Noise Reduction

Angelo Bosco

AST –
Advanced System Technology
Imaging Group
Catania Lab

Seminar
ST/UniCT

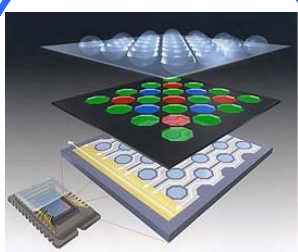
Overview

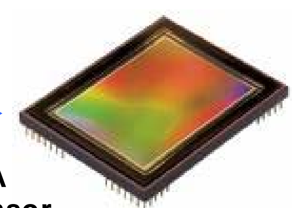
- CFA (Colour Filter Array) image sensors
- Image Noise Sources
- Luminance/Chroma Noise
- Defect Correction
- Noise Reduction

Acquisition: HW/SW Partitioning

Real Image

Lens





CFA Sensor

SW-Processing

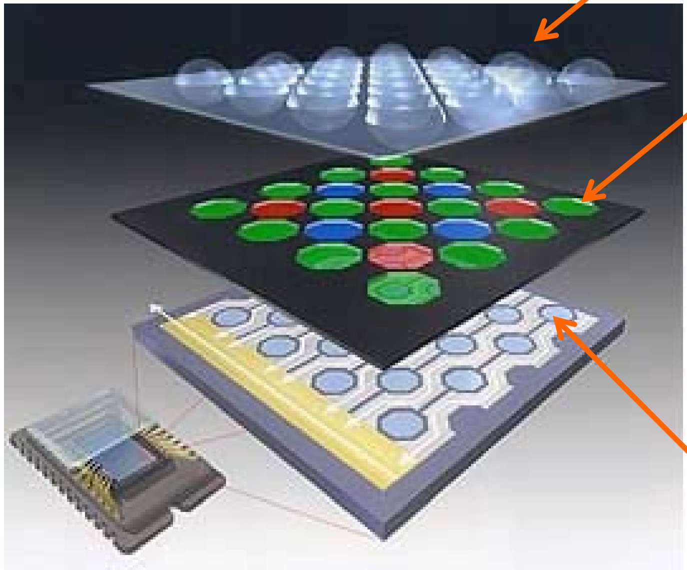
❖ The image is acquired by a sensor covered with a color filter (the CFA) that enables each photosite to capture one light color component only (either Red, Green or Blue).

❖ This sparse sampling requires interpolation to determine the missing two color components at each pixel to obtain the final color full RGB image.

SW-Processing:

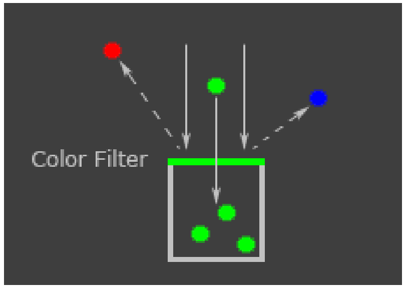
- ❖ black offset,
- ❖ histogram stretching,
- ❖ noise filtering,
- ❖ antivignetting,
- ❖ colour interpolation,
- ❖ …

CFA Image Sensor Structure



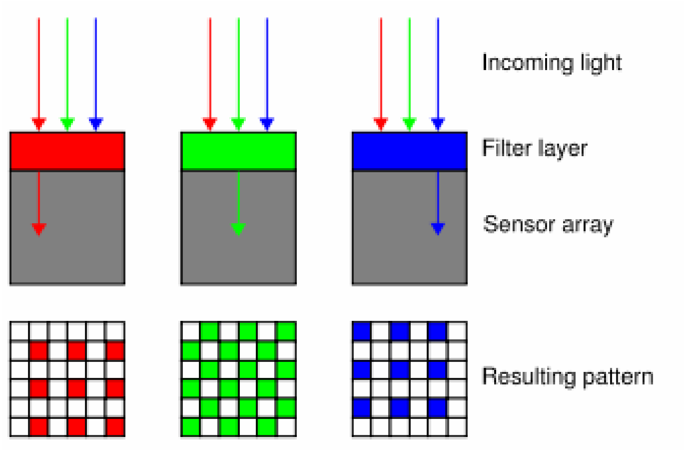
1) Microlenses focus light onto the CFA filter.

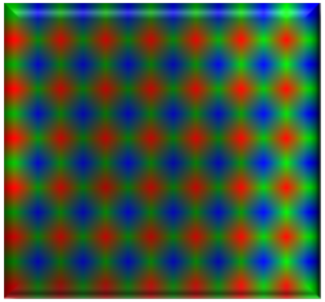
2) The CFA allows only one color component per pixel.



3) Photosites receive electrons and accumulate them. The voltages are transformed into numerical values by analog to digital converters.

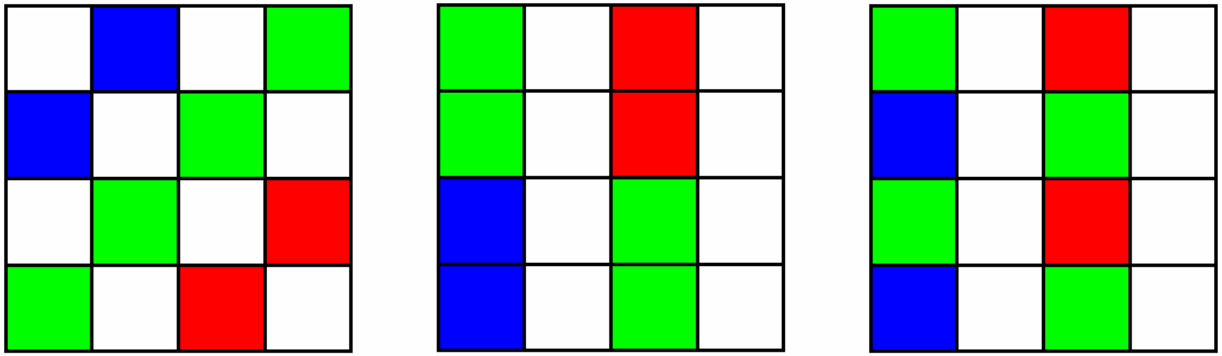
CFA Image Sensor – Bayer Format





Real Scene... ...as seen by the sensor (in false colours).

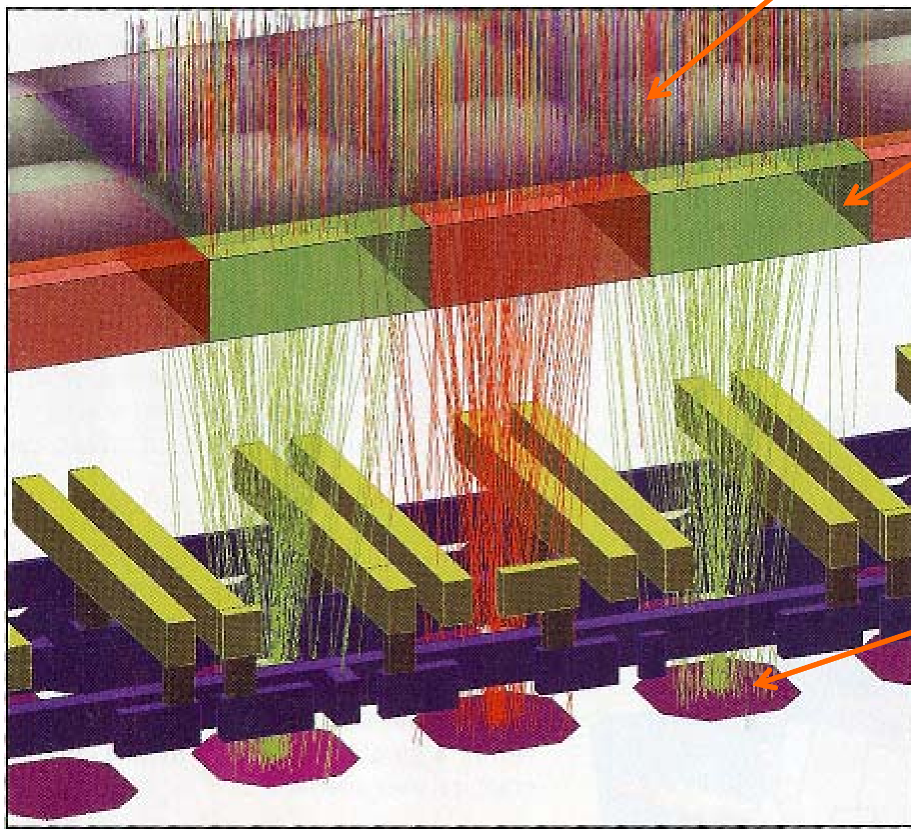
Recent Patent from Kodak



Panchromatic pixels are sensitive to all wavelengths.
Allowing higher sensitivity in low light.

Require more sophisticated algorithms, such as colour interpolation, defect correction is more complicated.

Magnified section of CFA sensor structure



Source: Photonics Journal (Nov. 2007)

1) Microlenses focus light onto the CFA filter.

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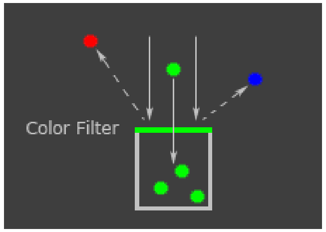
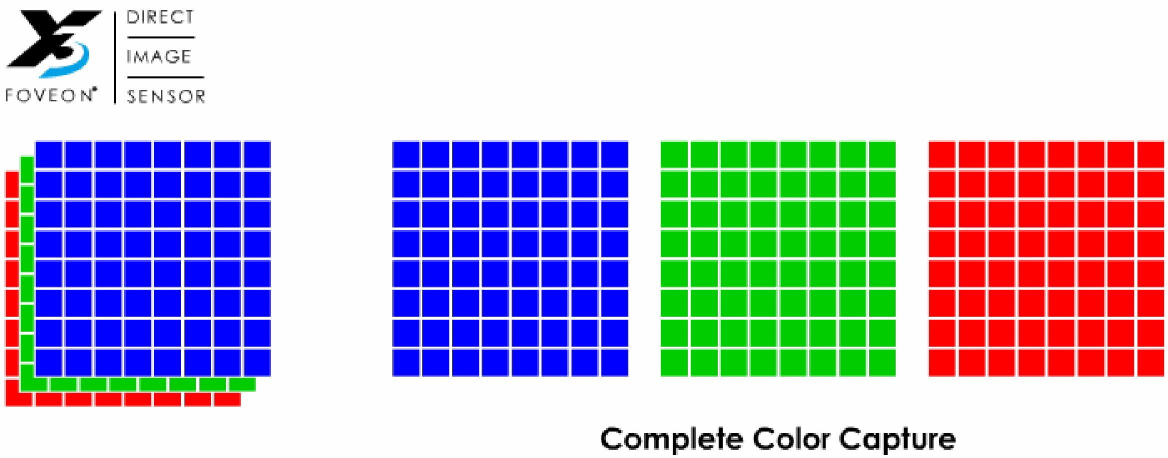
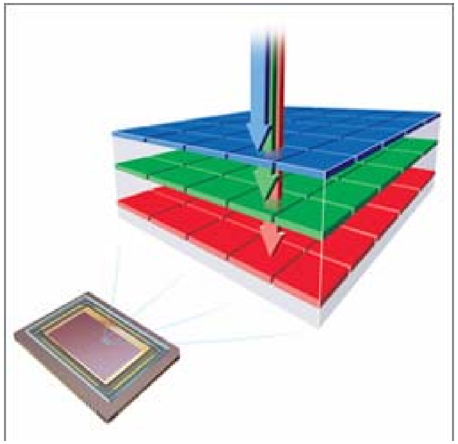


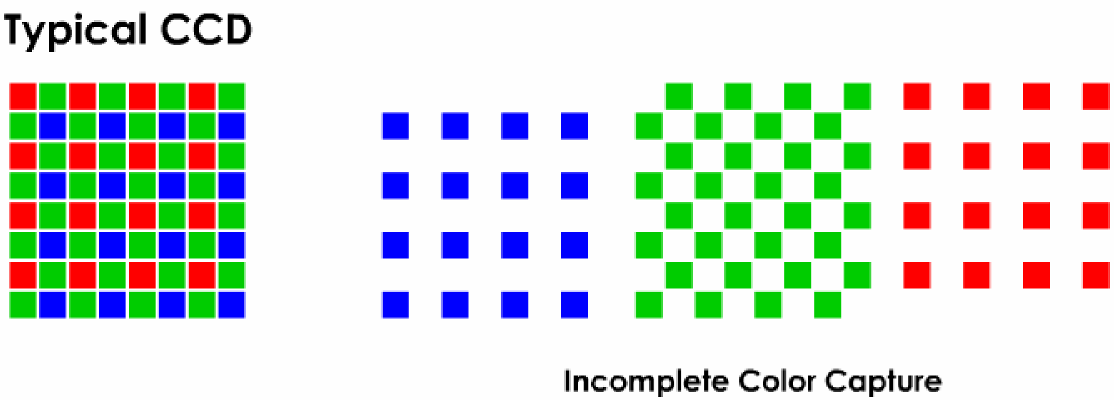
3) Photosites accumulate electrons that create voltages.
The voltages are transformed into numerical values by analog to digital converters.

4) Pixel crosstalk can be a problem. Microlenses must be well designed.

