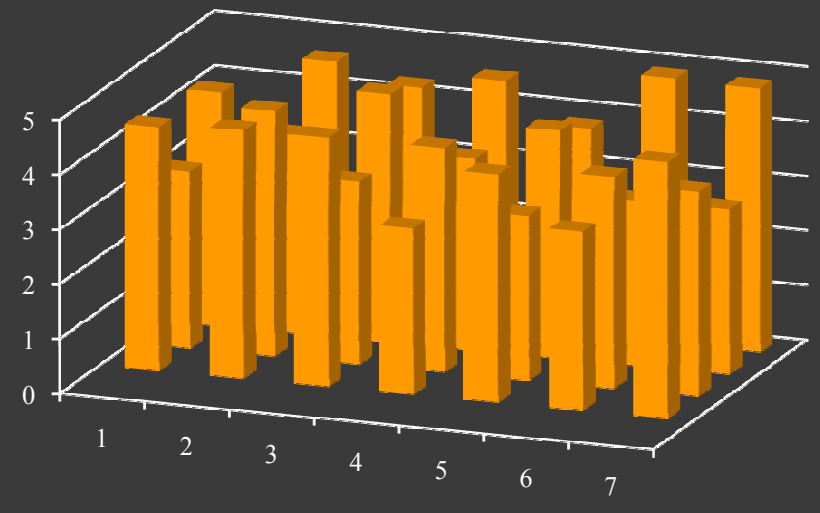
PRNU – Pixel Response Non-Uniformity:

- has two components:
  - Offset part: driven by dark current generation (temperature and exposure)
  - Gain part: driven by small pixel response differences to light
- requires full frame processing to correct
- requires per sensor calibration
- usually corrected as random noise



Additional pixel defects: Pixel nonlinearities (both low-end and high-end)



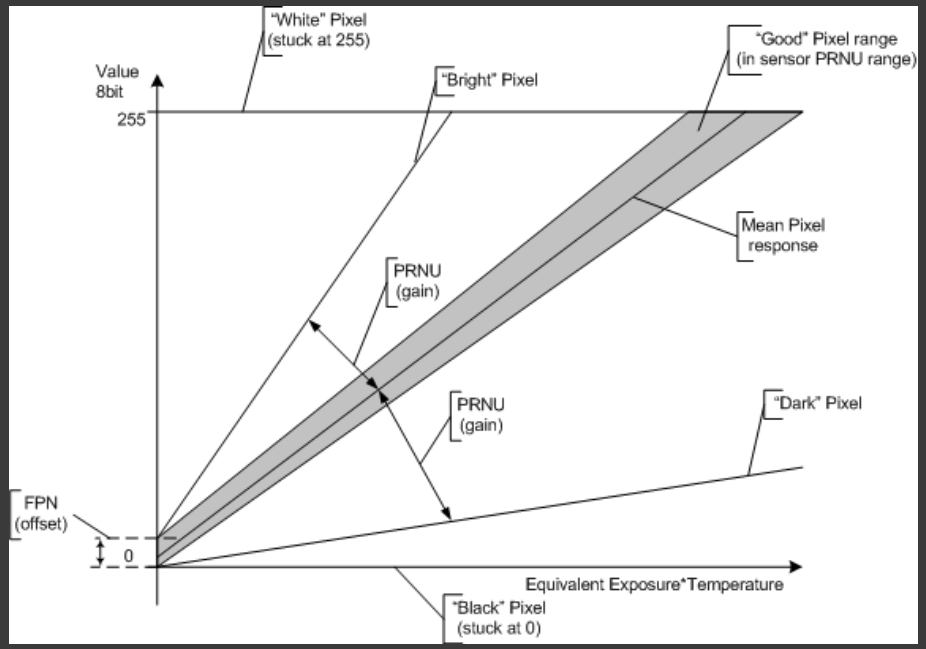


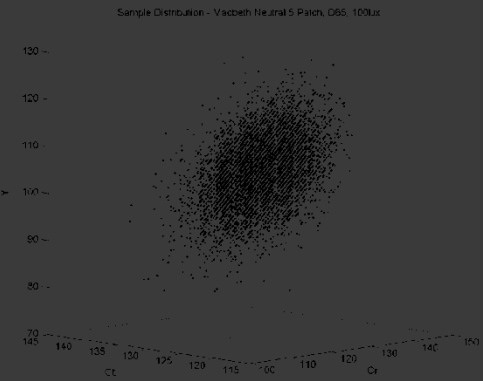
Bad pixel correction vs. noise reduction

Similarities:

- detection: pixels that have values deemed ‘unnatural’
- correction: detected pixels are replaced with an estimated value based on neighboring pixels

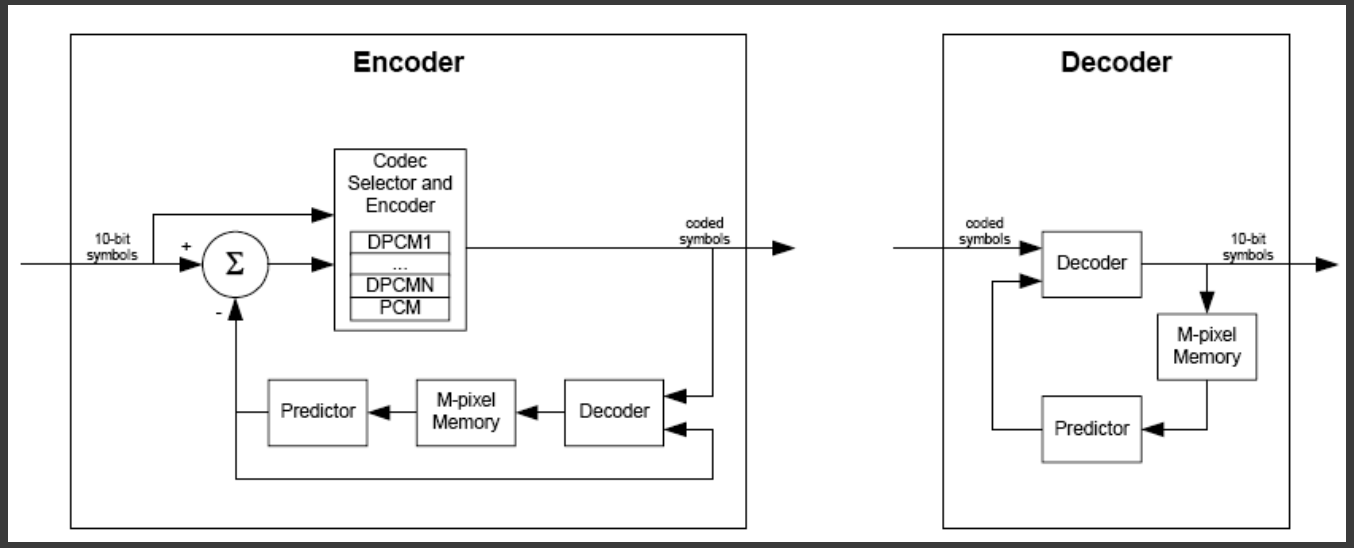
The problem: for low SNR sensors, PRNU can look both as noise as ‘bad pixels’





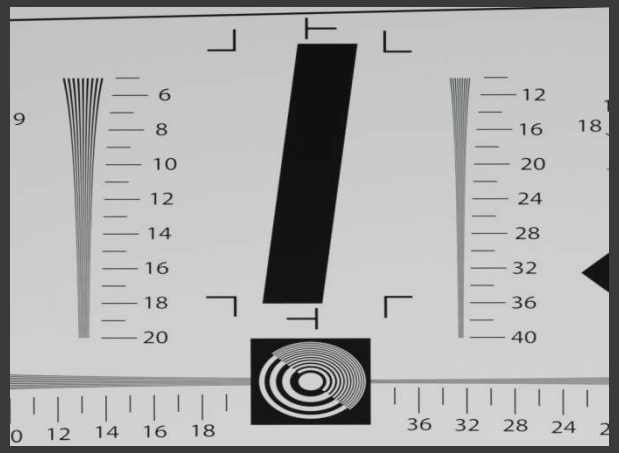
RAW data – DPCM compression

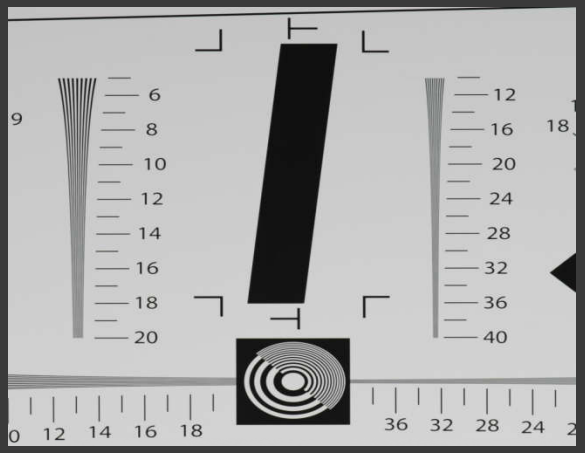
DPCM compression – very simple compression, visually lossless, used in several standards (ie. SMIA, MIPI, etc.). Used for interface bandwidth reduction (ie. 10bit->8bit->10bit). It is used on RAW data – mostly in CMOS camera phones, but, variants can be found also in high-end cameras (ie. PhaseOne digital backs).

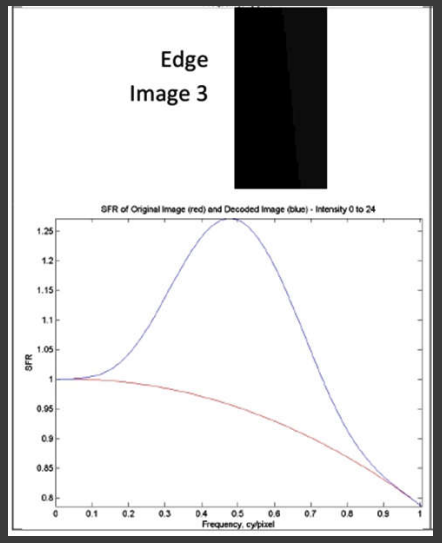


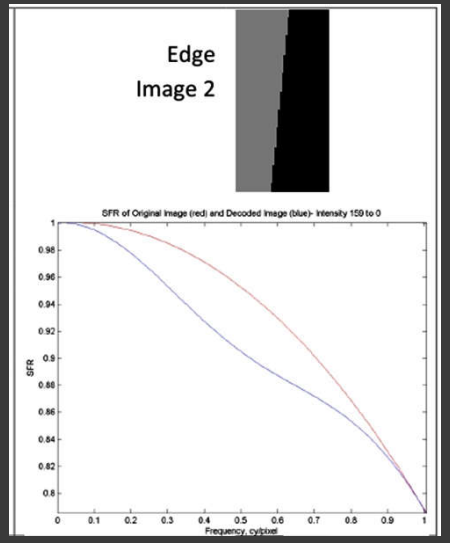
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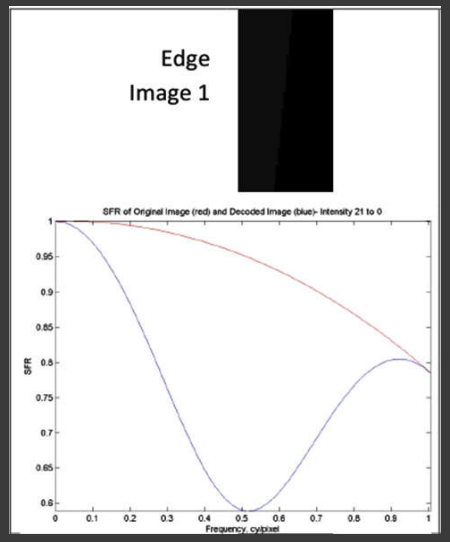
How misleading is ‘visually lossless’ for data processing ?

