An Introduction to Digital Camera Signal Processor

A Typical Image Pipeline for Digital Camera

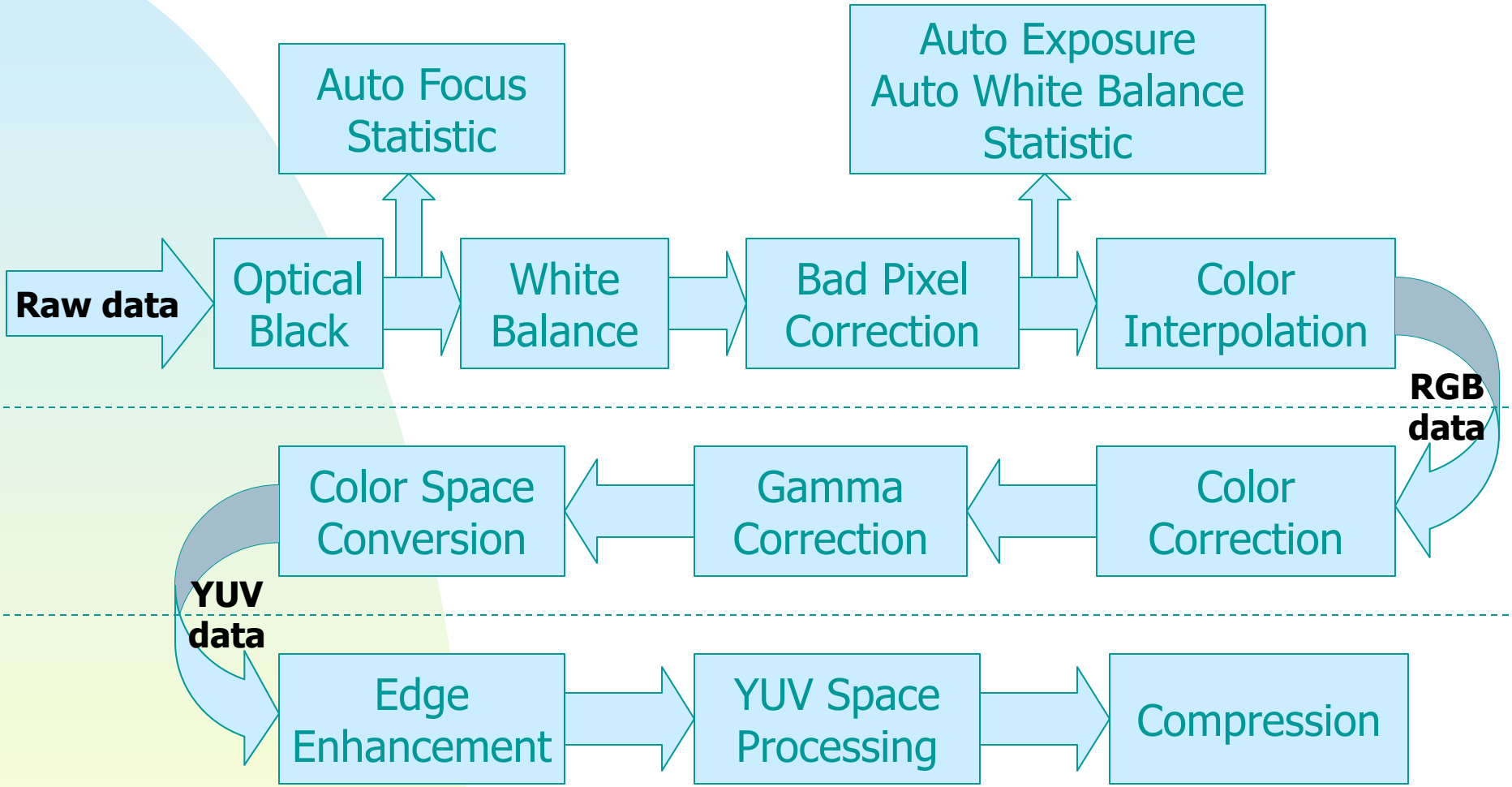


Image Pipeline Overview

- From image sensor raw data to final image
- Targeted at matching human perception
- Pipeline approach
- Linear or nonlinear
- Color depth consideration
- Calibration, Compensation, Correction, and Concealment

Image Pipeline Step by Step

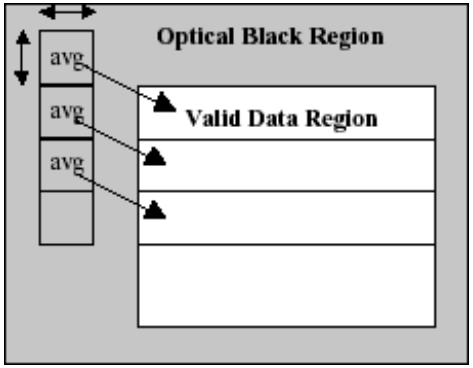
- Each step has its purposes.
- Instead of describing the techniques for each process, we like to focus on their general approaches and their meanings on the image pipeline.
- We will introduce the general why and how.