X3 sensors theoretically have better resolution

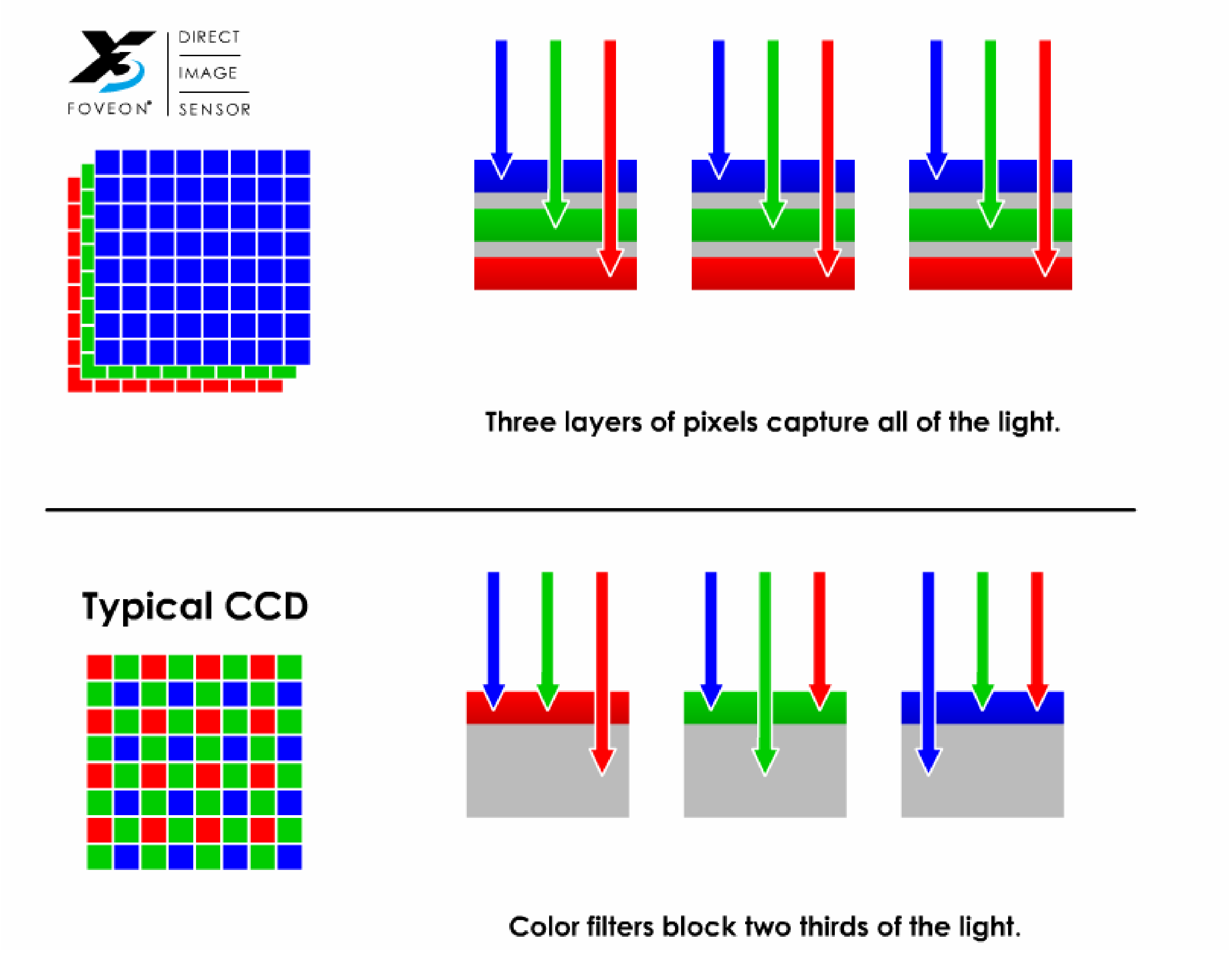






Here, colour interpolation is required to interpolate the missing colour information at each pixel. Because each pixel has only one colour available out of 3.

X3 sensors theoretically capture more light



Crosstalk between filters in X3 sensors is a problem

- Foveon sensor seems to have a very significant amount of cross talk between filters, i.e. filters for red, green and blue are not as clean as the optical color filters in a Bayer sensor.
- This is called spectral overlap, so blue bleeds into red, red bleeds into green and so on.
- To get a good output "RED" we must remove a large percent of captured "BLUE" and a percent of "GREEN" as well.
- In the process of subtracting out or post capture filtering out of these "extra" spectral values you're left with a much weaker value of the "RED" color you wanted.

http://www.auspiciousdragon.net/photowords/?p=880

Digital Still Cameras vs Mobile Phones

- CMOS image sensor must be small so that thickness of the mobile is small.
- The typical target height is about 6mm.
- The maximum diagonal sensor size with a 6mm height is about 4,5mm.
- To fit 2MP in such a small sensor, the size of each pixel must be 2µx2µ
- To achieve 3.2MP the pixels must be 1.75µx1.75µ.
- To achieve 5MP the pixels must be 1.4µx1.4µ.

- But the sensitivity of pixels below 2microns decreases and noise augments.
- Digital Still Cameras have bigger sensors and bigger pixels.

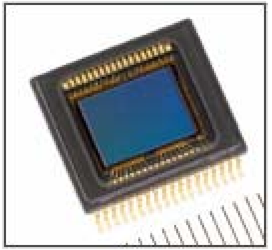
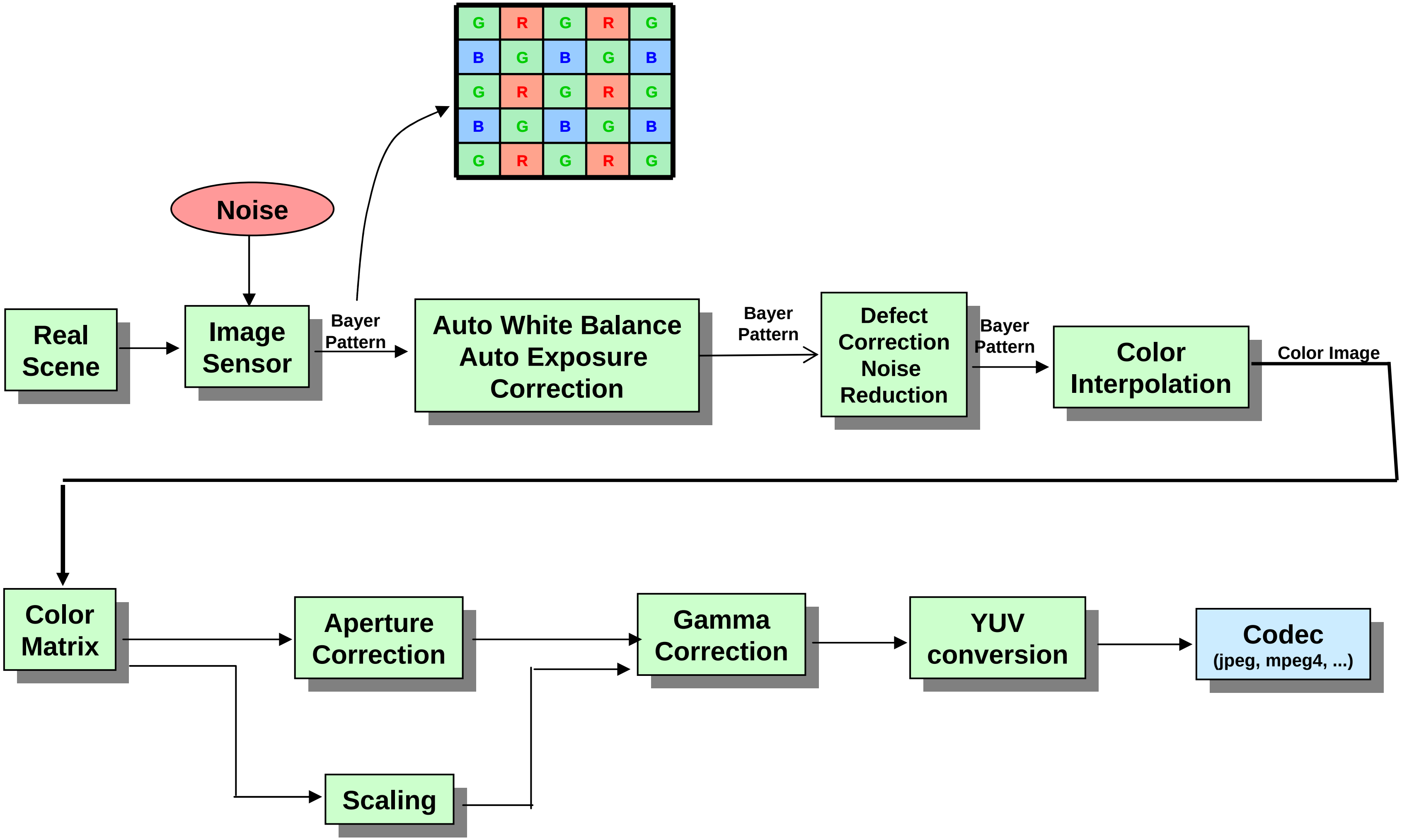
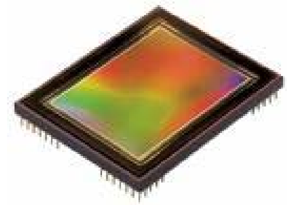
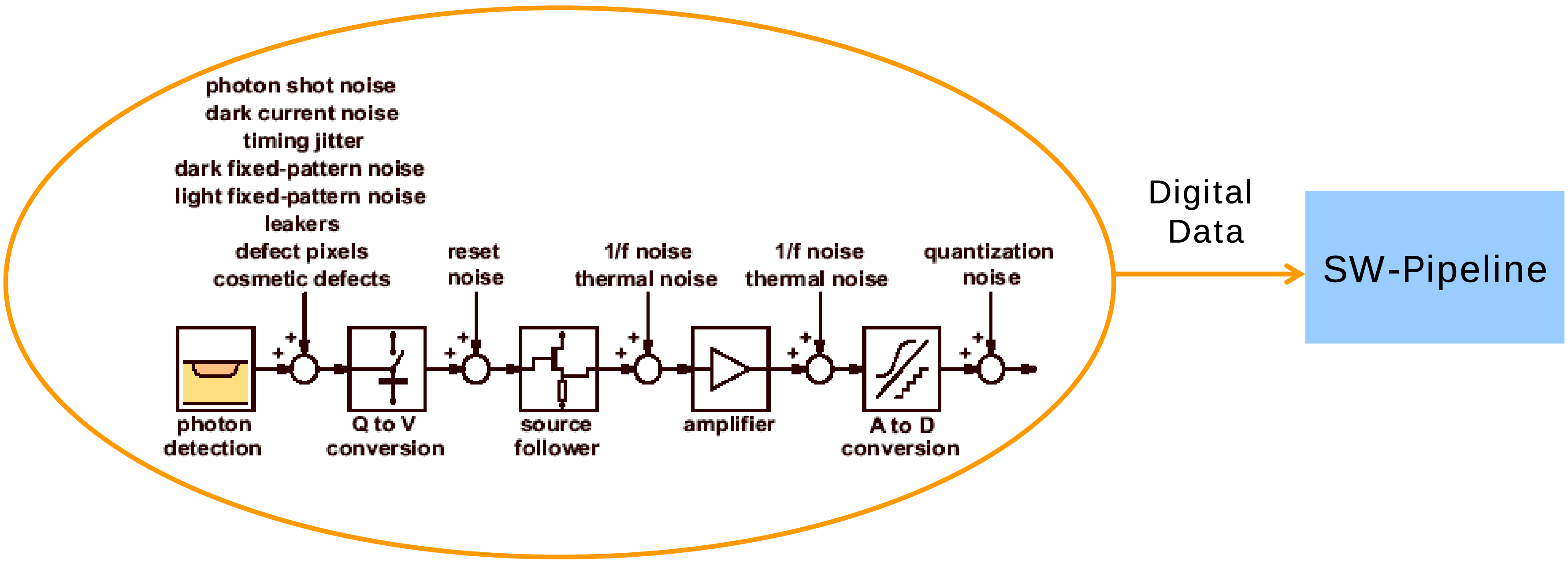


Image Reconstruction Pipeline



Noise Sources Diagram



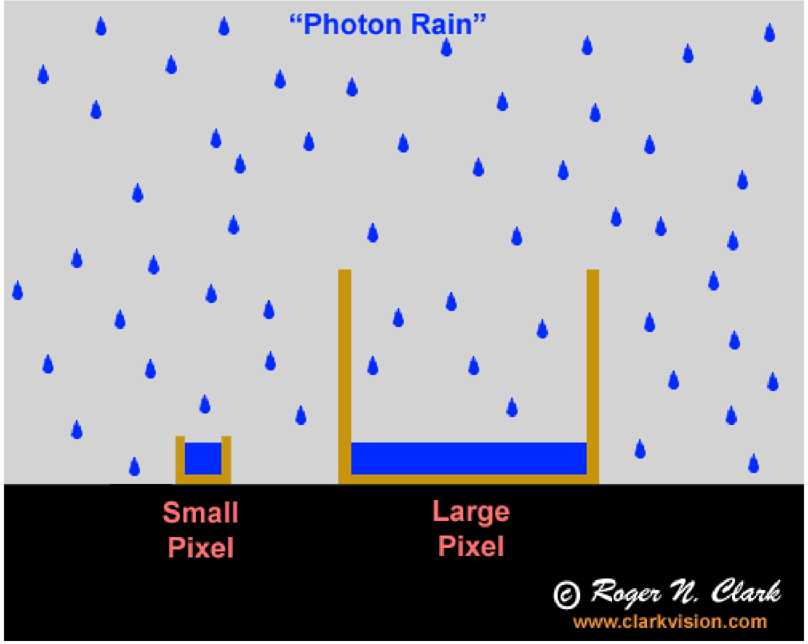


Ref. Theuwissen, Fraunhofer 2002

Noise Sources

- Photon Shot Noise
- Dark Current (Thermal Noise)
- Readout noise (Bias Noise)
- KT/C Noise (Reset Noise)
- Fixed Pattern Noise

Pixel Size



A larger pixel collects more photons. Given two sensors with equal numbers of pixels, and each with lenses of the same f/ratio, the larger sensor collects more photons yet has the same spatial resolution.

Pixel Size and Noise

Source: www.clarkvision.com

Photon Shot Noise

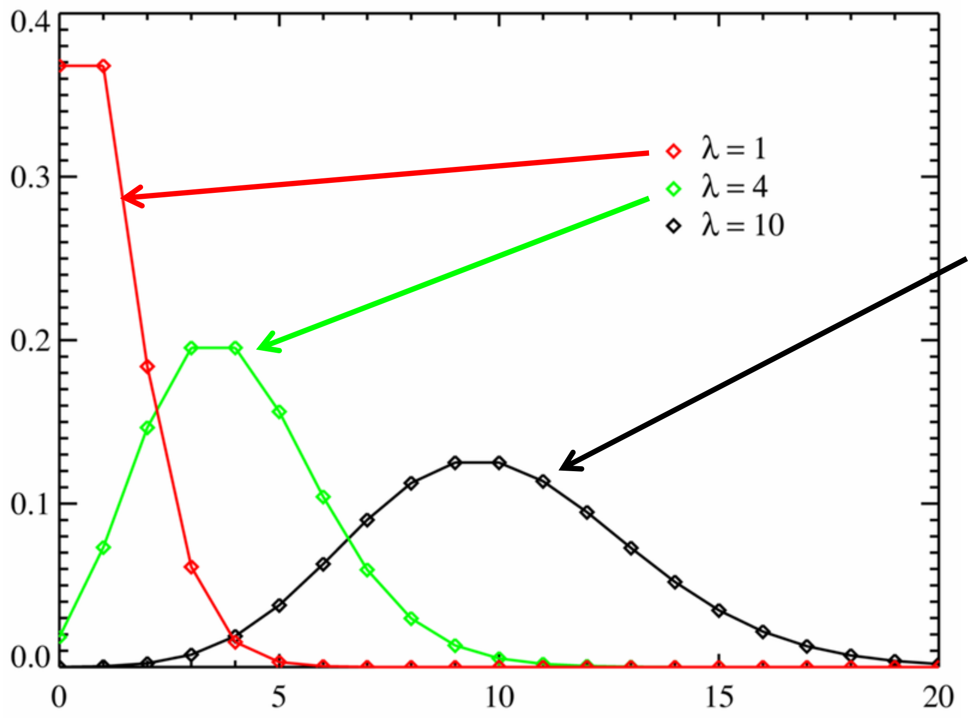
- Shot noise is a type if electronic noise occurring when a finite number of photons is small enough to give rise to detectable statistical fluctuations in a measurement.

- Shot noise is a problem with small currents and light intensities.

- Photon Shot Noise is Poisson Distributed: its variance is equal to the square root of the average number of photons hitting the sensor.