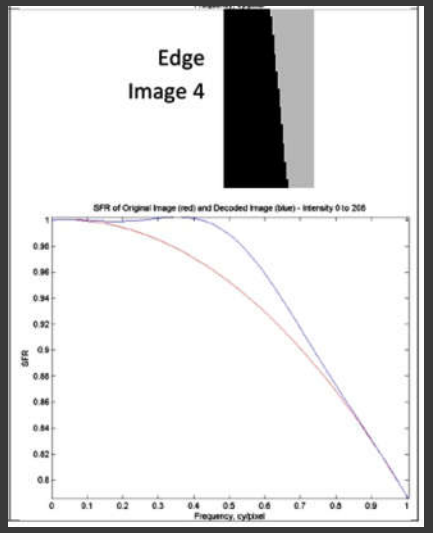










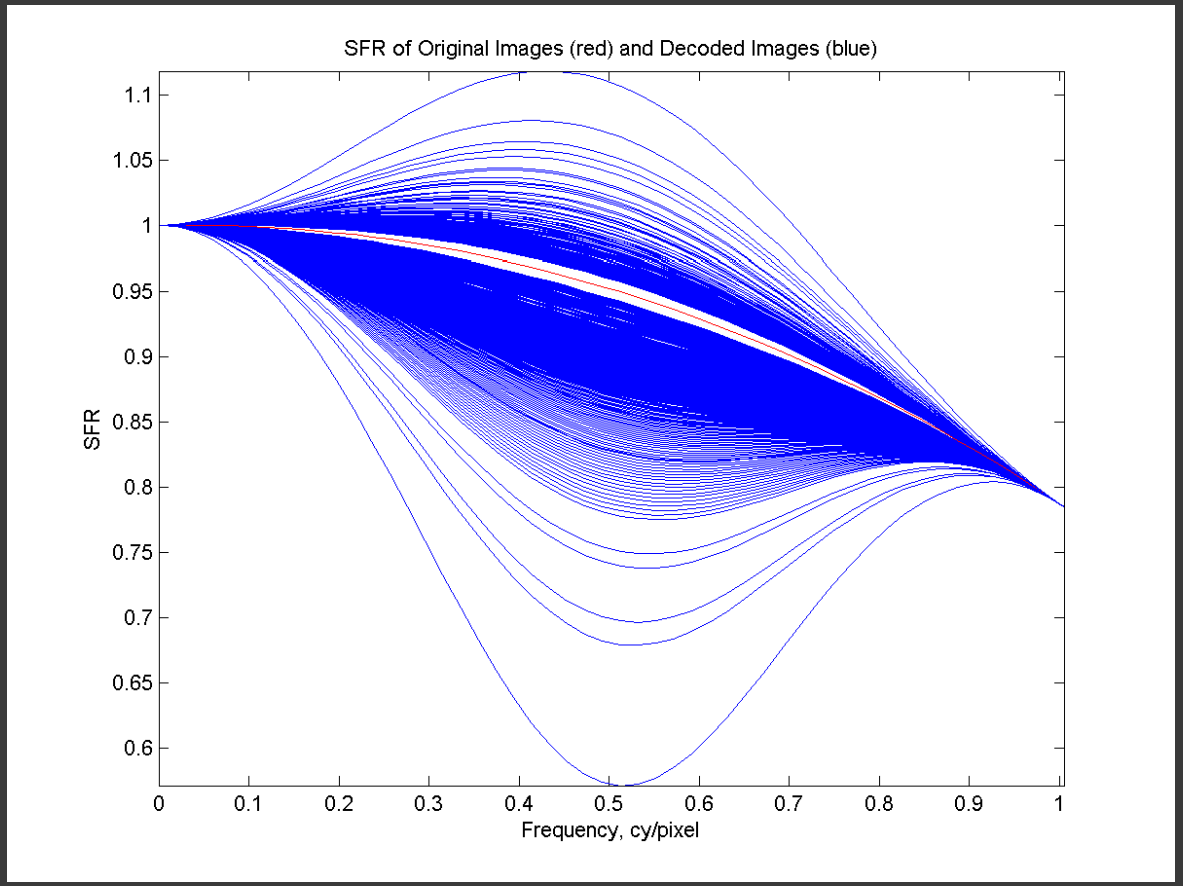


Comparison of the MTF responses for the slanted edges for different pixel value transitions. Notice that the MTF response is degraded as a function of level by the DPCM scheme

2011 S.Goma et all - ‘RAW camera DPCM compression performance analysis’

New Metrics – MTF integrity

To quantify the effects of algorithms that are affecting edges, new metrics are evolving: Modulation Transfer Integrity plot.

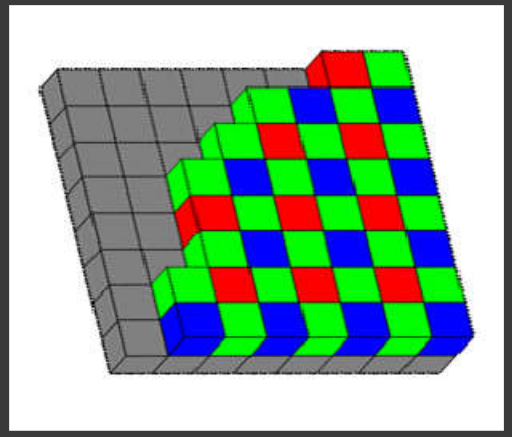


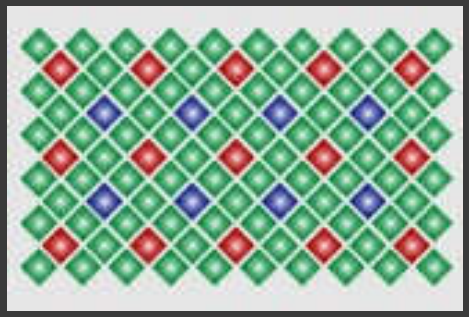
S.Goma et all - 'RAW camera DPCM compression performance analysis'

Color Filters

Filter types:

- RGGB (Bayer)
- RGBW (Panchromatic)
- RGBE (Sony-Emerald)
- CYMg
- Exotic types:
  - 3D stack (Foveon/Fujifilm)
  - Hexcomb (Fujifilm/Sony)
  - Metal gratings (Stanford)

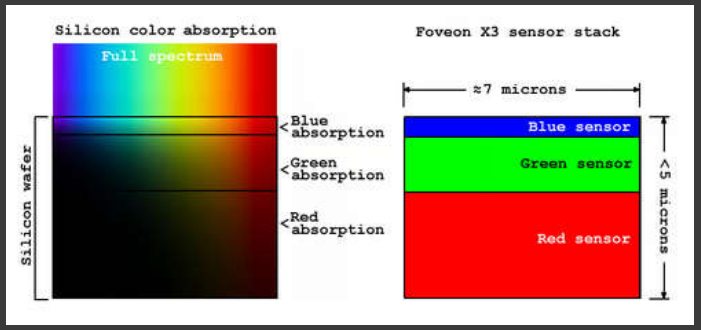


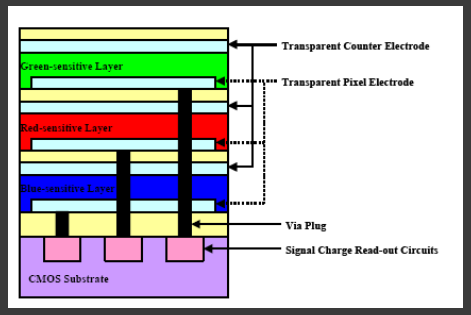


Color overlap:

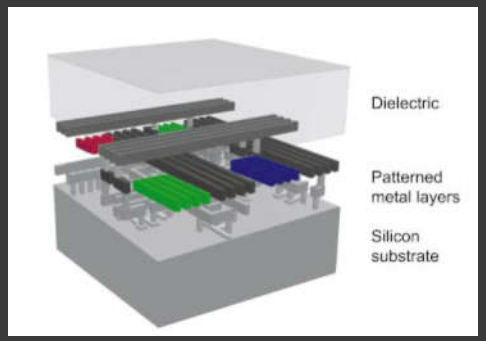
- Low color overlap -> ambiguous color, bad SNR
- High color overlap -> bad color, good SNR

IR/NIR – (N)IR is not useful for good color reproduction

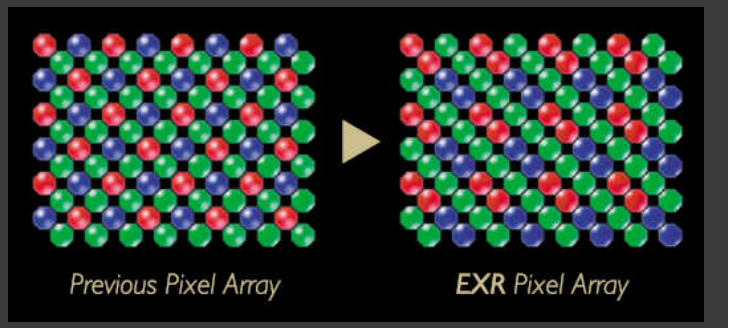




[14]fujifilm

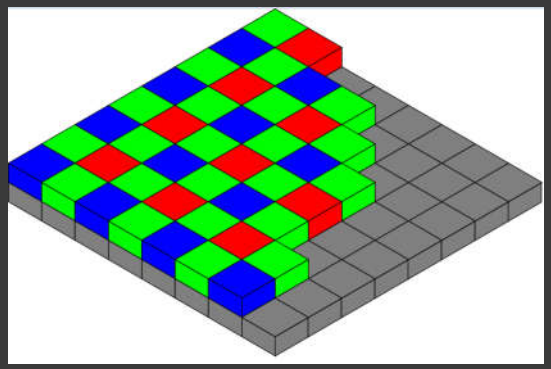


[9]Stanford

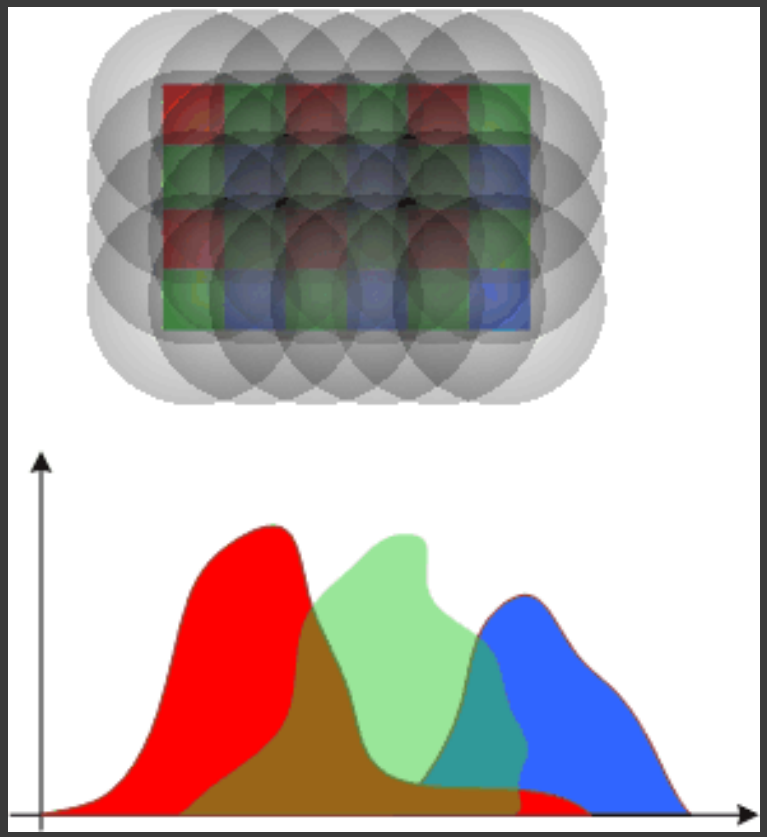


[8]FUJIC

Bayer pattern demosaic



Bayer filter mosaic (1976)