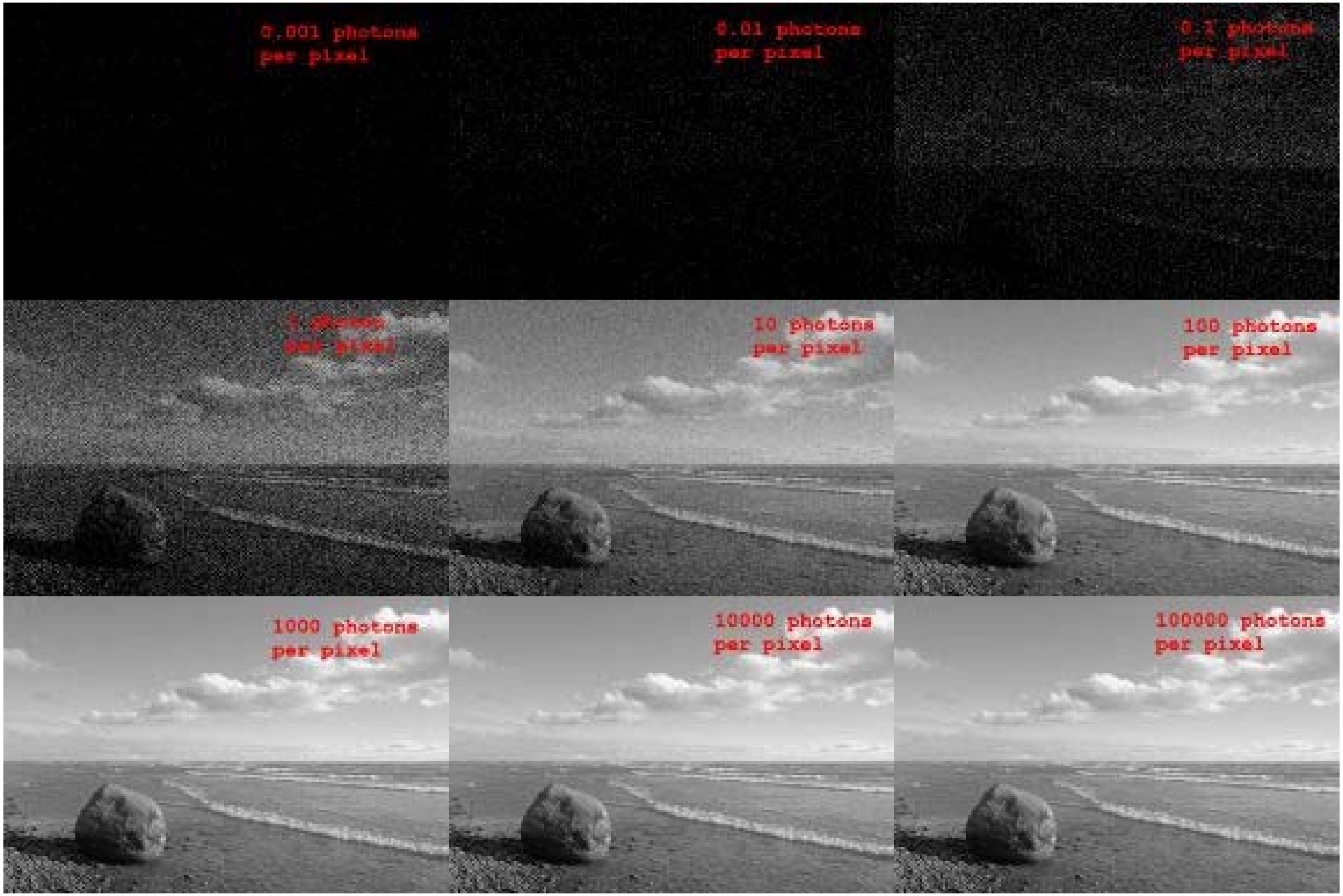
Photon Shot Noise

- Poisson distribution approaches a normal distribution for large numbers (i.e. for large numbers of collected photons).
- Hence, as light level increases, it can be treated as Gaussian distributed noise (i.e. Grain Noise).



For big lambdas (e.g. 10), the Poisson distribution approaches the Gaussian Distribution and noise starts to look as grain.

Photon Shot Noise Simulation



*Source Wikipedia

Poisson Noise converges to Gaussian Noise as the light increases.

As the number of photons increases, the PSN converges to normal distribution. As it can be seen, the image looks as affected by Gaussian Noise.

Noise Sources

- Photon Shot Noise
- Dark Current (Thermal Noise)
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- KT/C Noise (Reset Noise)
- Fixed Pattern Noise

Dark Current

- **Photons** reach the sensor and **excite electrons** (the photons do this by transferring energy to the electrons).

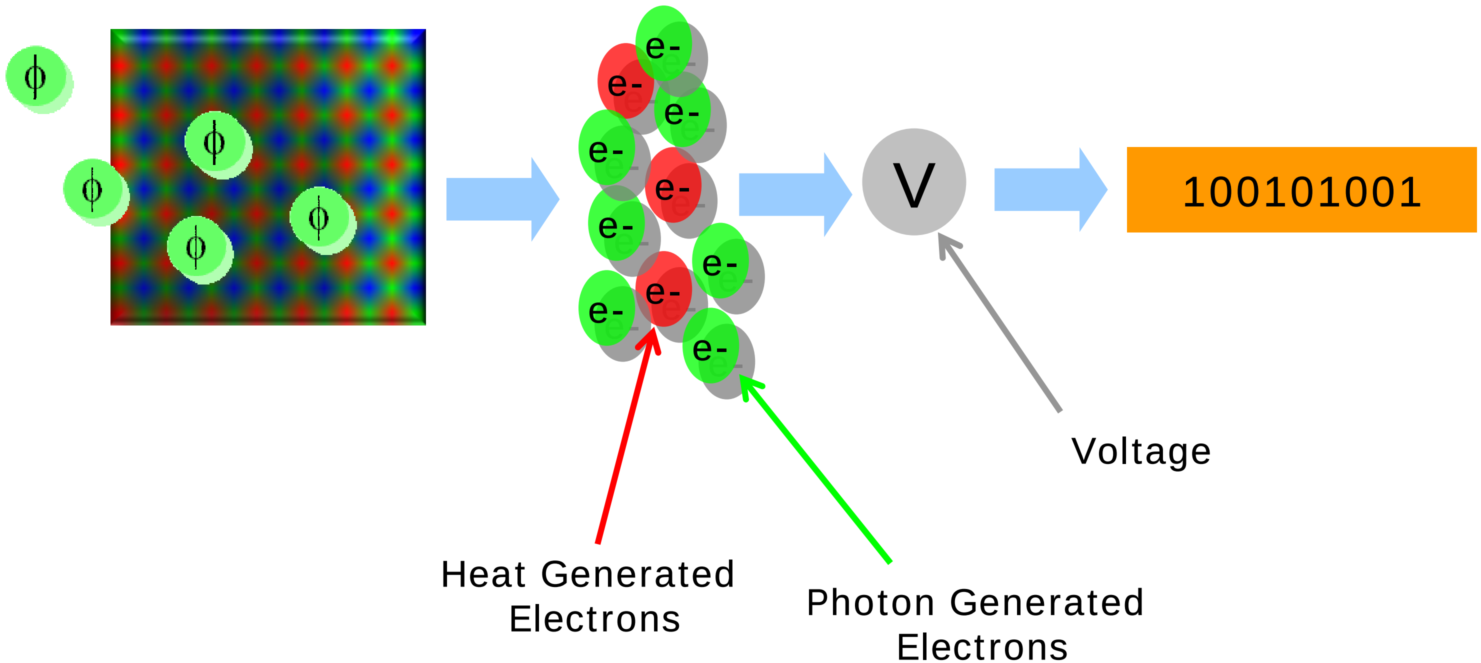
- Excited electrons are freed from the molecules to which they are attached. When a voltage is applied, these free electrons **create a current and flow into a capacitor**, creating a charge in it.

- The charge is then **measured** to create a **voltage measurement**. This voltage measurement is processed by the camera to determine how much light reached the pixel during exposure.

- Electrons are also freed by heat, because heat transfers energy to the electrons.

- Electrons that are freed by heat combine with the electrons that are freed by the photons. This creates a type of noise known as **dark current noise**. This type of noise exists even when the sensor is not receiving any light due to the fact that dark current noise depends on heat not light.

Dark Current



- **Dark Current Noise exists even when the sensor is not exposed** to any incident light, and **increases as the temperature** of the sensor **increases**.

Noise Sources

- Photon Shot Noise
- Dark Current (Thermal Noise)
- Readout noise (Bias Noise)
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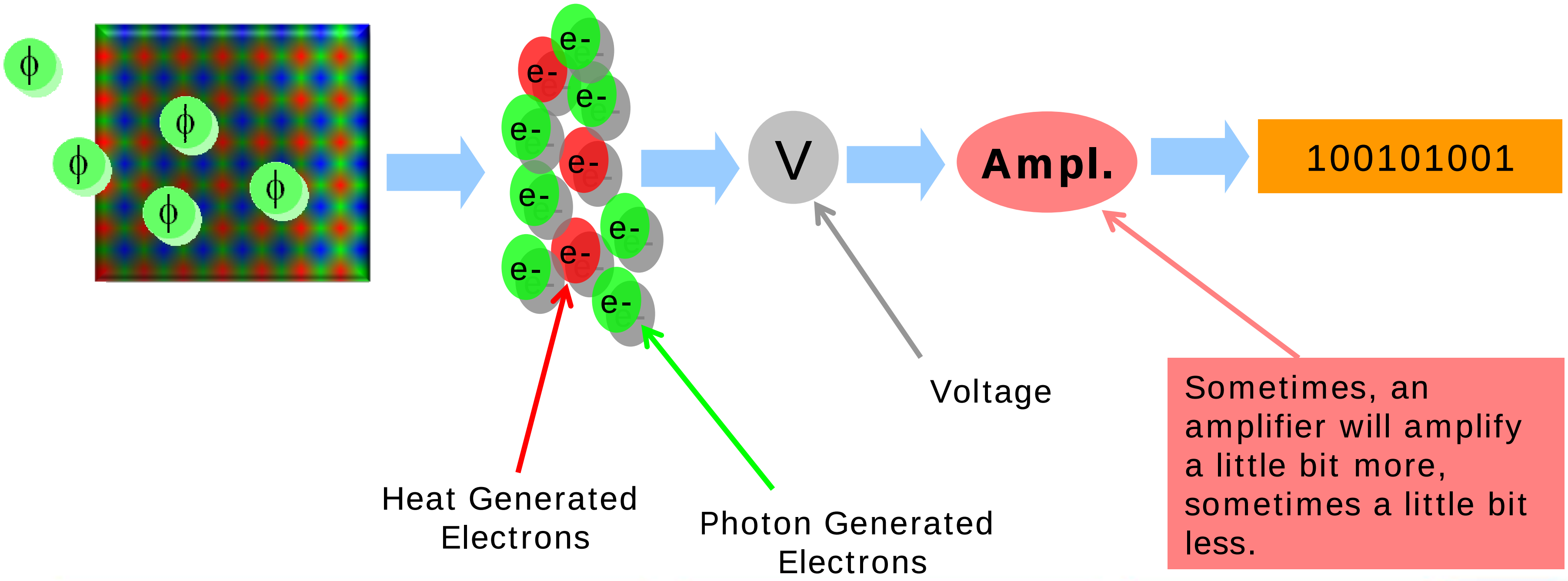
- Fixed Pattern Noise

Readout Noise

- It is the **noise generated during the readout** of the sensor; and does **not depend on the shooting conditions**.

- It is affected by the **amplifier gain** (**ISO** setting for the end-user) and remains the same as long as the gains do not change.



Noise Sources

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- Fixed Pattern Noise

KT/C (Reset) Noise

- KTC Noise happens when resetting the pixel, prior charge accumulation. **Pixel does not exactly reset to zero**.

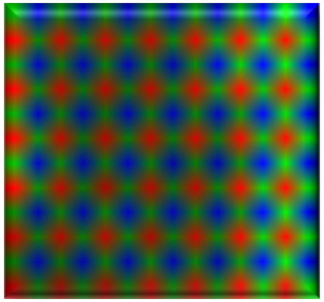
Each time the pixel is reset, **the thermal noise of the reset transistor channel is sampled onto the photodiode capacitance**. This creates an uncertainty in the reset level, which can be expressed in electrons as:

$$N_{reset} = \sqrt{\frac{kTC}{q}}$$

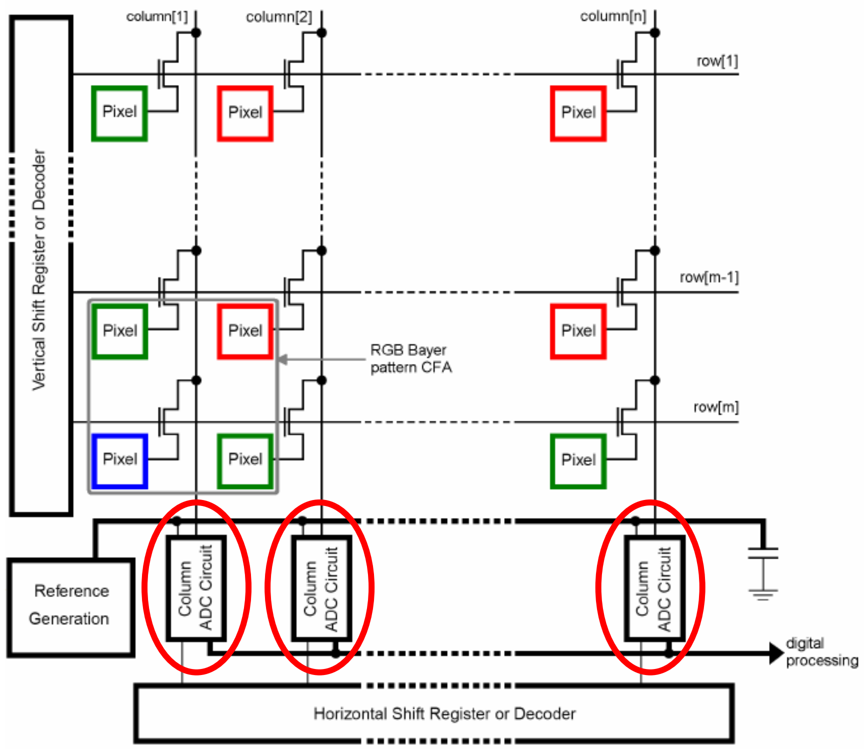
Fixed Pattern Noise

- Photon Shot Noise
- Dark Current (Thermal Noise)
- Readout noise (Bias Noise)
- KT/C Noise (Reset Noise)
- Fixed Pattern Noise
- Quantization Noise

FPN / Column Noise



The column sample/hold capacitors store the pixel value before digitisation occurs. Thus the column capacitors introduce a noise.

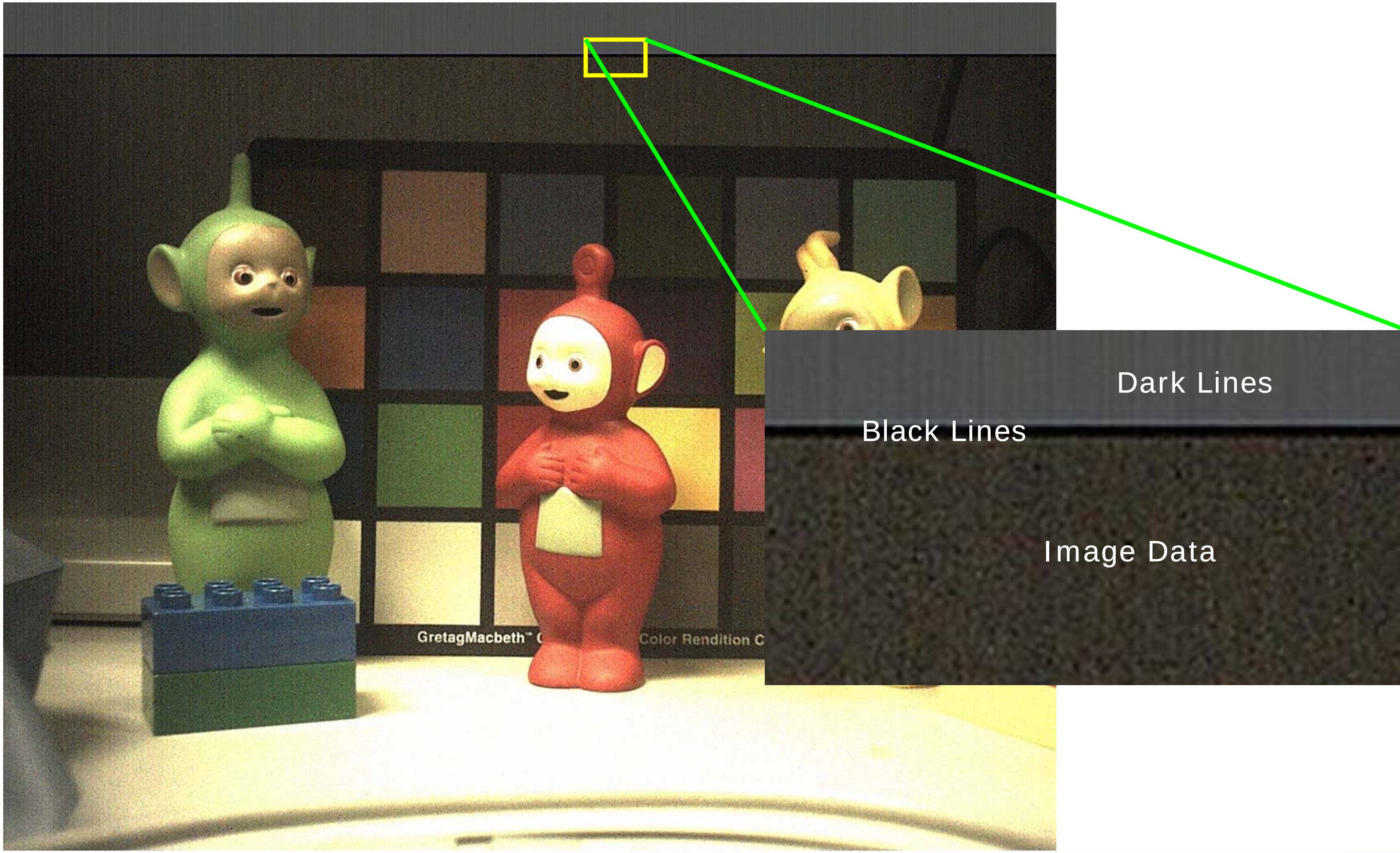


- In CMOS sensors, the *FPN* is constant along the vertical lines.
- Analyzing few lines is enough to retrieve the line noise entity.

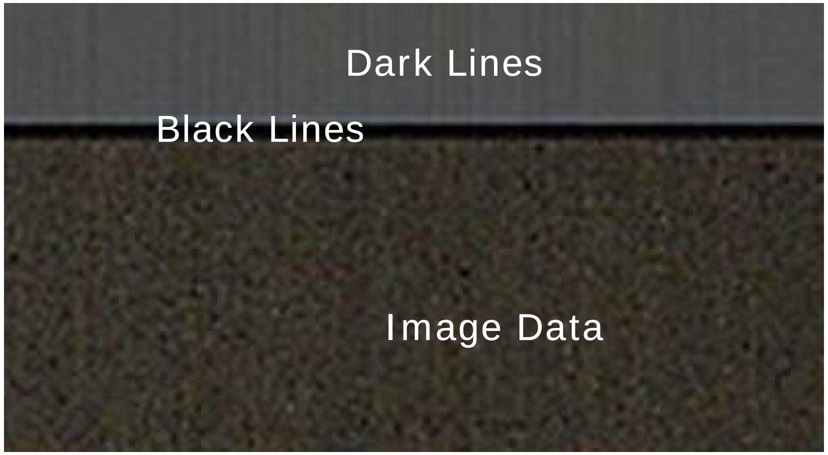
Fixed Pattern Noise / Column Noise

FPN does not vary in time and remains the same across frames.

FPN-Cancellation based on non-image data



Fixed Pattern Noise Cancellation



- Dark lines are shielded from light but have the same exposure as the image lines, hence FPN data is mixed with other noise sources.

- **Black lines** are **exposed** to incident light but have **zero exposure**, hence they are **good** to '**learn**' the FPN **signature**.

- By **averaging Dark Lines multiple times** (using multiple consecutive frames) it is possible to **estimate** the **signature** of the **FPN**, which is **subtracted** to the image, removing FPN.

This solution is Patented.

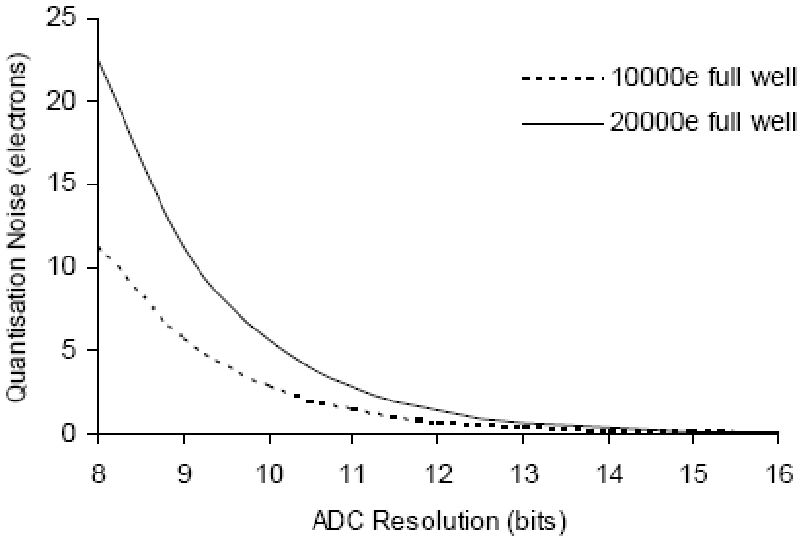
Quantization Noise

- Photon Shot Noise
- Dark Current (Thermal Noise)
- Readout noise (Bias Noise)
- KT/C Noise (Reset Noise)
- Fixed Pattern Noise
- Quantization Noise

Quantization Noise

The analogue to digital converter in each column introduces noise due to the quantisation process. This can be referred to the pixel and expressed in electrons as:

$$N_{quantisation} = \sqrt{\frac{1}{12}\left(\frac{V_{range}}{2^N}\right)^2} \times \frac{C_{pix}}{G_{sf}\,q} = \frac{1}{\sqrt{12}}\left(\frac{Full\_Well}{2^N}\right)$$

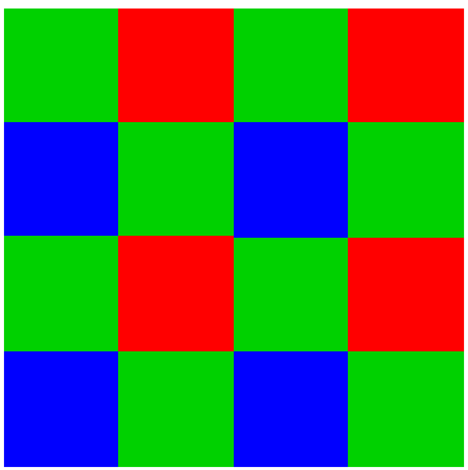


More *ADC* resolution (**bits per pixel**), **implies less quantization noise**.

Overall Noise

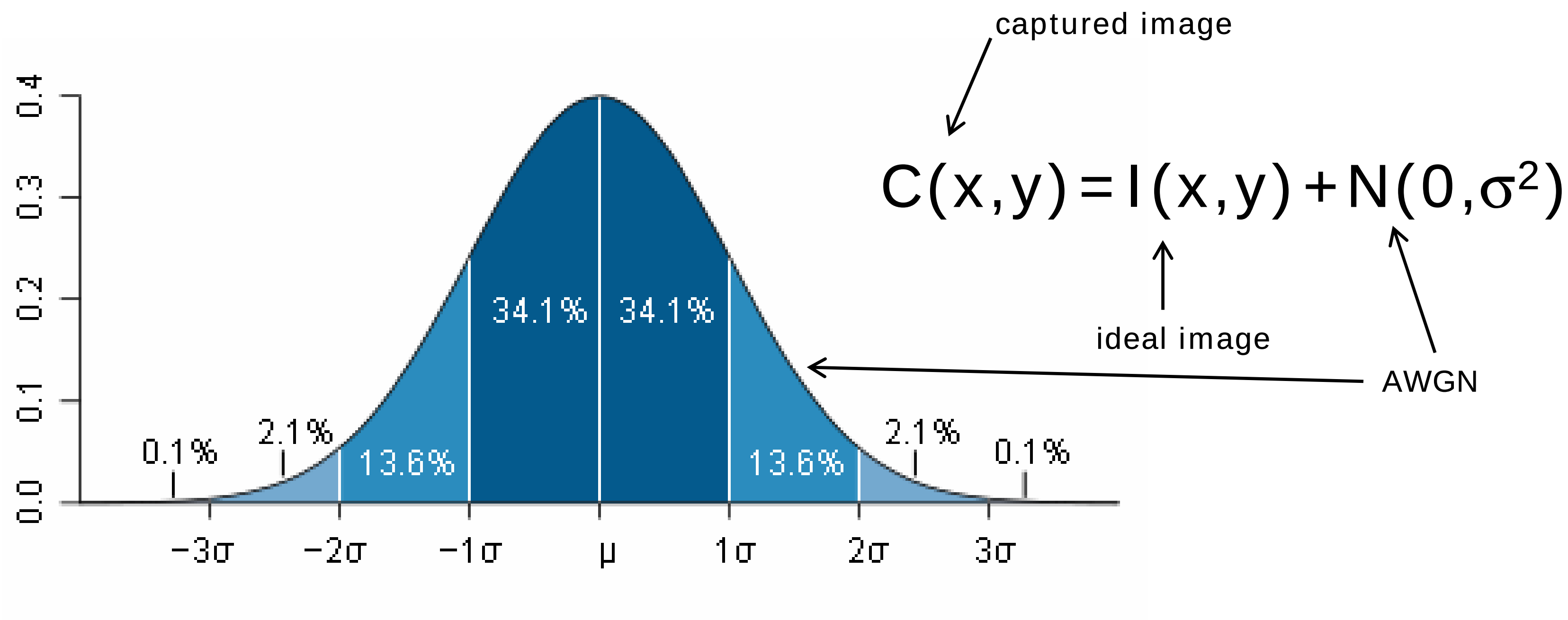
- Considering the presence of many noise sources, it is reasonable to model the **overall noise** as a **zero mean Additive White Gaussian Noise (AWGN)**, affecting each color component and pixel position independently.

- Noise variance may be different across Bayer color channels.



To obtain better filtering results it is better to estimate the noise level on each Bayer channel separately, producing three different noise estimates per image.

AWGN



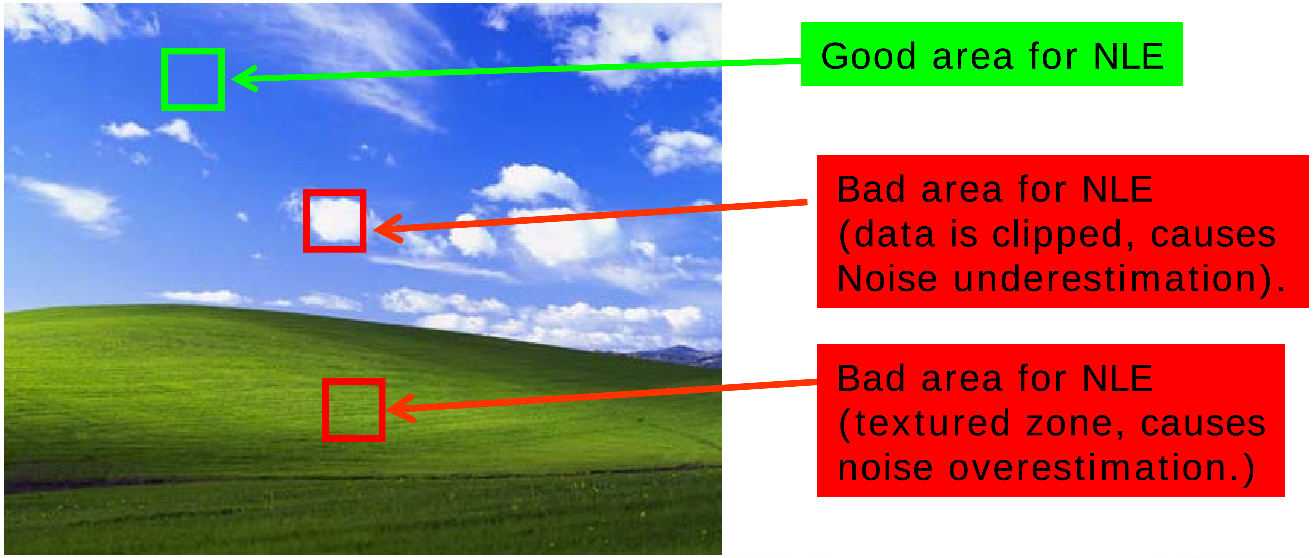
$$C(x,y) = I(x,y) + N(0,\sigma^2)$$

- 68% of the noise samples fall within one standard deviation from the mean.
- 95% of the noise samples fall within two standard deviations from the mean.
- 99% of the noise samples fall within three standard deviations from the mean.