The spatial sampling is contaminated by adjacent pixels (optical cross-talk, electric cross-talk, PSF of the lens, etc)

Bayer Demosaic evaluation

What can go wrong? As an example, well known AHD applied to lighthouse produces clean results…

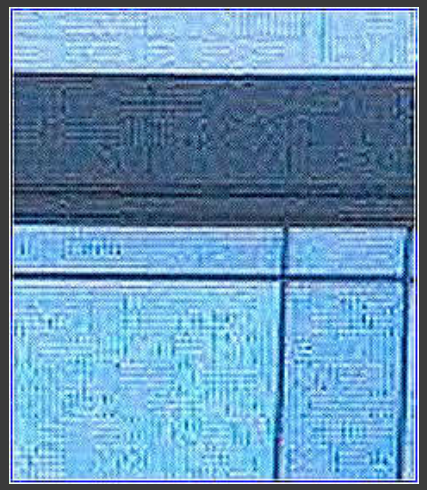




Bayer Demosaic evaluation - noisy

Noise presence





Bayer pattern demosaic fallacies

Common evaluation of demosaic algorithms:

The usual framework:

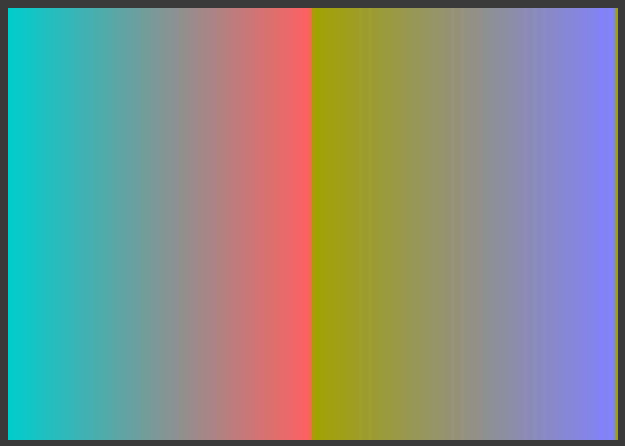
- Kodak stock photo -> subsample -> apply demosaic -> PSNR with original

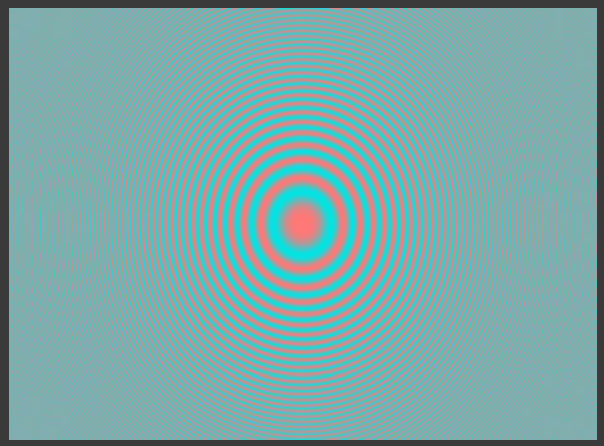
Assumptions usually not valid for a real camera:

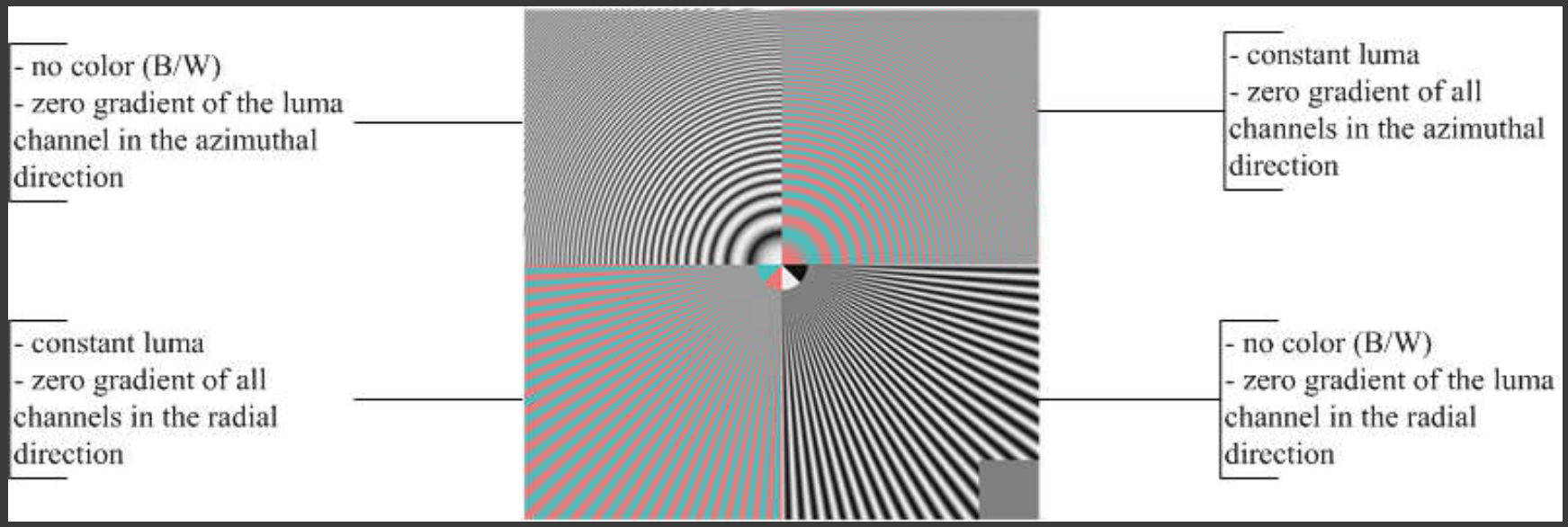
- Input image is white balanced – it is not
- Input image has low color crosstalk – it doesn't
- Input image has no noise – it has

Demosaic evaluation

Equiluma patterns







2010 S. Goma, K.Atanassov "Evaluation Methodology for Bayer Demosaic Algorithms in Camera Phones"

Demosaic evaluation - chart

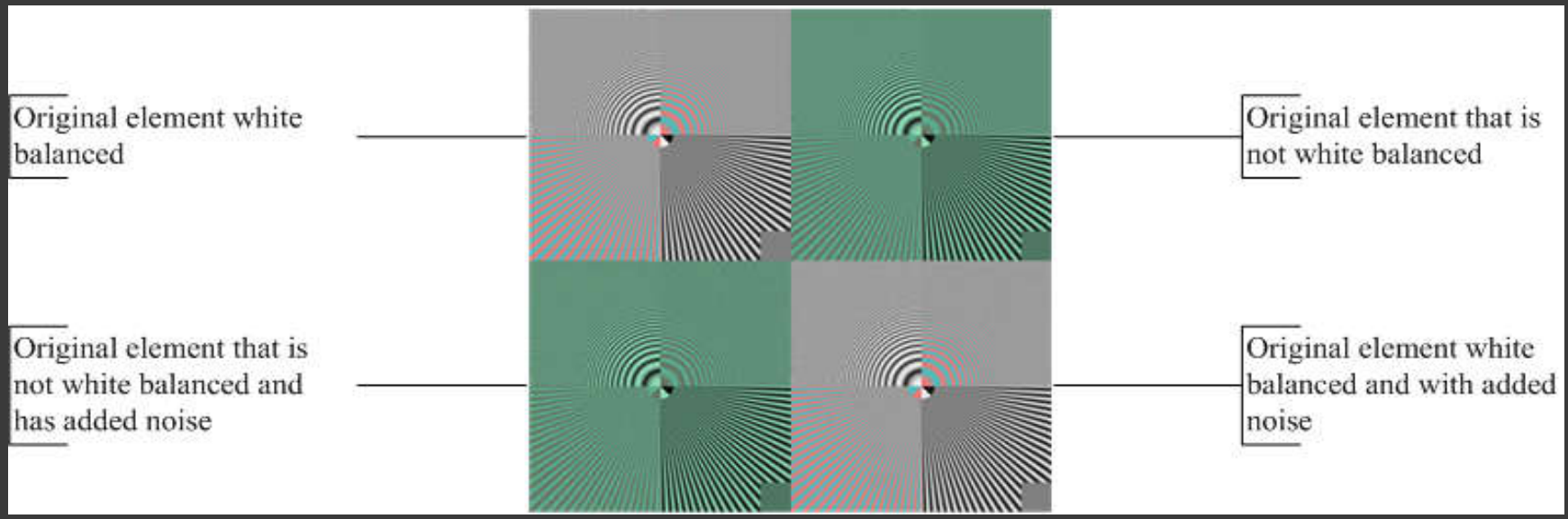
Demosaic algorithm checks:

- High Frequency restoration

-Artifacts

-Noise robustness

-White balance robustness

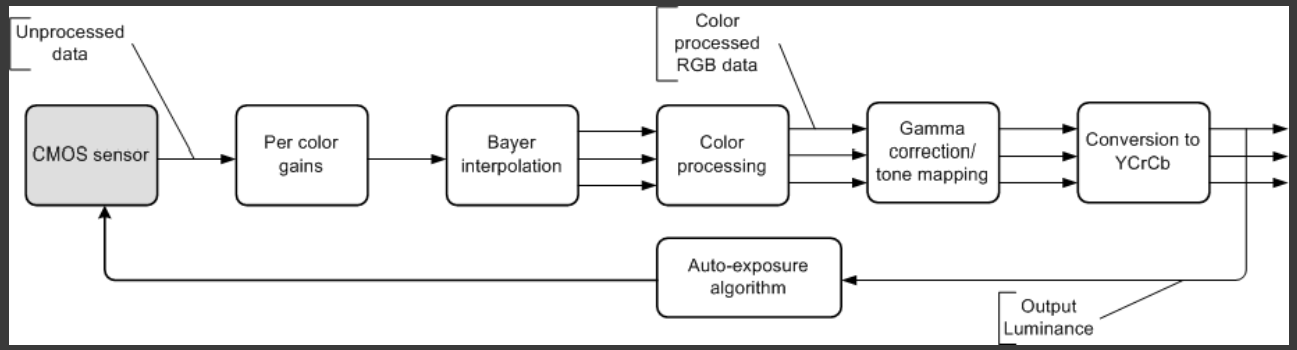


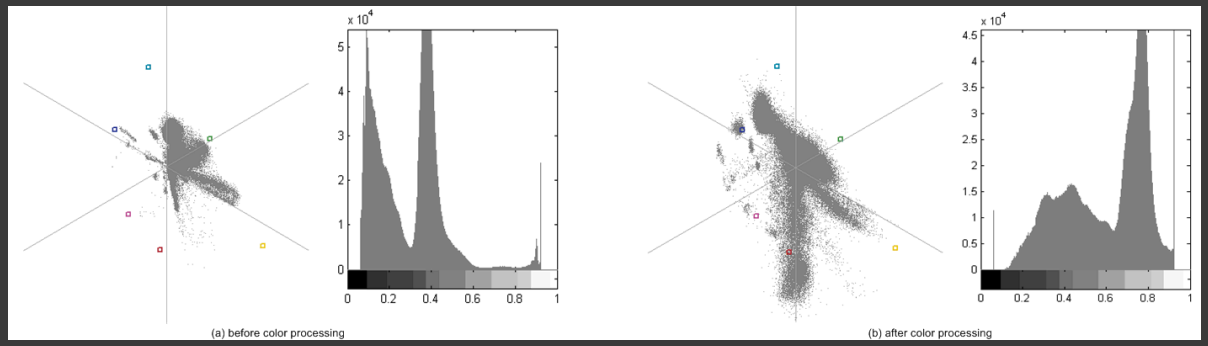
2010 S. Goma, K.Atanassov "Evaluation Methodology for Bayer Demosaic Algorithms in Camera Phones"

Color processing and noise

System level perspectives:

- color correction is applied before luminance is calculated
- exposure adjustment is done based on resultant luminance

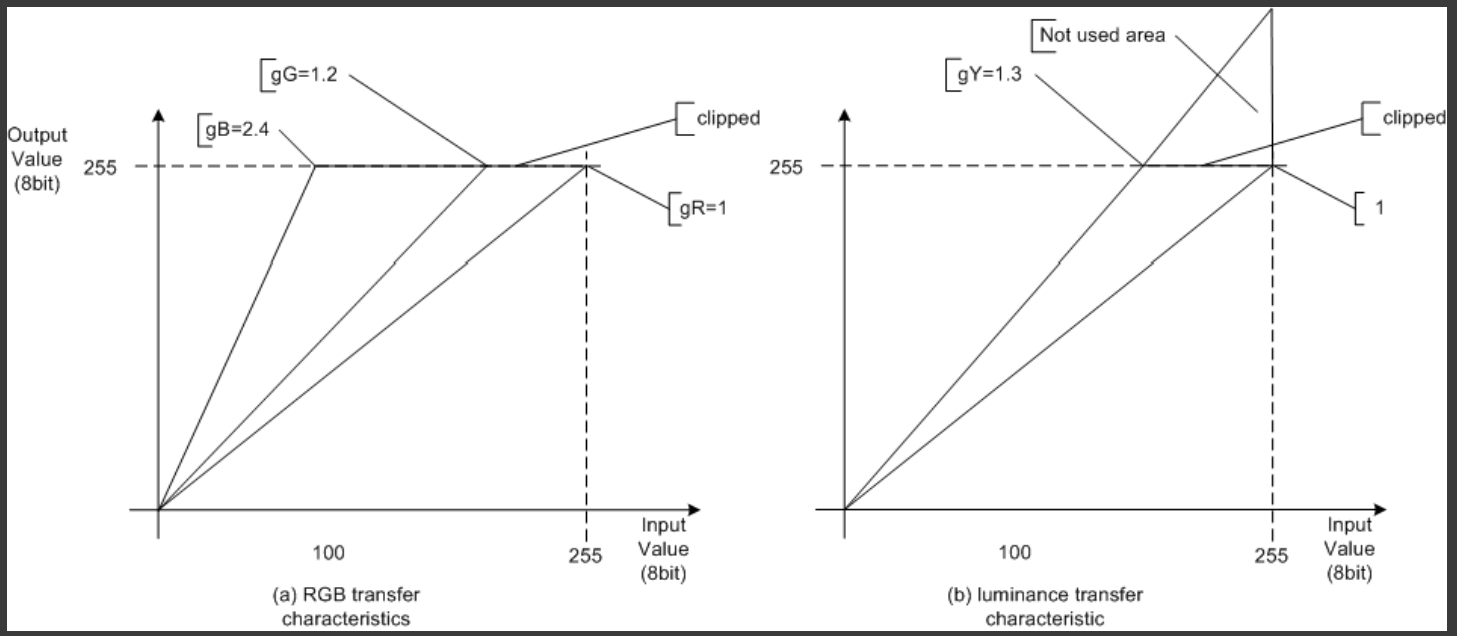




Goma S., Aleksic M., "Improving the SNR during color image processing while preserving the appearance of clipped pixels"

Color processing and noise

Implication: Linear color processing with above unity gains degrades sensor signal.



$$\begin{vmatrix} g_{RR} & g_{RG} & g_{RB} \\ g_{GR} & g_{GG} & g_{GB} \\ g_{BR} & g_{BG} & g_{BB} \end{vmatrix} = \begin{vmatrix} ag_R & 0 & 0 \\ 0 & ag_G & 0 \\ 0 & 0 & ag_B \end{vmatrix} \cdot \begin{vmatrix} cc_{RR} & cc_{RG} & cc_{RB} \\ cc_{GR} & cc_{GG} & cc_{GB} \\ cc_{BR} & cc_{BG} & cc_{BB} \end{vmatrix} \cdot \begin{vmatrix} pg_R & 0 & 0 \\ 0 & pg_G & 0 \\ 0 & 0 & pg_B \end{vmatrix}$$

$$Sdev_R = \sqrt{g_{RR}^2 + g_{RG}^2 + g_{RB}^2} \cdot \sqrt{3} \cdot Sdev_{sensor}$$

Extended Depth of Field (EDOF) promises

WWW Quotes:

"EDoF stands for **Extended Depth of Field** and is a new idea, borne of the digital age. Rather than having a bulky and expensive auto-focus mechanism, the idea is that a cheaper fixed focus camera can be dramatically improved by using a custom lens which has been designed to focus the different colour components of light differently"**

"…allows further miniaturization of camera-phones by embedding functions such as the EDoF processor used to maximize the camera's depth of field. This saves designers implementing auto-focusing capability and also keeps the cost and mechanical size in line with standard Fixed-Focus modules."**

(**) http://www.allaboutsymbian.com/features/item/Camera_Nitty_Gritty_Supplemental-EDoF.php

EDOF - evaluation

The problem: No evaluation method for EDOF…

Measurements:

-MTF at different distances

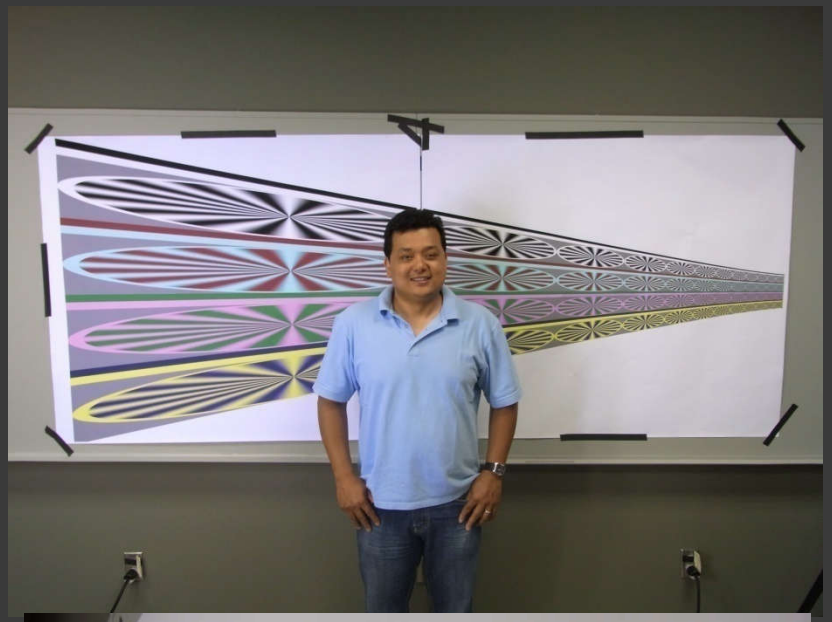
-Noise

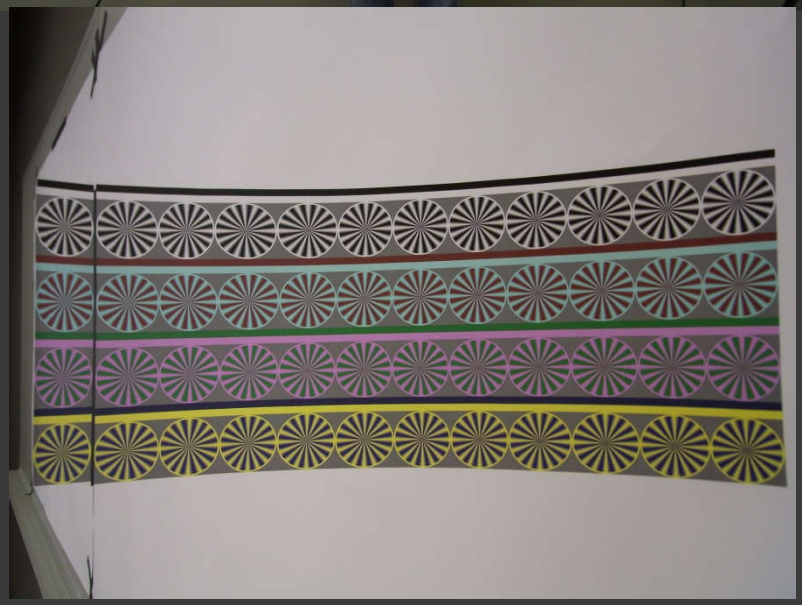
-Artifacts

-Color noise

Chart: perspective corrected, titled from close-up to 3m.

Features: siemens stars B/W and complementary colors plus bright/dark stripes for DC.