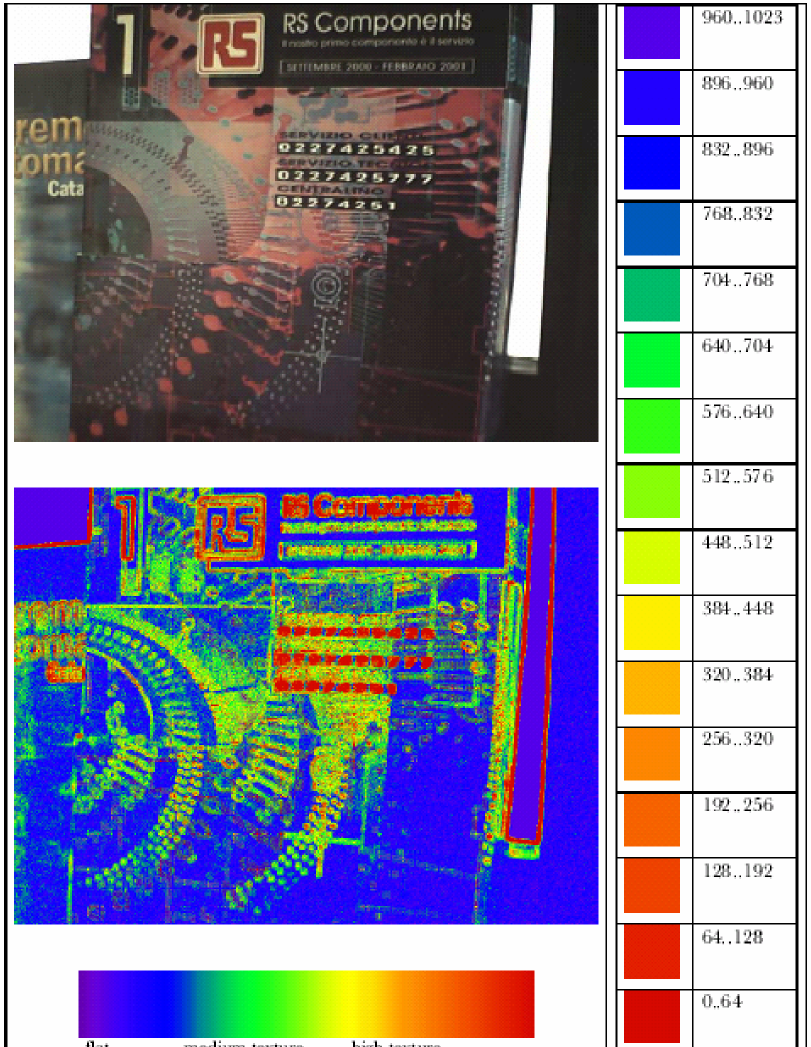
Images contamined by AWGN typically appear grainy: each pixel deviates from its theoretical ‘correct’ value by some amount that is drawn by the Gaussian distribution. The noiser the image, the wider the Gaussian bell.

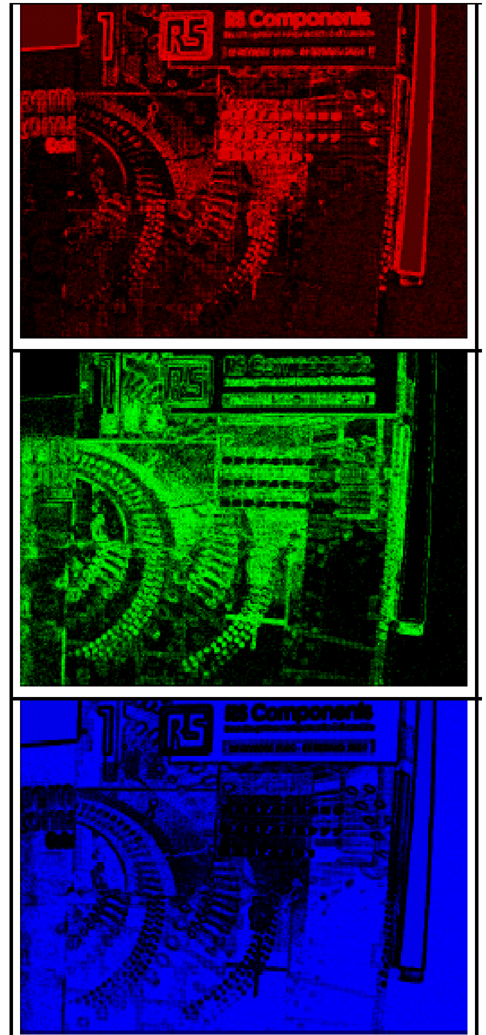
Noise Level Estimation

- Use a texture detector to locate the flat areas in the image.
- In flat areas, pixel fluctuations are supposed to be caused exclusively by random noise. Hence, flat areas are good for estimating the noise level (i.e. standard deviation of the underlying Gaussian distributed noise).



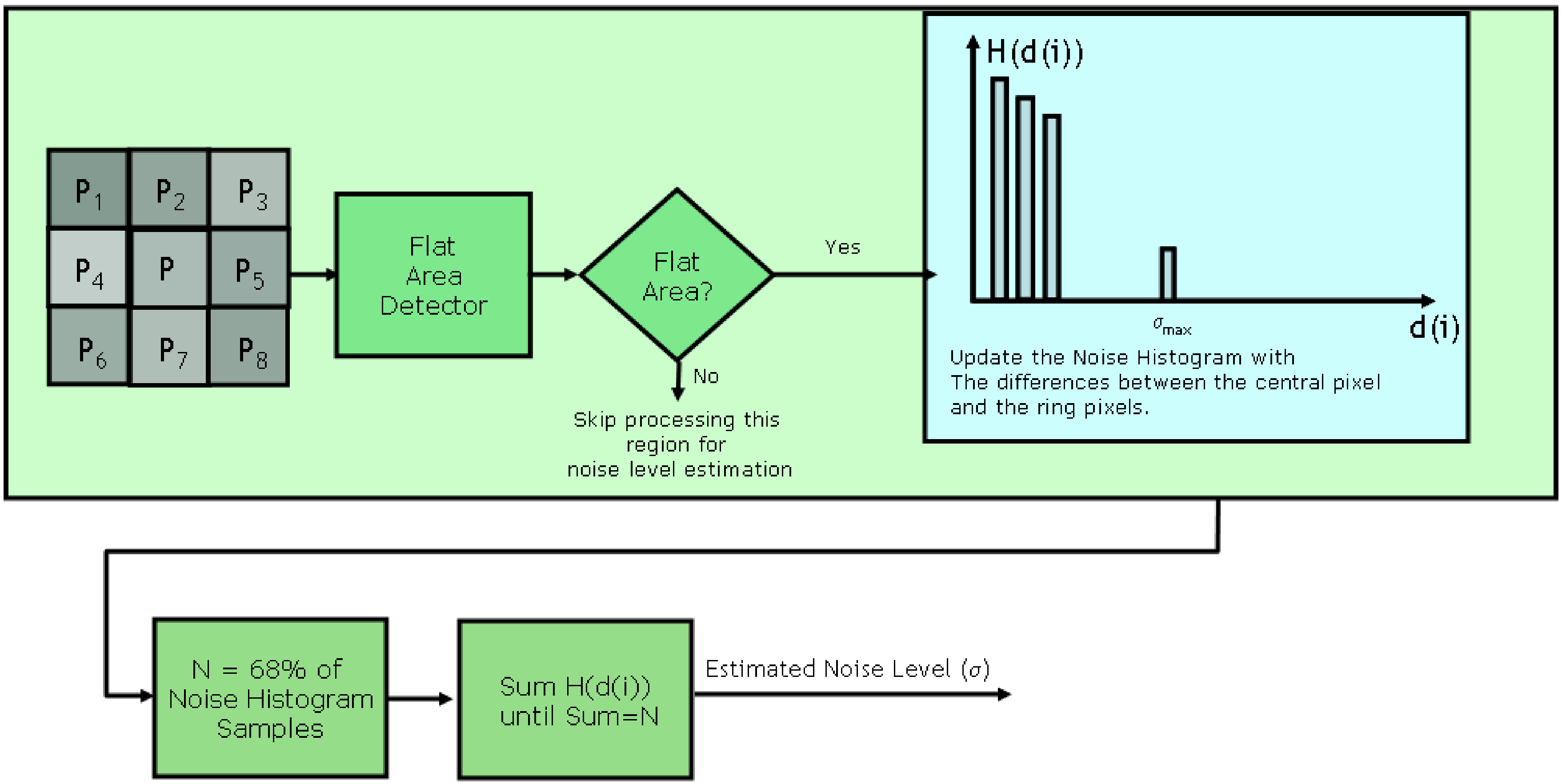
Noise Level Estimation



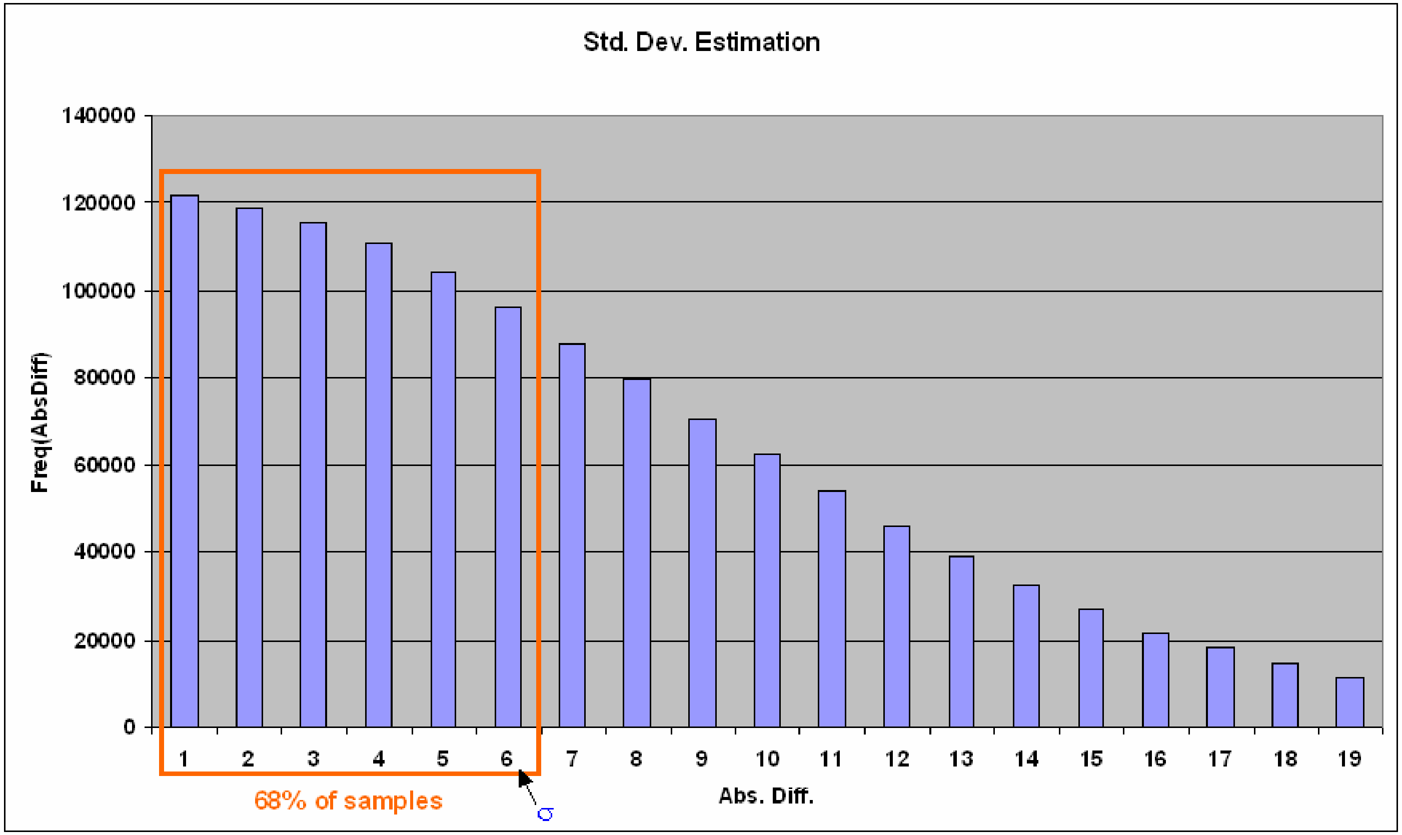


Noise Level Estimation must be performed on low textured areas.

Noise Estimation



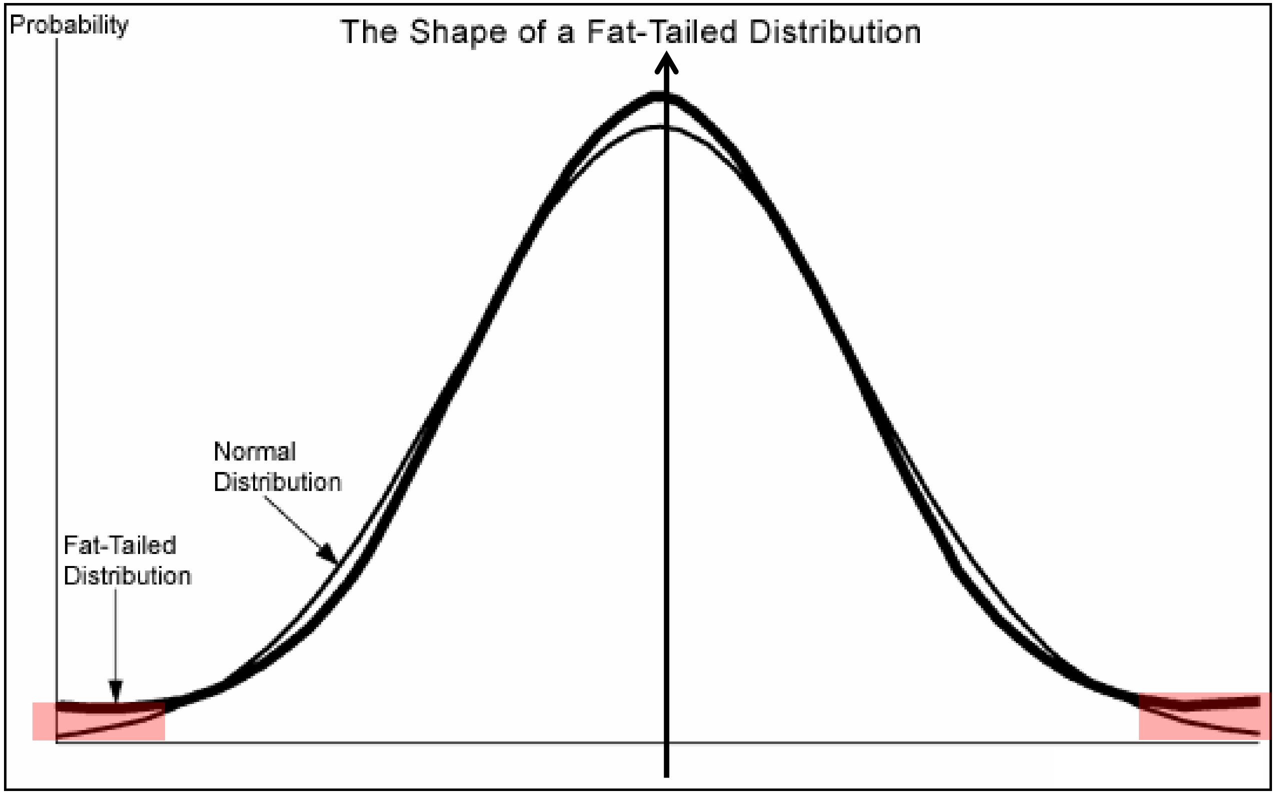
Noise Estimation



This solution is Patented.
Paper: "Fast Noise Level Estimation Using A Convergent Multiframe Approach" – IEEE ICIP 2006

Fat-Tailed Noise

- In case of very **dim light** (e.g. <10 lux), **noise** level increases dramatically and noise distribution is no longer purely Gaussian shaped and becomes **fat-tailed**.