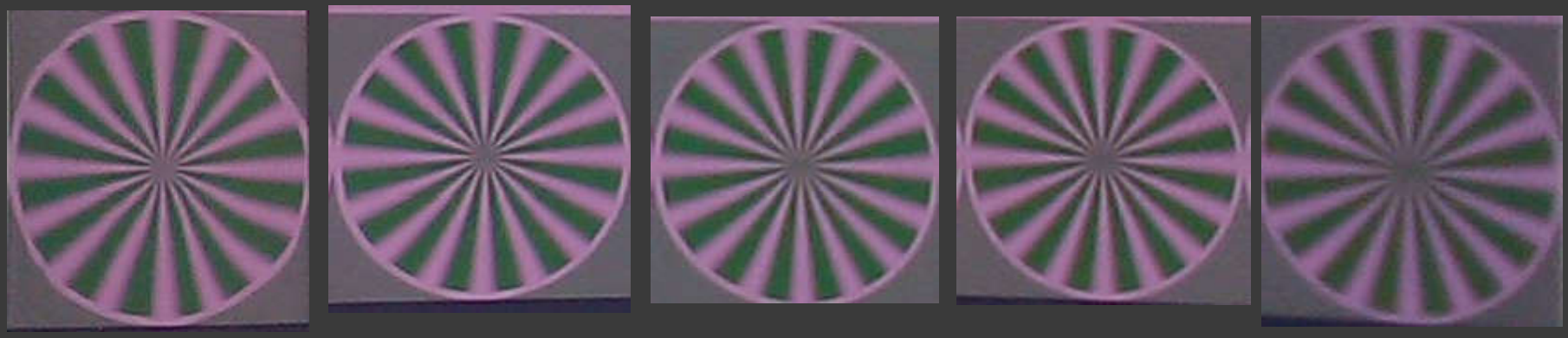




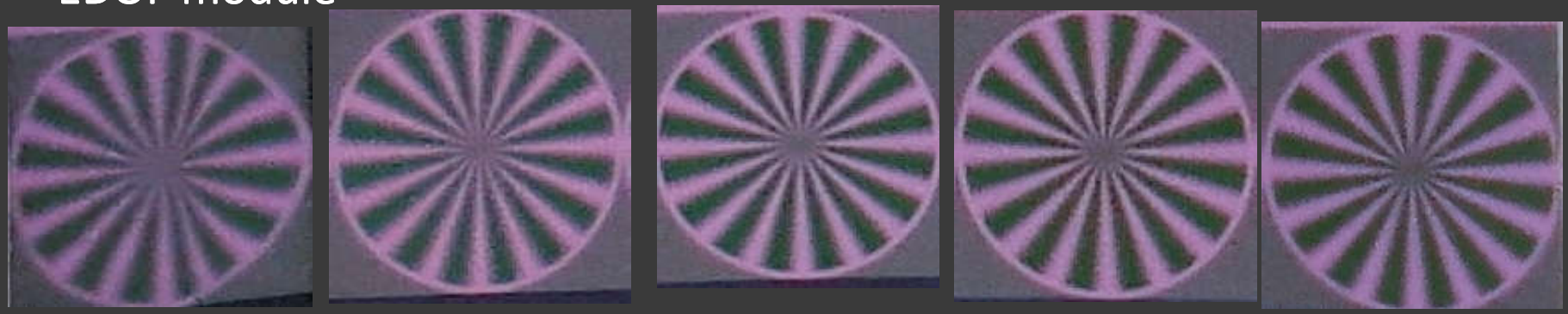
EDOF – evaluation example

5 distances sampled from close to far

AF module – fixed focus in the middle of chart



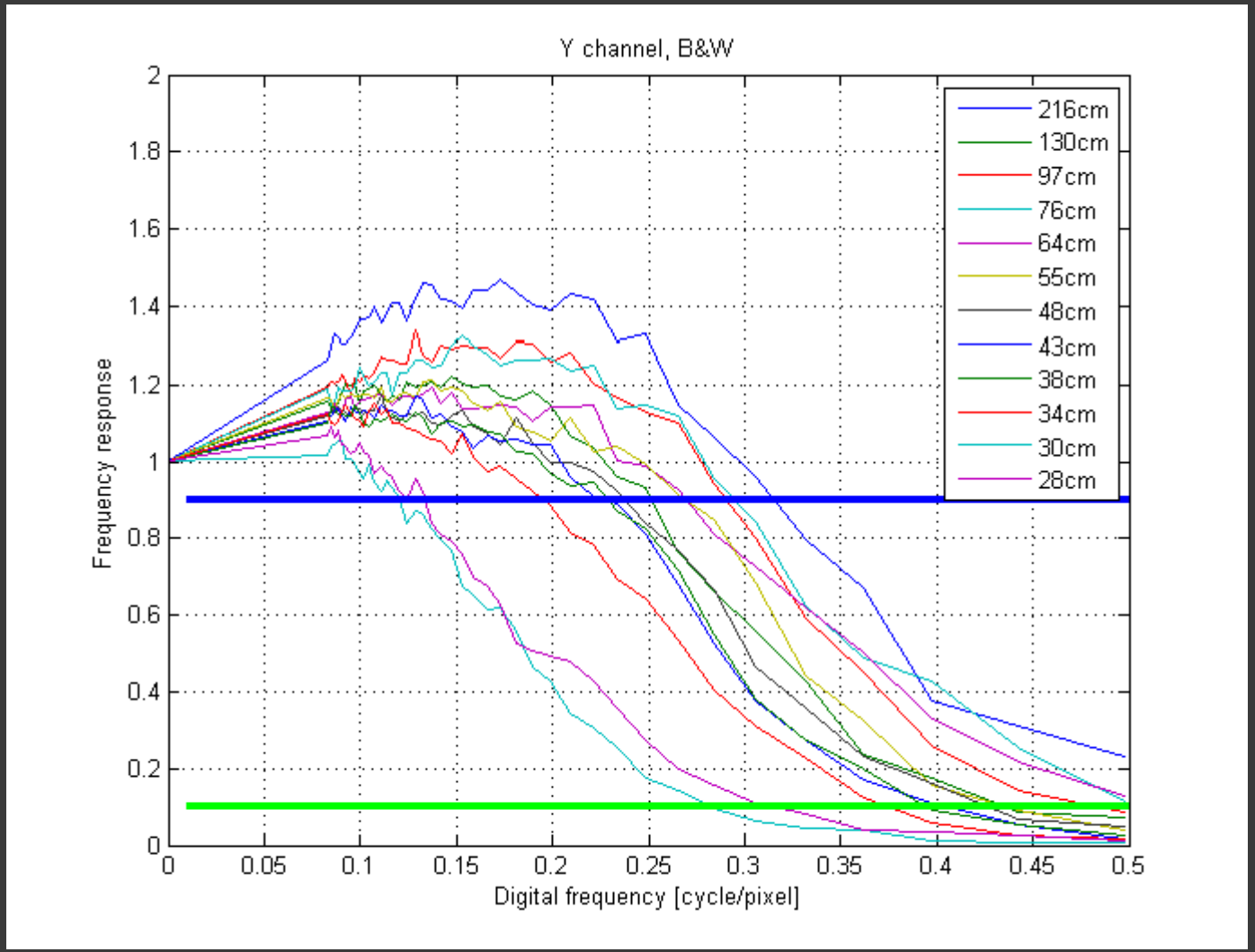
EDOF module



2010 K.Atanassov S. Goma, "Evaluating the quality of EDOF in camera phones"

EDOF – MTF curves

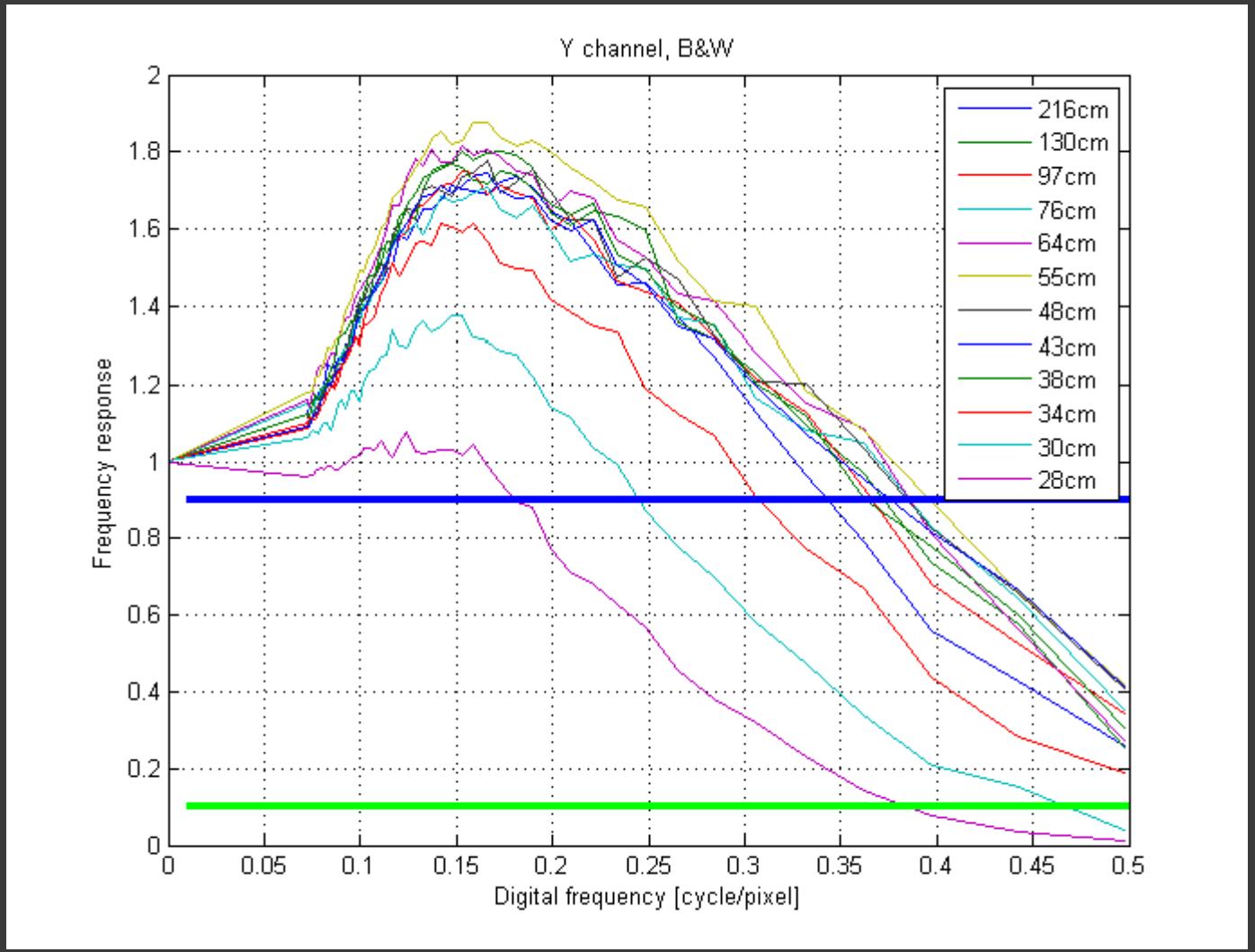
EDOF module transfer function drop-off (Y channel , B&W)



2010 K.Atanassov S. Goma, "Evaluating the quality of EDOF in camera phones"

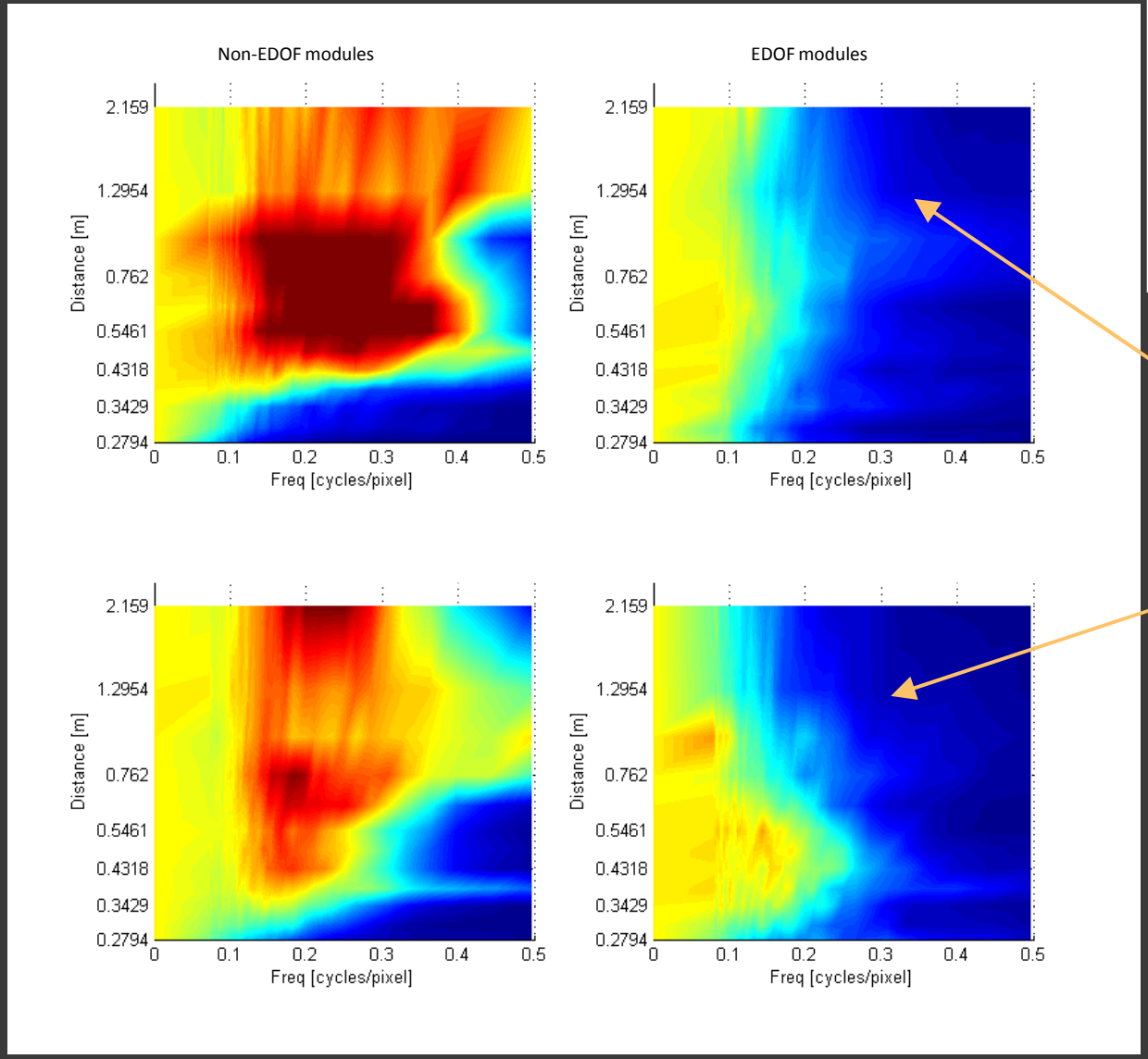
EDOF – MTF curves

AF module – fixed focus transfer function drop-off (Y channel , B&W)



2010 K.Atanassov S. Goma, "Evaluating the quality of EDOF in camera phones"

EDOF – evaluation example



1 is mapped to yellow

1.6 is mapped to dark orange

0 is mapped to blue

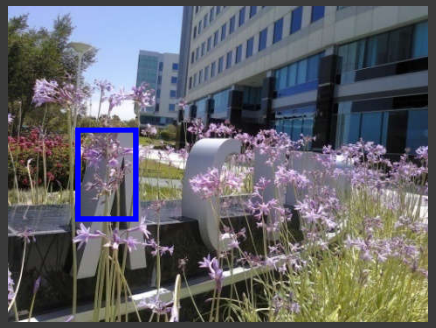
Warmer color == higher frequency response

High frequencies lost due to absence of green

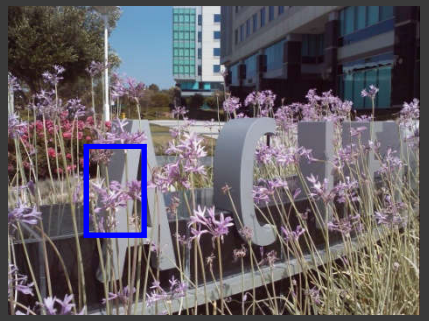
Frequency response is dependent on the presence of certain colors

EDOF vs fixed focus - 1

EDOF



Fixed focus

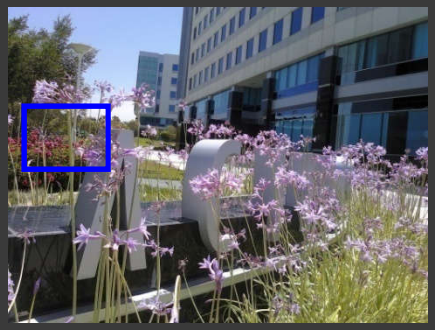






EDOF vs fixed focus - 2

EDOF



Fixed focus

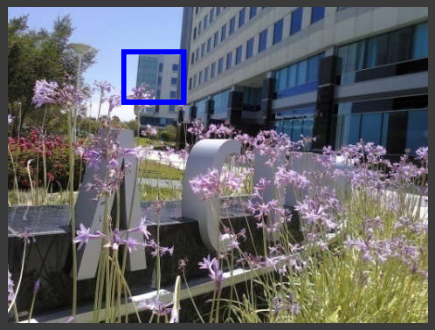






EDOF vs fixed focus - 3

EDOF



Fixed focus







Sharpening vs resolution

‘*Is … a EDOF camera that bad?*‘. It’s difficult to answer that question. It depend on what do you want from a camera in your smartphone. *



Reduced resolution and sharpened

original

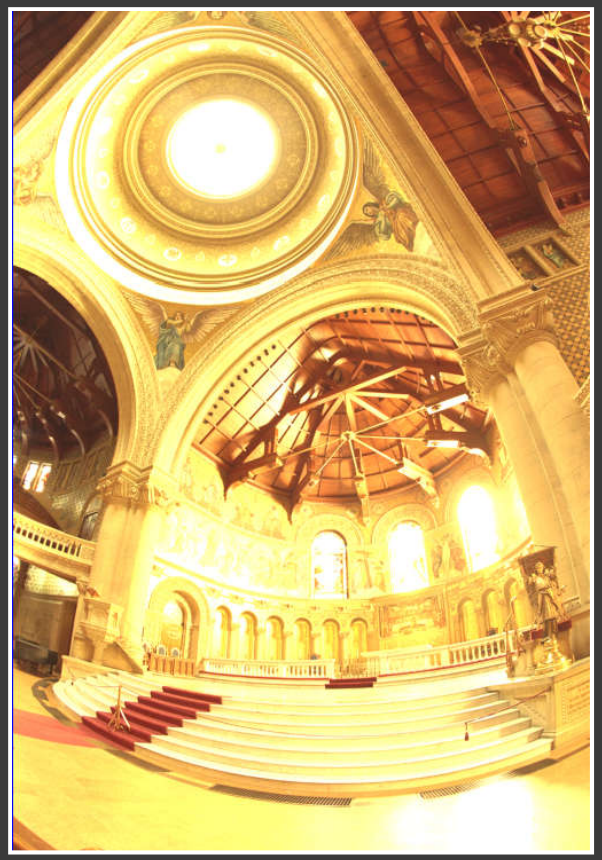
Pic- www.i3a.org/wp-content/uploads/2008/03/cpiq_white_paper.pdf

(*) http://mobilegeekinc.com/2010/10/06/ultimate-camera-smackdown-is-e5s-edof-camera-that-bad/

HDR

High Dynamic Range (HDR)

highlights saturated



30 sec (ISO 100)

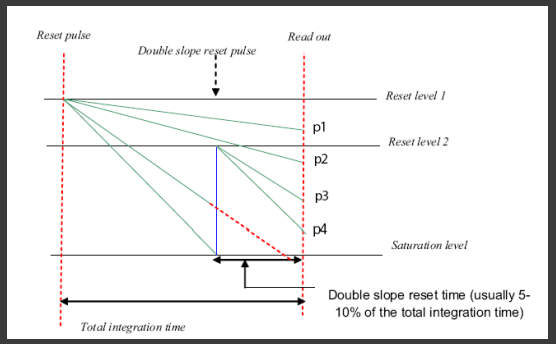
poor shadow detail

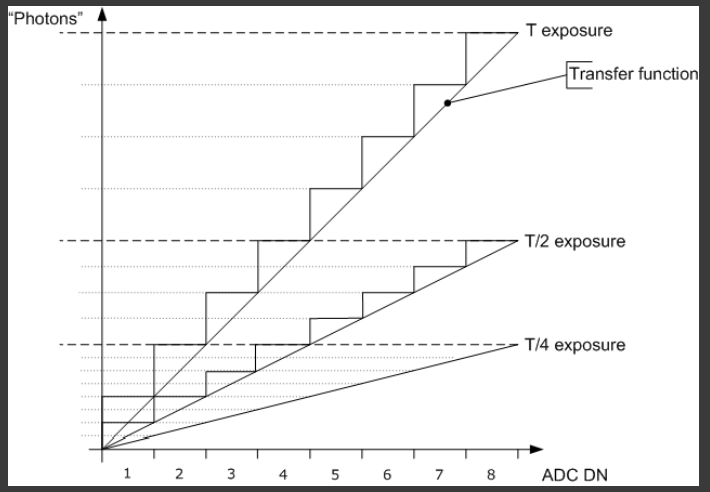


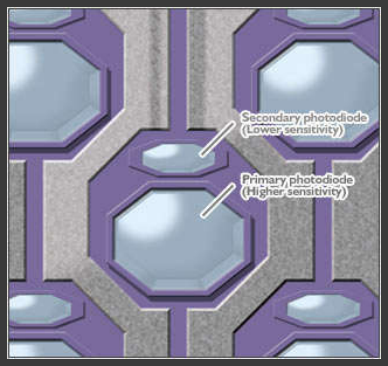
1/60 sec (ISO 100)

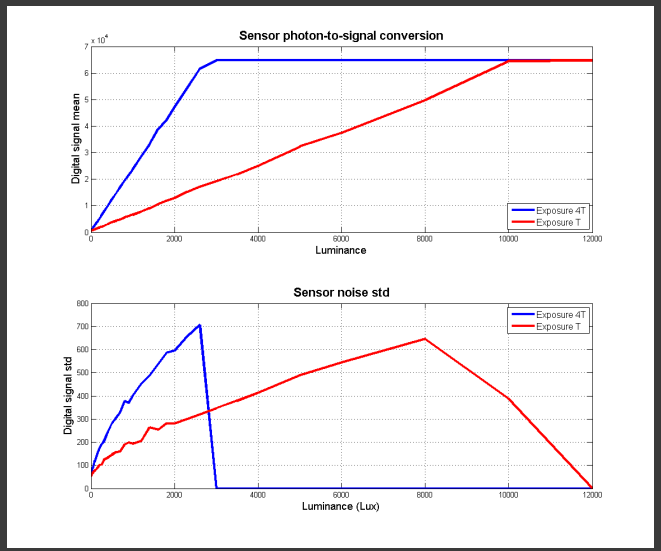
HDR – multiple exposures

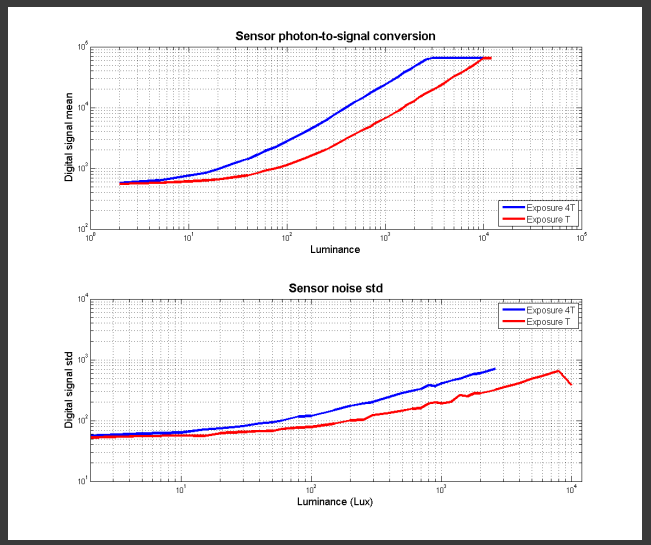
What is claimed: through multiple exposures (or equivalent) the dynamic range of a captured image is increased.