Defects + Fat Tailed Noise

- **Fat tailed** noise adds to defects (impulse noise) **generating** overall **non predictable** **defects** at ‘run time’ as the image is taken.

- The presence of these defective elements **depends** on **light**, **gains**, **temperature**, etc.

- An algorithm capable to deal with unpredictable defects must be devised.

- **Simple defect-maps cannot be used** because the **position** of the **defects** caused by fat-tails **is not predictable**.

Defective Pixels

i) Salt & Pepper, **Fixed-Valued Noise**:

a.k.a. **Dead Pixels** (0), **Spike Pixels** (255)):

ii) Impulsive Uniform, **Random-Valued Noise**:

a.k.a. **Stuck** Pixels, **Leaky** Pixels, **Blinking** Pixels:

iii) **Extended Impulse Noise Model in Color Space** (RGB/YUV/...):

$$x_{ik} = \begin{cases} v_{ik} & \text{with prob. } \pi \\ o_{ik} & \text{with prob. } 1-\pi \end{cases}$$

Fixed-Valued Noise: $v_{ik} = (0,255)$

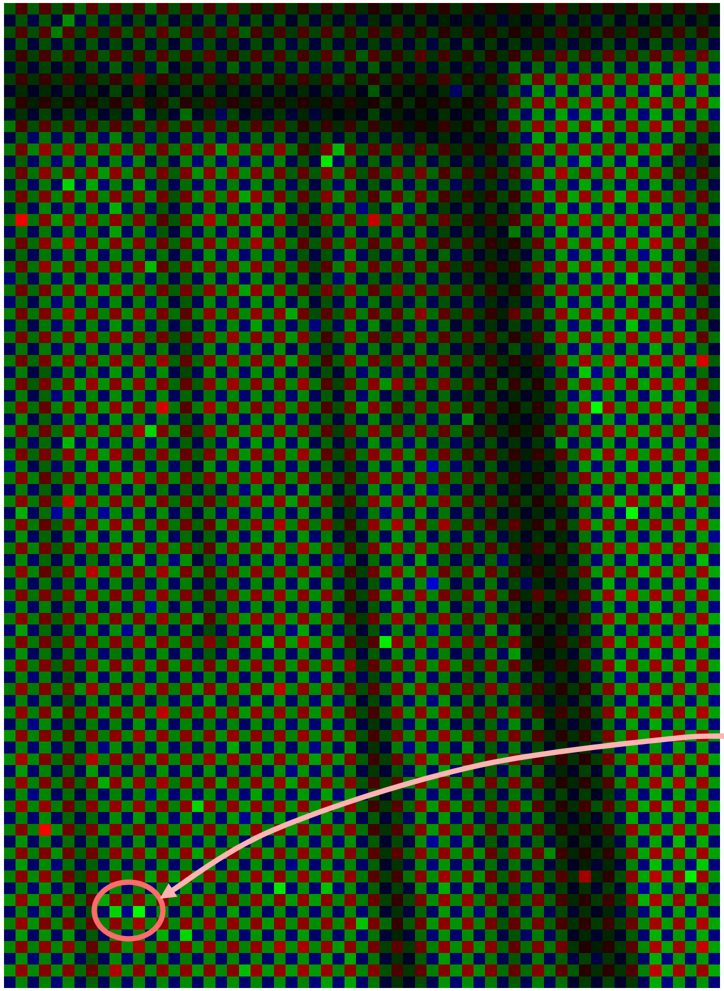
Random-Valued Noise: $v_{ik} \in [0,255]$

Extended Model:

$$\vec{x}_i = \begin{cases} \vec{o}_i \text{ with prob. } 1-\pi \\ \{v_{i1}, o_{i2}, o_{i3}\} \text{with prob. } \pi_1\pi \\ \{o_{i1}, v_{i2}, o_{i3}\} \text{with prob. } \pi_2\pi \\ \{o_{i1}, o_{i2}, v_{i3}\} \text{with prob. } \pi_3\pi \\ \{v_{i1}, v_{i2}, v_{i3}\} \text{with prob. } \pi_4\pi \end{cases}$$

$v_{ik} \in [0,255]$

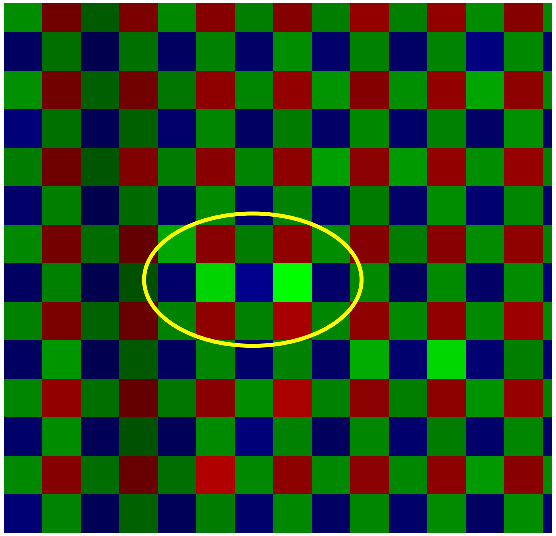
White Tailed Gaussian Noise



- It is a noise visible in low light conditions.
- Low light condition requires high gain values in digital amplifiers to obtain a well exposed image.
- High Gain values amplify the noise obtaining isolated white pixels.
- It can be associated to “defective pixels” in CMOS sensors.

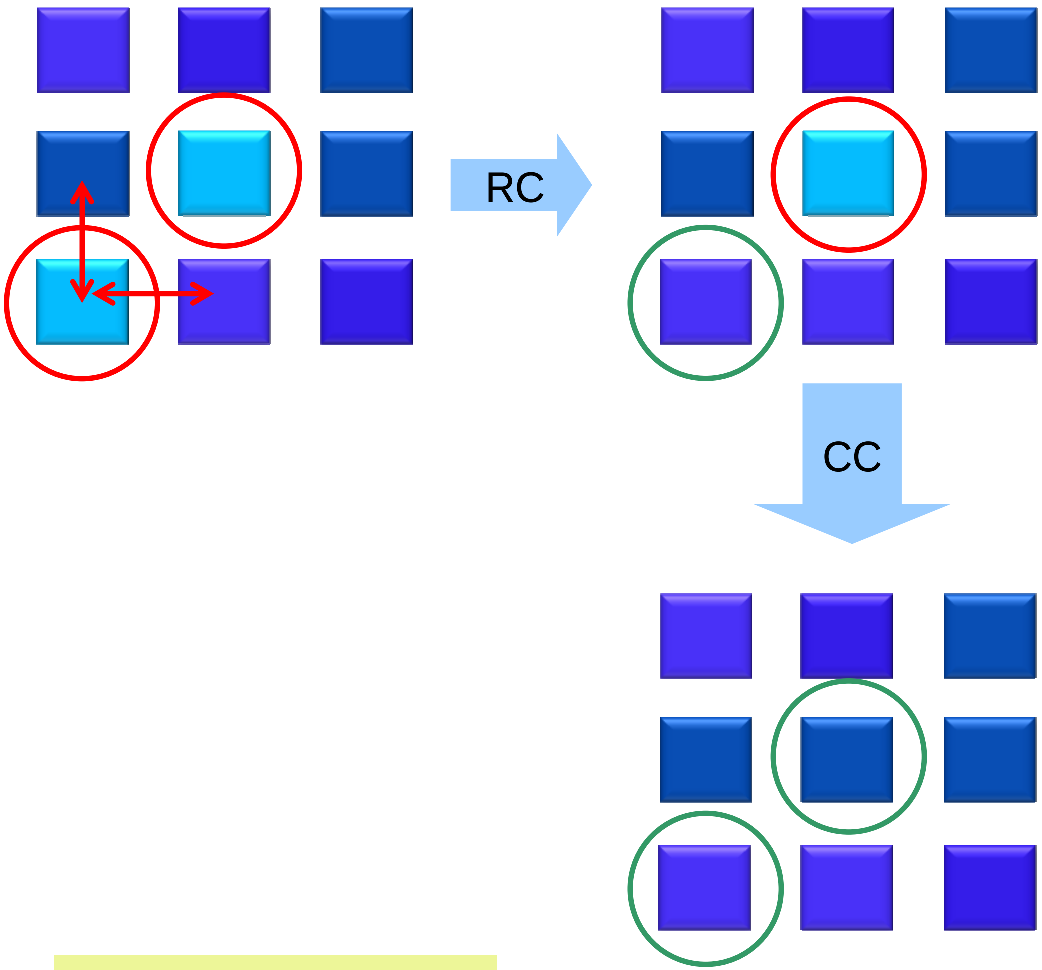
Due to the fat tails, couplets of defective pixels are probable.

Defective Couplets



- Couplets cannot be directly treated as impulse noise.
- The presence of two defective elements inside the same filter mask does not allow couplets cancellation using standard impulse noise removal techniques.
- By using standard defect cancellation methods, the couplet is regarded as an edge or texture information and is not removed.

Combined Ring+Central Corrector



❖ After correcting the ring, the central pixel is treated as impulse noise using proprietary impulse noise cancellation algorithm.

❖ Finally, the couplet has been completely removed.

This solution is Patented.

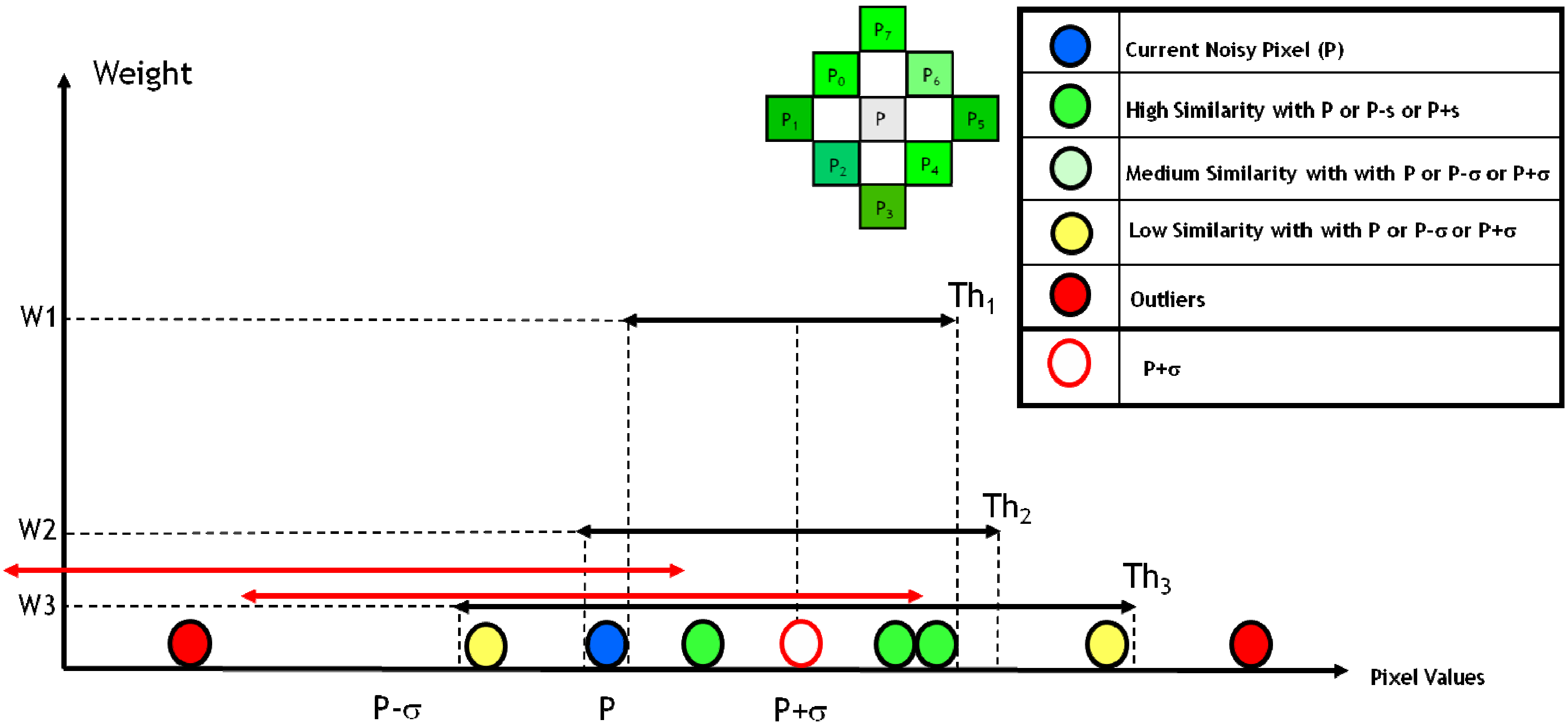
Gaussian Noise Reduction

- Gaussian Noise Reduction (***GNR***) takes place **after defect correction** in the pipeline.
- The objective of *GNR* is to **remove** relatively **small pixel fluctuations** generating too much grain in the image.
- *GNR* filter strength **must be adaptive**. Filter strength must scale with the level of noise in the image.
  - **High noise level → High filter strength**.
  - **Low noise level → Low filter strength**.

But, anyway:

- Textured areas must be not heavily filtered in order to maintain details.
- Flat areas can be more heavily filtered to reduce pixel fluctuations.

Sigma Filter



The intervals centered on P and P-σ contain less pixels than the interval centered on P+σ, thus they are discarded.

We average the pixels of the interval that contains the maximum number of pixels

Filter Strength

- The **noise** in an image is not the same everywhere and **varies with** the **lightness** level, this fact must taken into account by the noise filter.

- Detail is easier to discriminate in luminance information than in color information. We need to treat luminance noise and color noise differently.

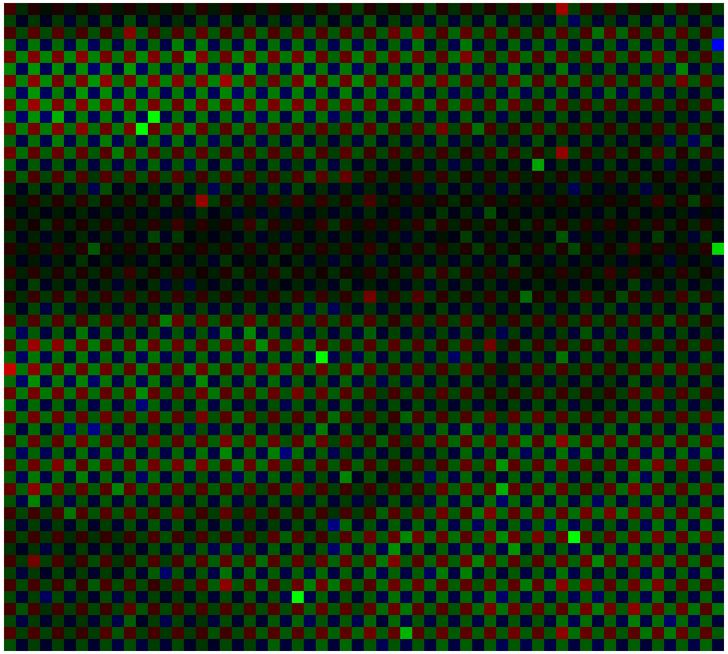
- **Fine textures** (grass, carpets, etc.) **hide noise** (**texture masking**).

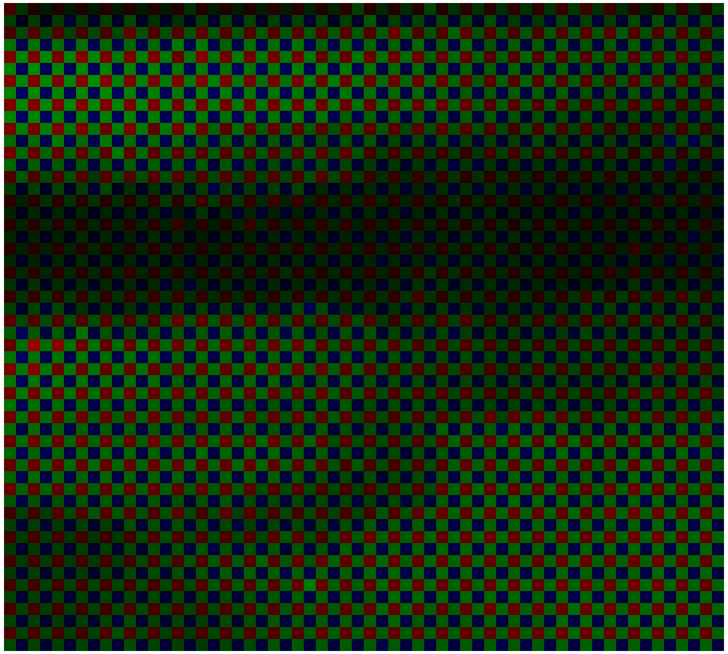
- A given level of noise may be excessive for a face or sky, which we know to be smooth in real life. However, if the same amount of noise is removed from vegetation, we may judge the removal to be excessive even though nothing but noise has been removed, simply because **we expect texture to be present in real life, even in flat areas**.

- **An image completely devoid of noise** looks unnatural.
Skin and other materials in such an image acquire a ***plastic* look**.

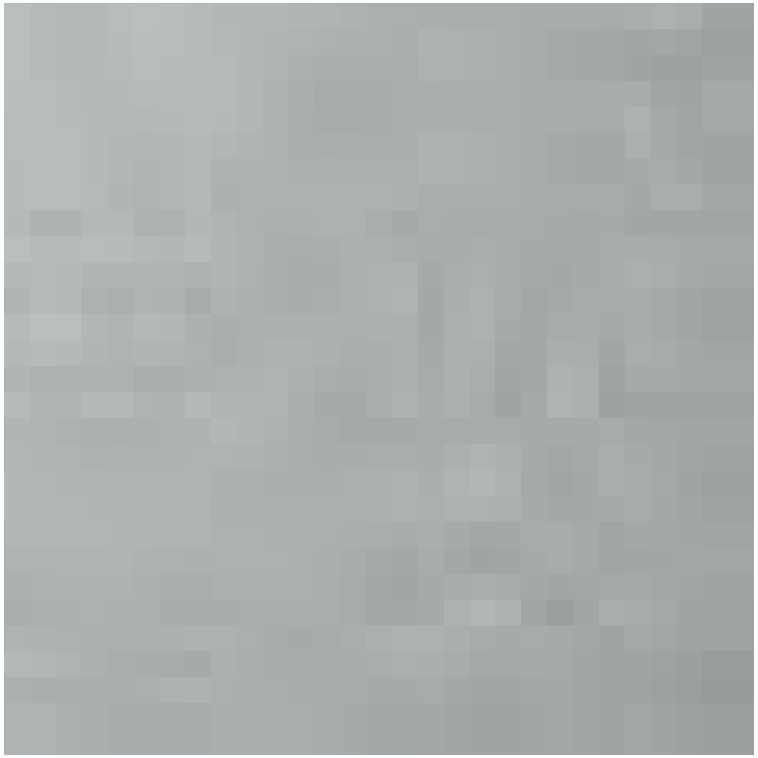
- The filter must **retain** a **low level natural noise**.

Defect Cancellation

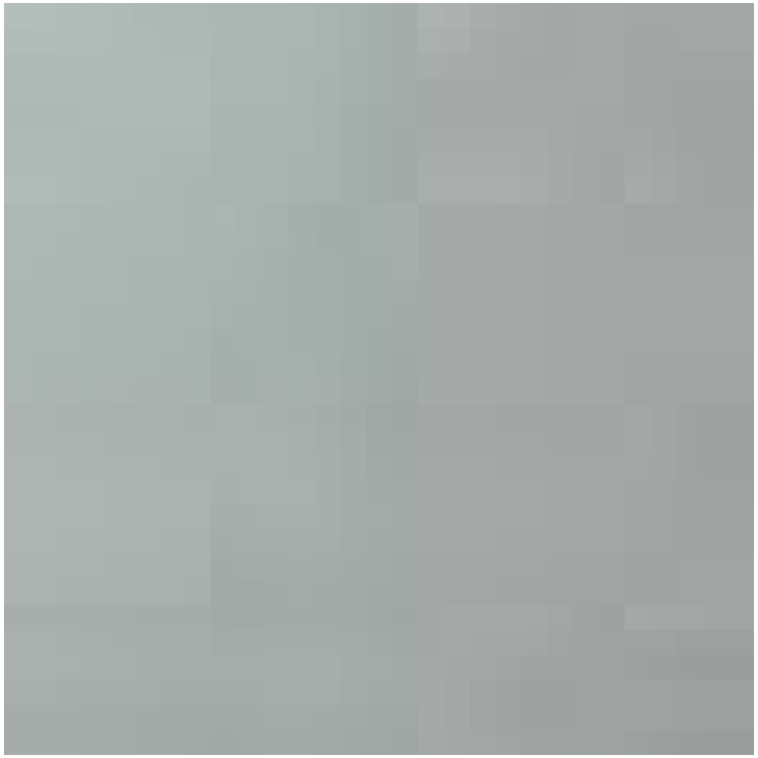

Colorized Original Bayer


Colorized Filtered Bayer

Gaussian Noise Reduction
Flat Areas Heavily Filtered



Original



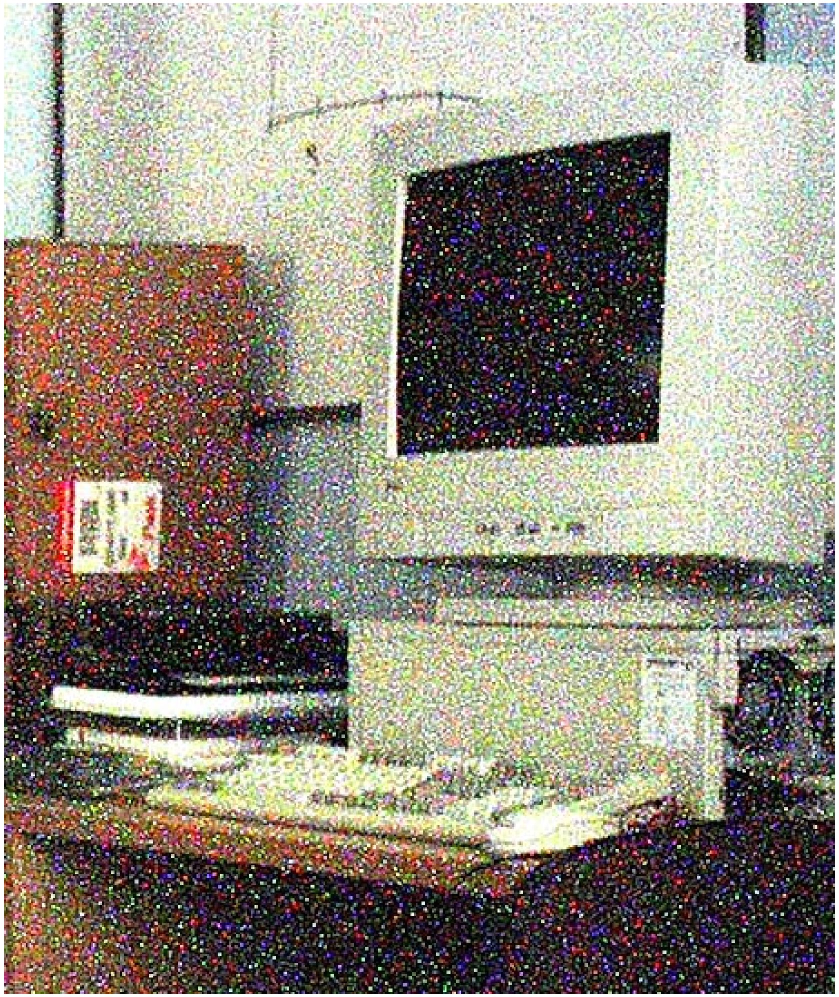
Filtered

Gaussian Noise Reduction
Textured Areas slightly filtered.

Original

Filtered

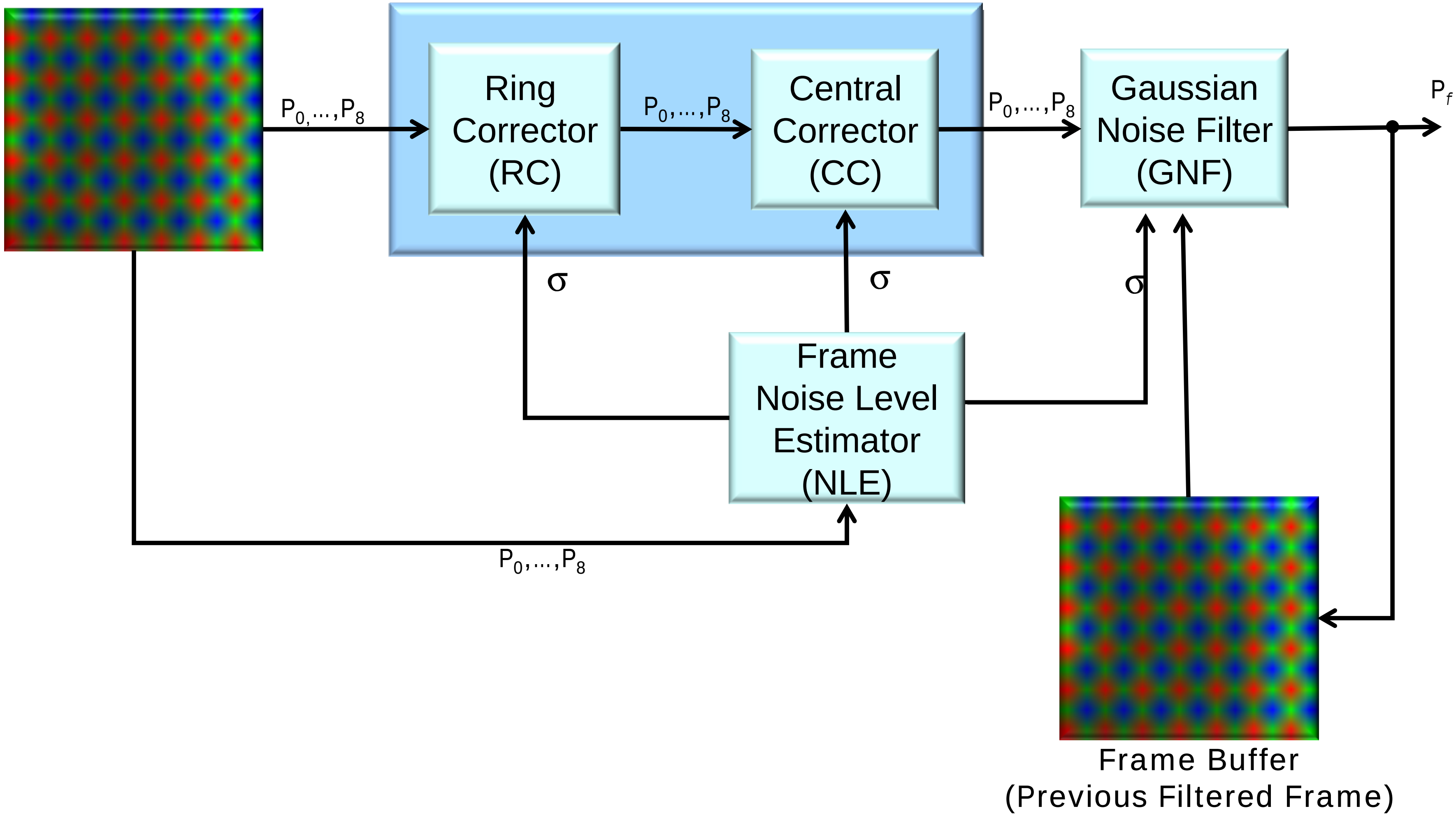
Filtering Example (Very low light using bad sensor)



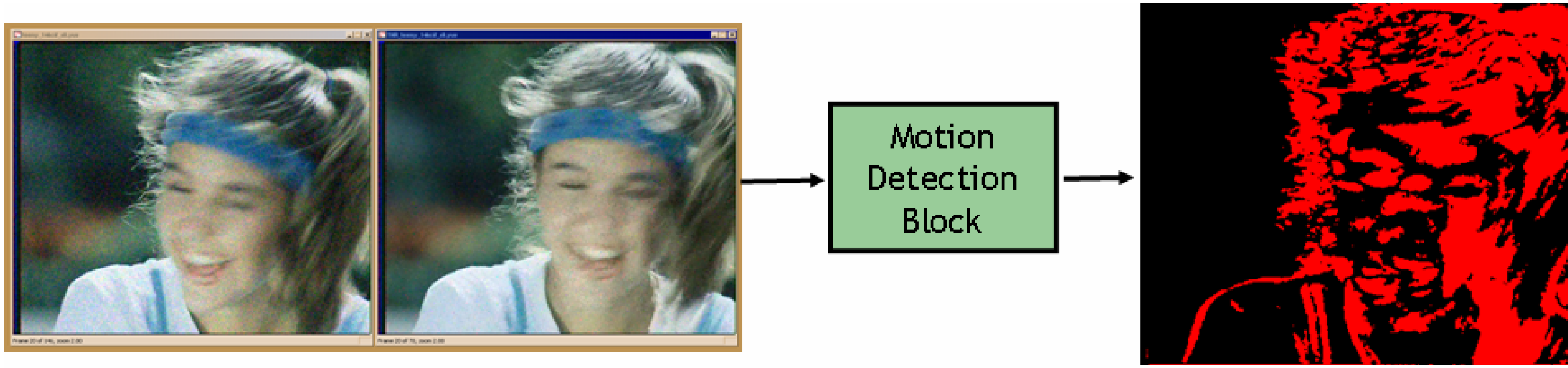
Temporal Noise Reduction

- **Video** sequences contain **strongly correlated frames**.
- Main **Idea**:
  - The **previous frame information** can be used to remove the noise in the current one.
- **Motion compensation** techniques can **improve** the **pixel matching** generating better filtering.