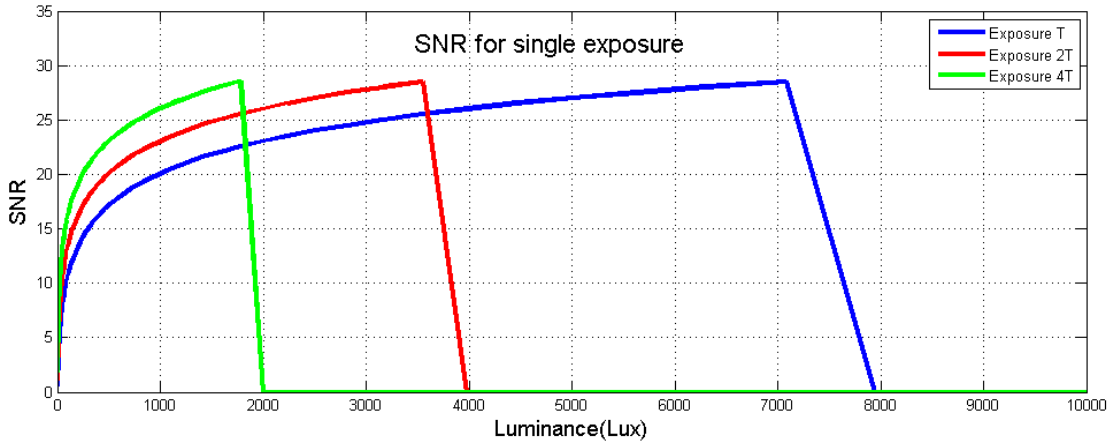


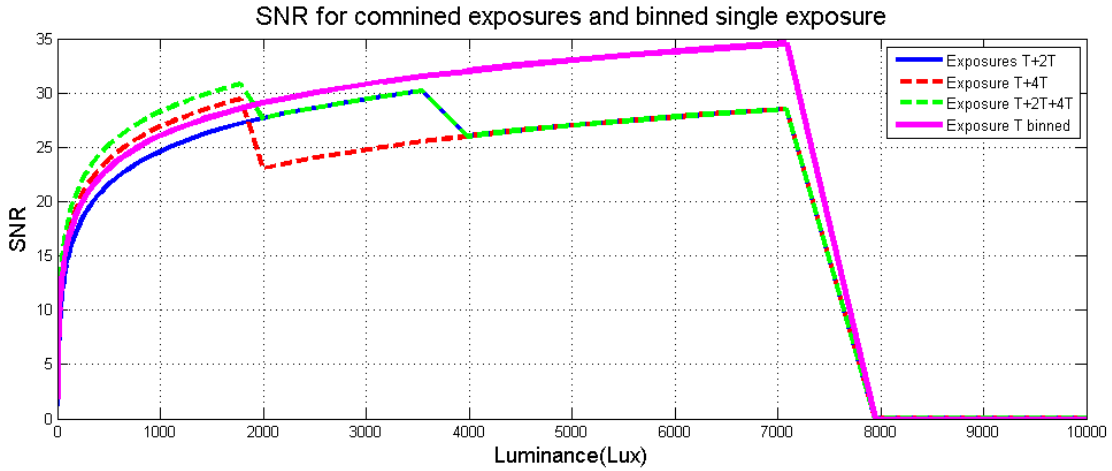




HDR – combining exposures

Combined exposure compared with a pixel 4x times larger





HDR algorithms – claims analysis

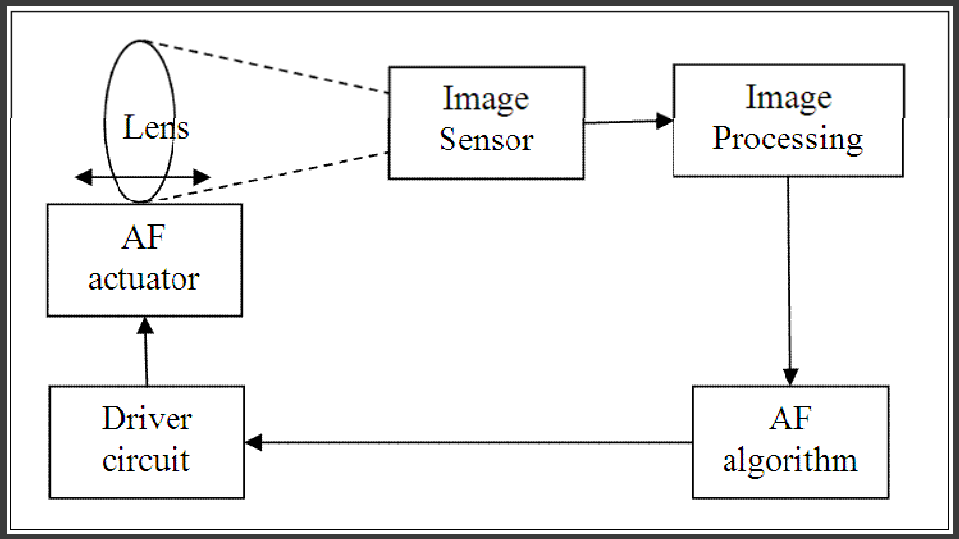
Dynamic range is not expressed appropriately through a ratio – it needs a curve (ie. dynamic range vs signal).

The standard HDR methods would really increase dynamic range if density of intensity sampling would be uniform.

The incorrectly understood claim of HDR is an increased number of bits. The true achievement of the HDR methods is effectively a nonuniform sampling of the range.

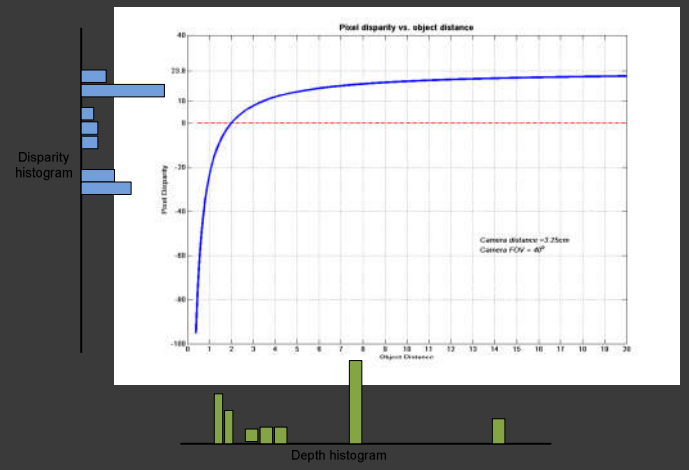
Innovative thinking example: Auto-Focus

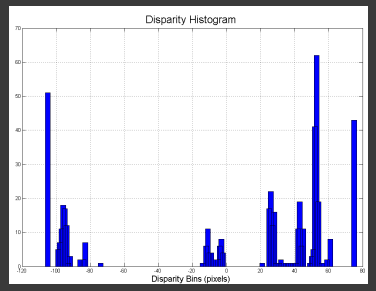
Commonly auto-focus algorithms used in cameras are closed-loop, requiring several iterations to converge. What would it take to make it open-loop?



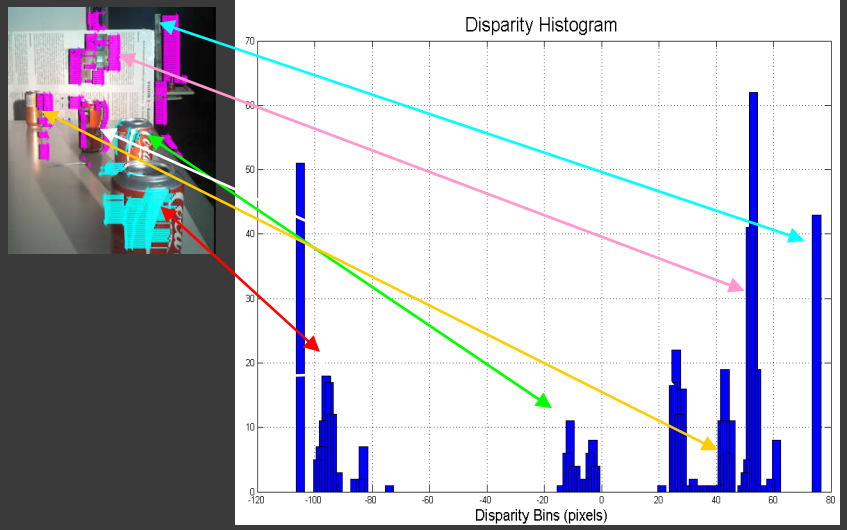
Innovative thinking example: Auto-Focus

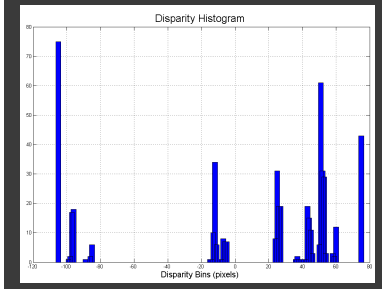
Use a calibrated stereo-camera module –> infer depth from disparity













Conclusions – use cases

- Bad pixel beware: there's a thin line between bad pixel and noise reduction, but they are not interchangeable.

- Lens roll-off beware: after this block, noise is anisotropic.

- Demosaic beware: input data is not white-balanced, noisy and colors are correlated.

- Color correction/Gamma beware: low color saturation means high color crosstalk – the noise increase tradeoff might not justify it. White balance is not a replacement for illuminat correction

- Tone mapping beware: after this block, transfer characteristic is nonlinear and content dependant.

- Auto Exposure beware: backlight situations require 'HDR' treatment

Conclusions – camera system

Beware of system level perspective and always consider error propagation.

Beware of techniques that appear to increase the amount of information in the image or claim visually lossless interference:

- check MTF integrity if edge processing is suspected (ie. DPCM compression).
- check 3D MTF if EDOF is claimed.
- check SNR over the whole output range if HDR is claimed.

Beware of 'RAW' data! Unless you know what's happening in the camera, RAW is not RAW – this cuts off most commercial cameras.

Canon quote (***EOS-1D Mark III***):'Even when high-speed noise reduction is turned "off," varying amounts of noise reduction are still applied to all images, even RAW images.'

http://www.usa.canon.com/dlc/controller?act=GetArticleAct&articleID=1886

Q&A

System level – computing for image processing

Image processing is one of the most taxing activities in computing resources.

Available computational blocks:

-Dedicated hardware - fastest 1x size/power

-Programmable architectures - >2.5x size/power

-Homogenous computing: - >10x size/power

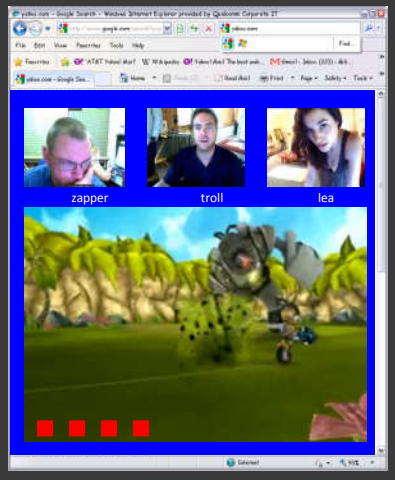
- Multi-core CPU
- Multi-core GPU
- Multi-core DSP

Due to complexity of algorithms, implementation is critical in achieving performance.

System level - OpenCL platform

Standard for general-purpose parallel programming of heterogeneous systems.