Temporal Noise Reduction



Temporal Filtering



Frame i   Frame i+1

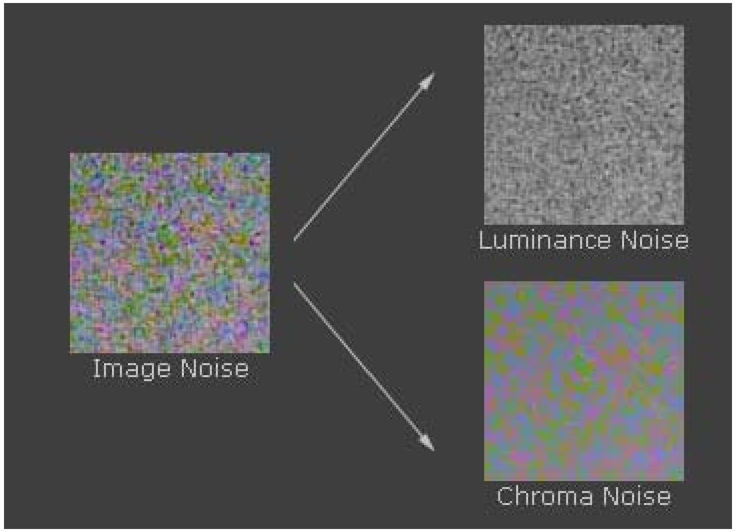
Red areas represent pixels where temporal information is not reliable for filtering.

- Motion estimation and compensation can be used to increase matching between frames and improve filter perfomance.

Luminance & Chrominance Noise

- So far, we have presented methods that perform noise reduction directly on the RAW data (Bayer CFA).

- At the end of the image pipeline, however, the **residual noise** appears as **luminance** noise and **chrominance** noise.



- Brightness (**Luminance**) Noise looks like **grain**; the random variations caused by noise are not colored. There is almost the same level of variation on all color channels.

- Colored (**Chrominance**) Noise, consist of **colored blotches** particularly **visible in shadows** and areas of uniform color; random variations caused by chroma noise are colored. The variations occur independently in each color channel.

- To the human eye, **color noise is more noticeable** (greater impairment) than brightness noise.

Image Source : http://www.cambridgeincolour.com/tutorials/noise2.htm

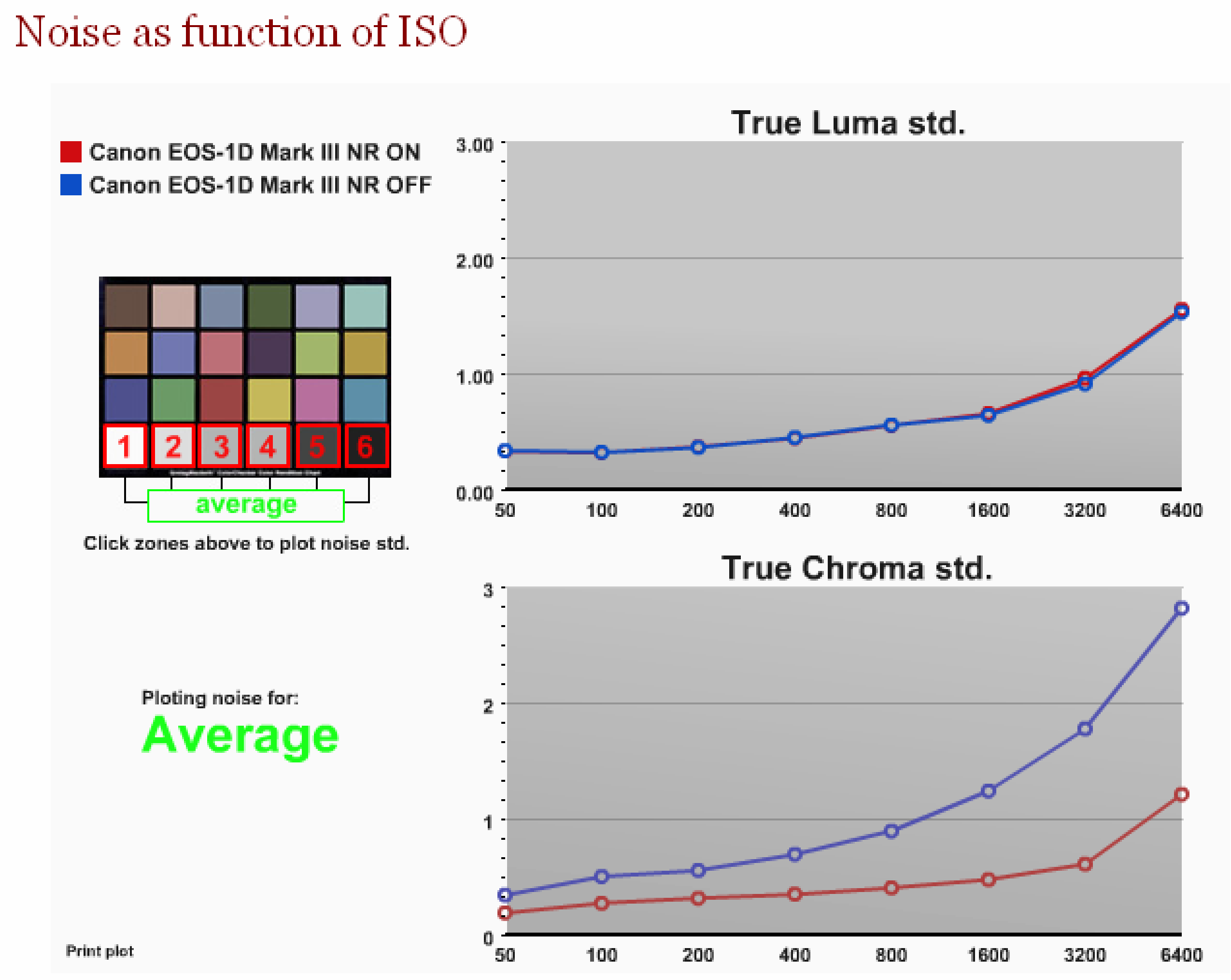
Chromatic Low Light Noise

- In general, **high frequency noise** is **prevalent** in the **luminance** channel and it can range from grain to speckle noise.
- **High frequency color noise** is noticeable, especially in **low light**.
- **Low frequency color noise creates blotchy color patches**, which is very annoying.

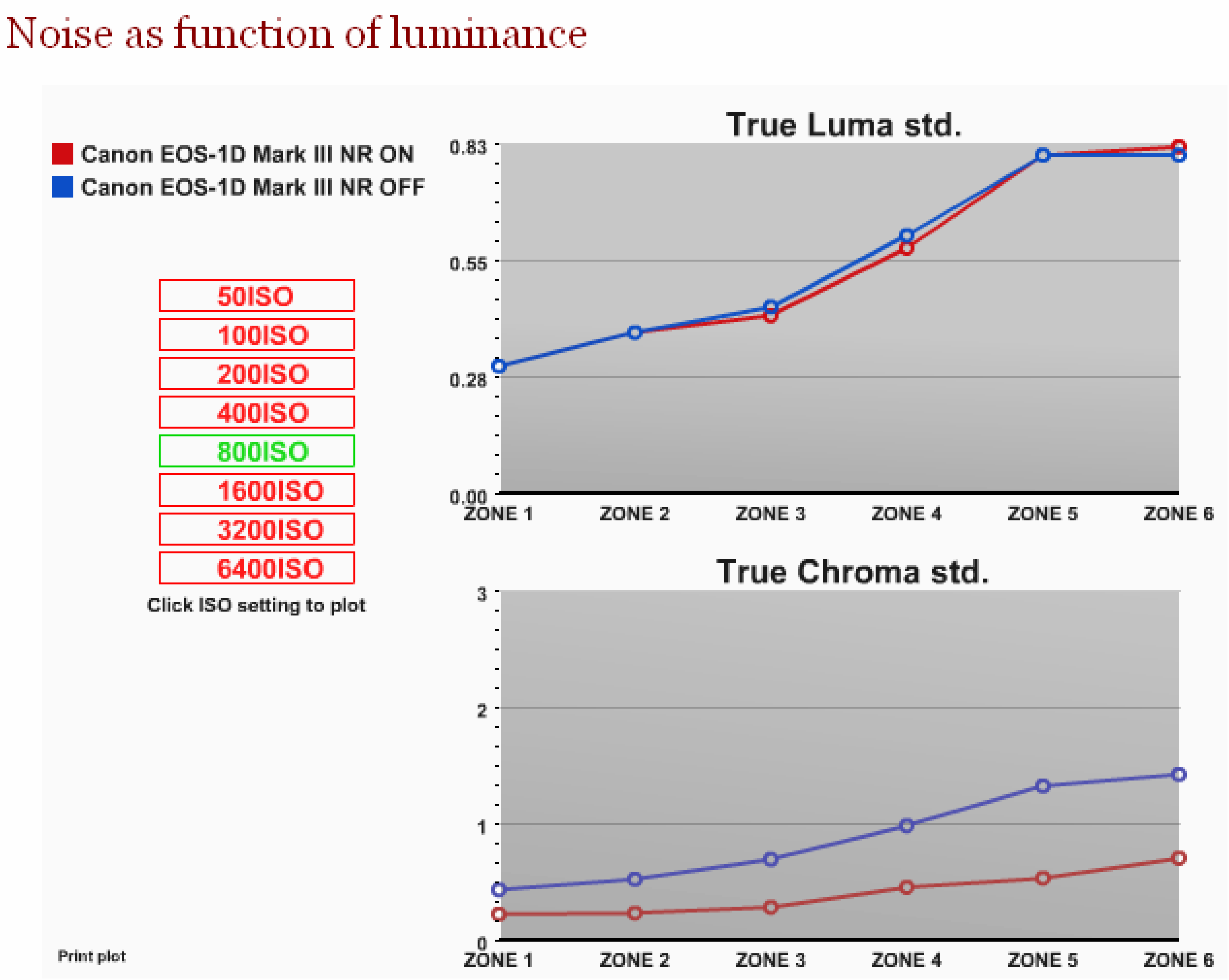
High Frequency Color Noise

Low Frequency Color Noise

Average Noise on gray patches as a function of ISO



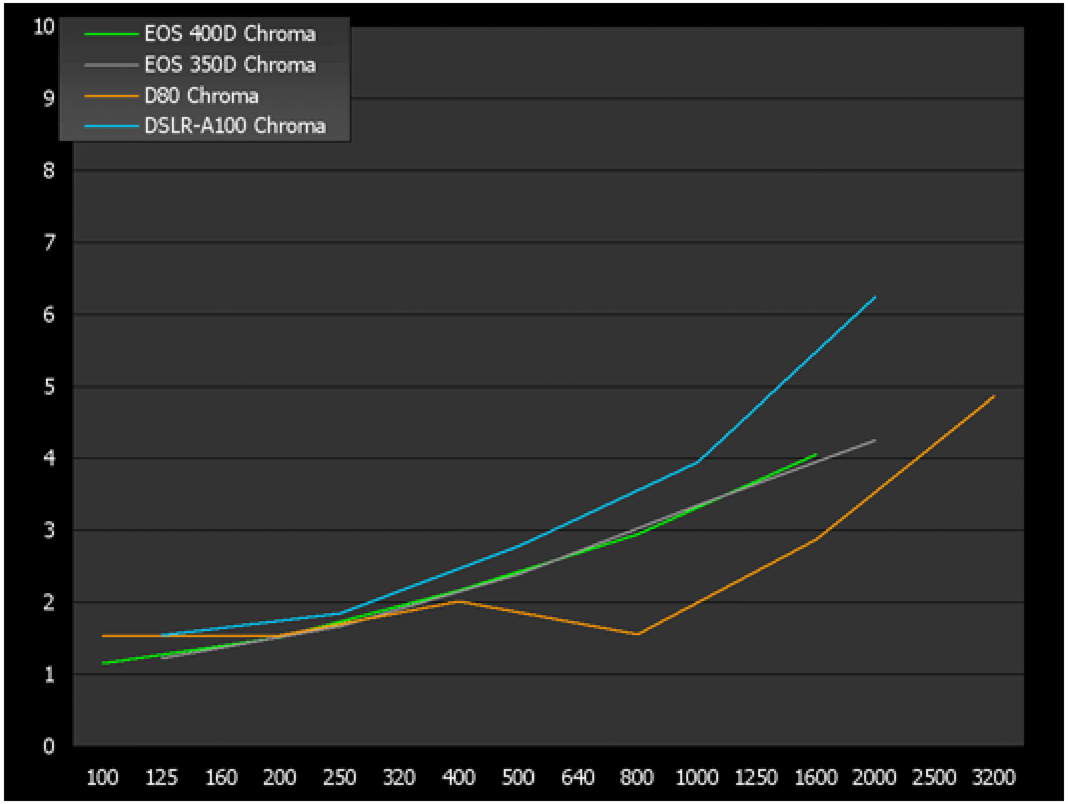
Noise as a function of Luminance (800 ISO)



Luminance Noise

Source: dpreview.com

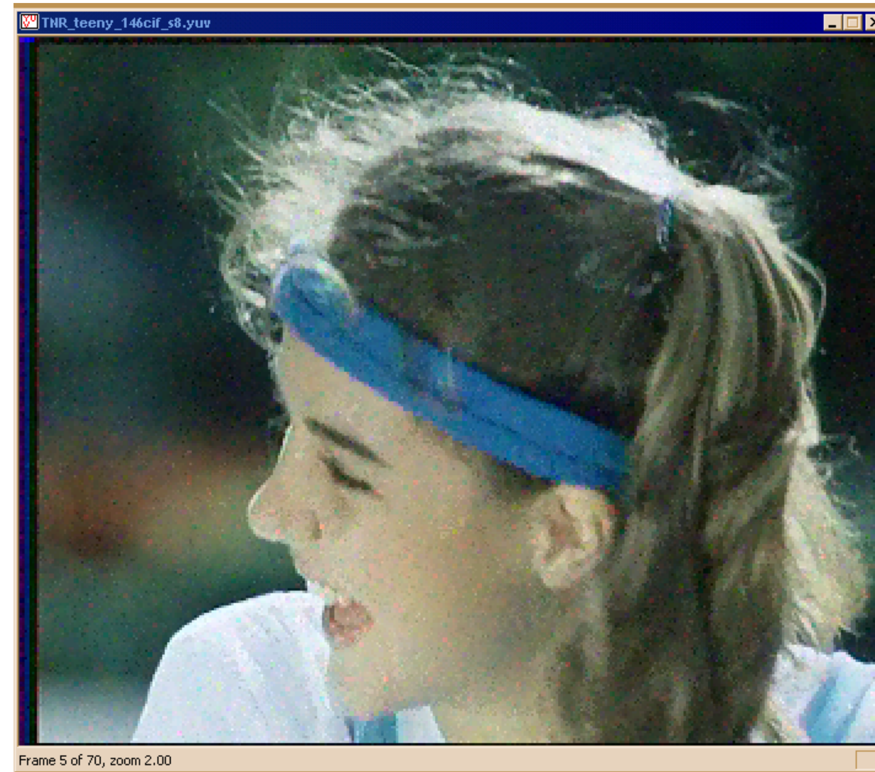
Chroma Noise



Source: dpreview.com

YUV Post-Processing Filter

Noisy frame from a YUV 4:2:0 sequence.
Luminance noise σY = 8
Chroma noise σCb = σCr = 8.



Corresponding filtered frame

The end