- Video conferenced game example



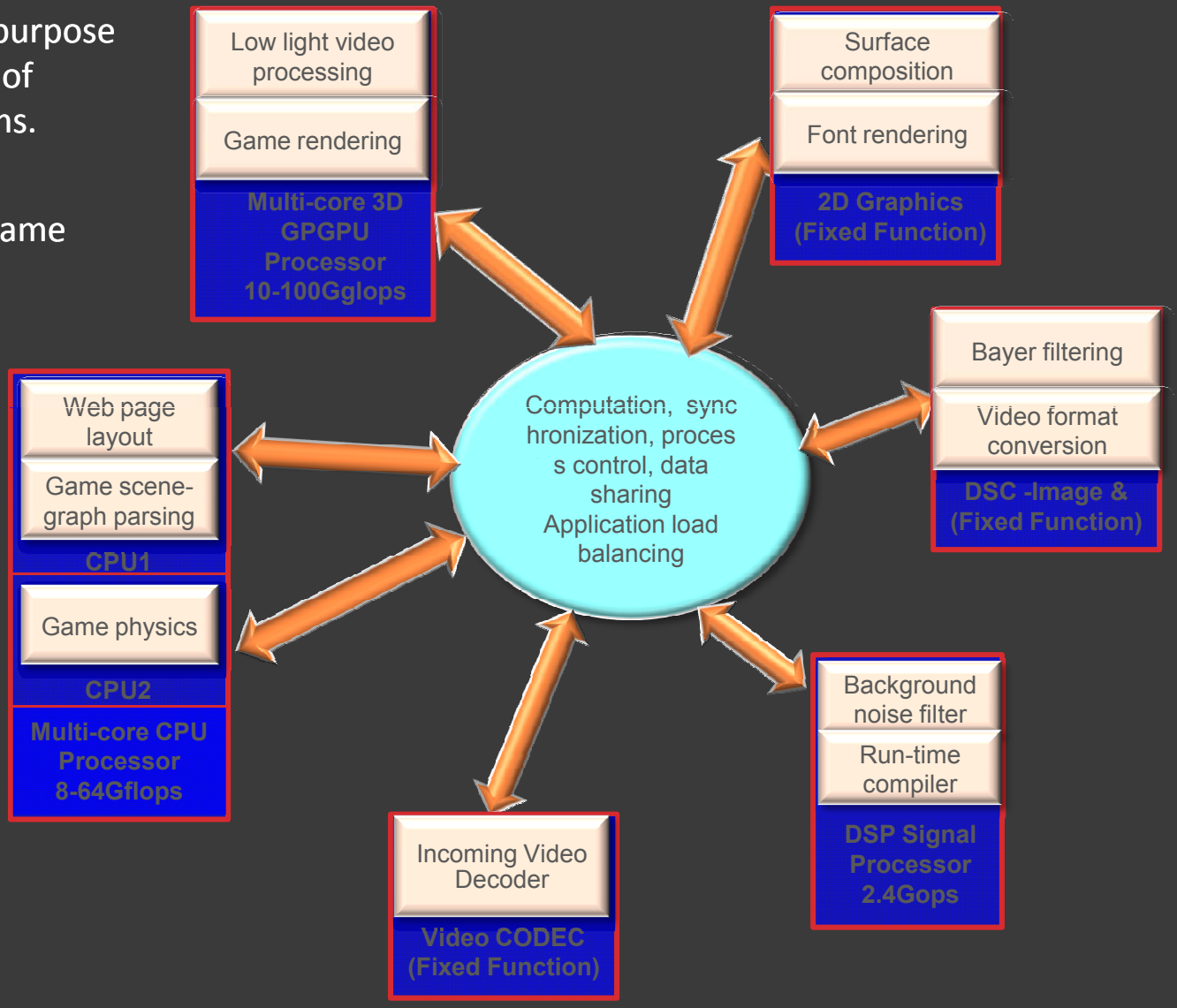
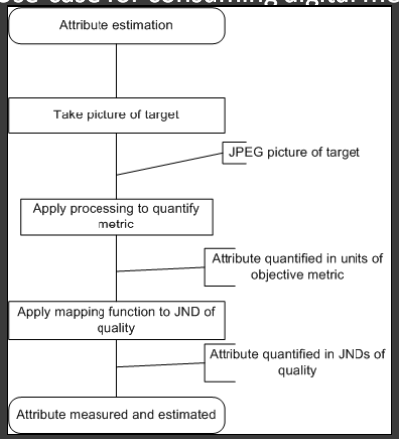
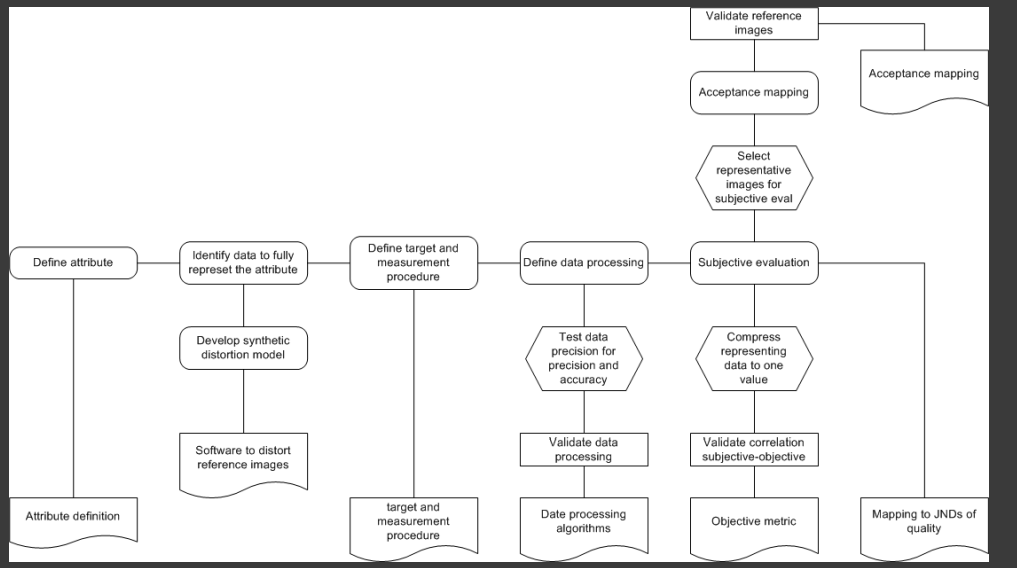
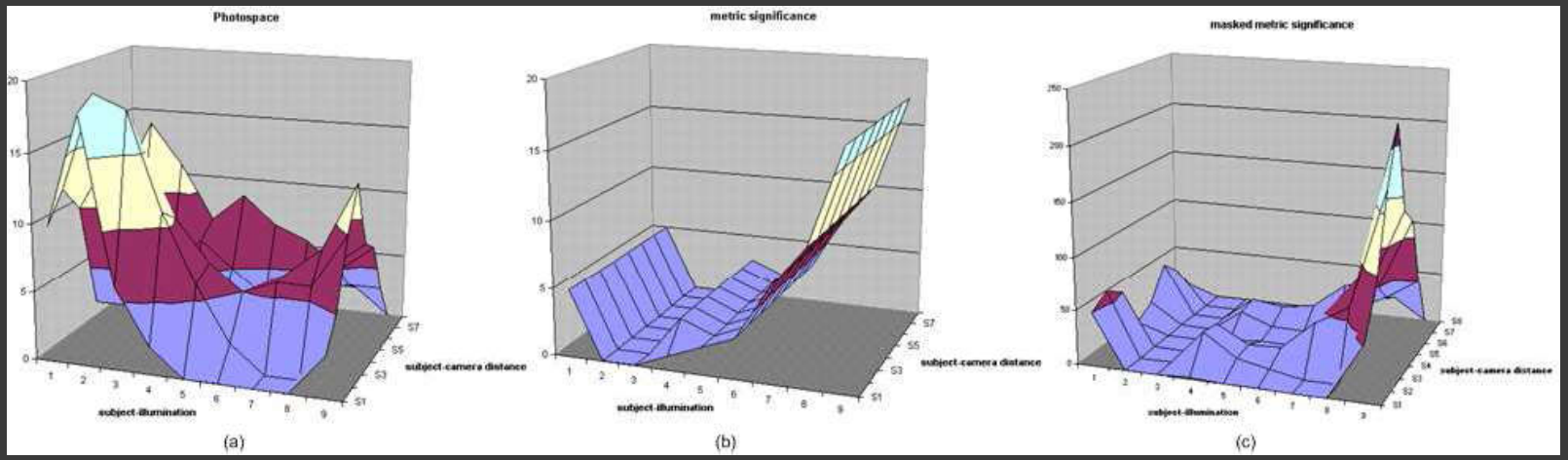


Image Quality – Science, standards and industry practice

ISO standardization for DSC
Nokia benchmark competition
SMIA standard for Nokia modules (open)-> SMIA++(proprietary)
CPIQ investigation-> ISO standardization
JNDs of Quality and Photospace
Use-case for consuming digital media: is it stable?







Noise

Any processing increases noise (error propagation) – instead of reducing the noise of the source, can we try to reduce the introduced noise?

PTC – Photon Transfer Curve

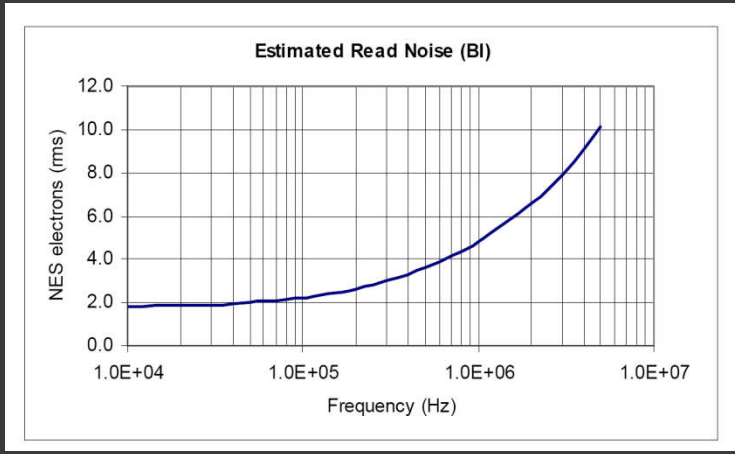
Noise processing – critical requirement for CMOS -> frame based processing

Binning: CCD vs CMOS

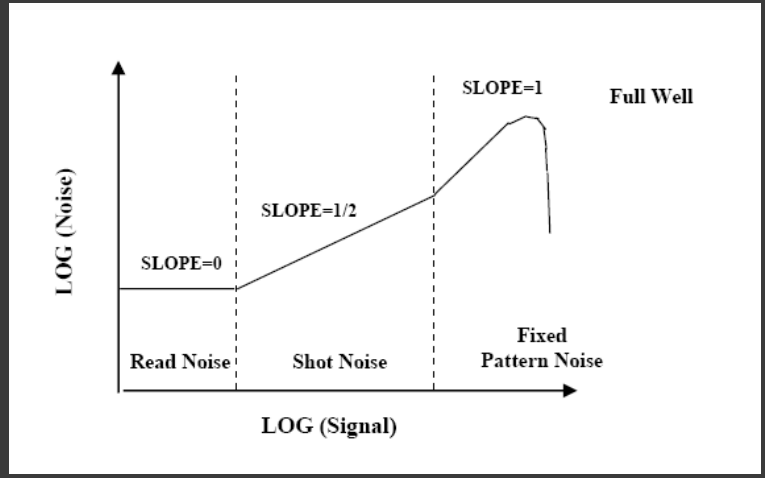
- In CCD binning is cell charge summation in 2D
- In CMOS binning is horizontal analog summing and vertical digital summing



www.dpreview.com



[7]Marconi



[13]Janesick