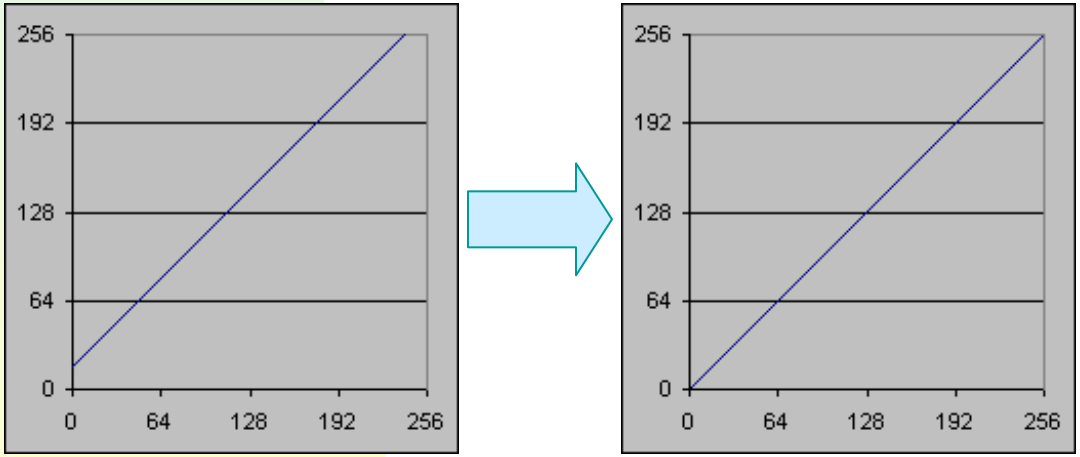
Image Sensor Output

- CCD (Charge-Coupled Device)
  - Monitor mode (preview): full width * 2XX sub-sampled line
  - Capture mode (still): full frame output
  - AF mode: faster frame rate with less lines output
- CMOS (Complementary Metal-Oxide-Semiconductor)
  - Monitor mode: Down sampling output by two or ...
  - Capture mode: full frame output
  - Special mode: window output with panning feature

Optical Black Clamping

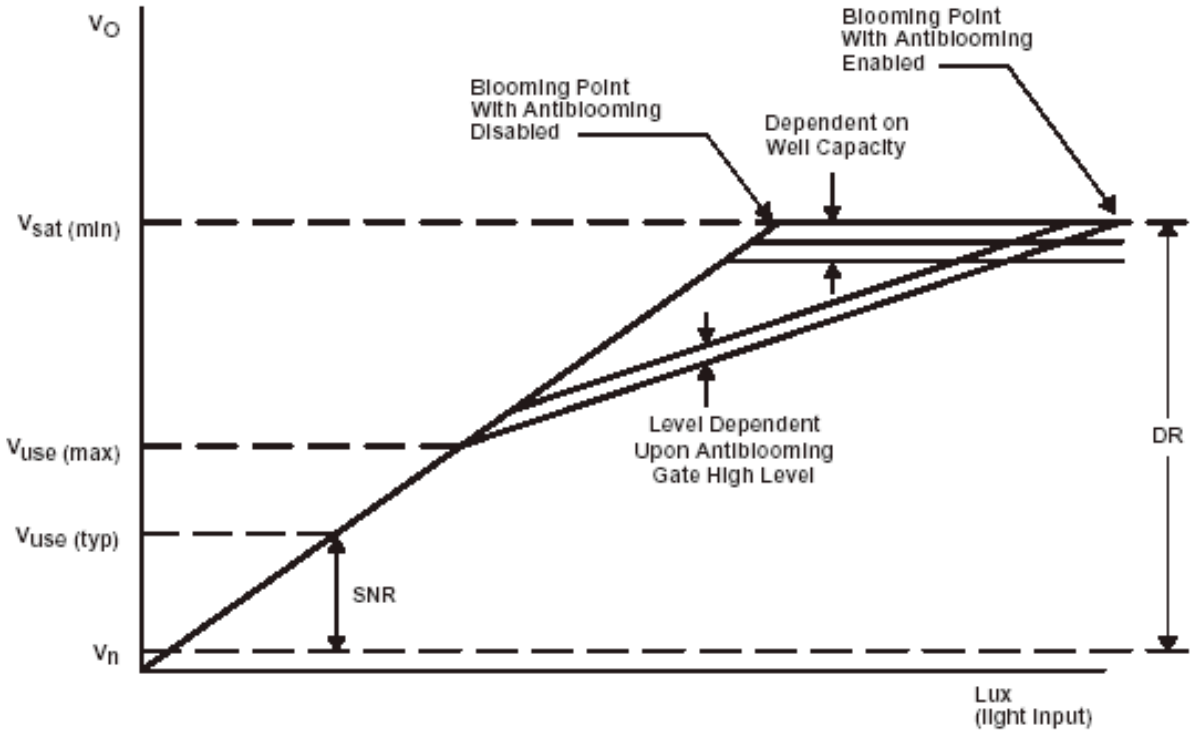
- Compensate image sensors' dark signal
- Subtract OB (Optical Black) from pixel signal
- OB value
  - Computed by DSP from image sensor's OB area
  - Manually set by firmware





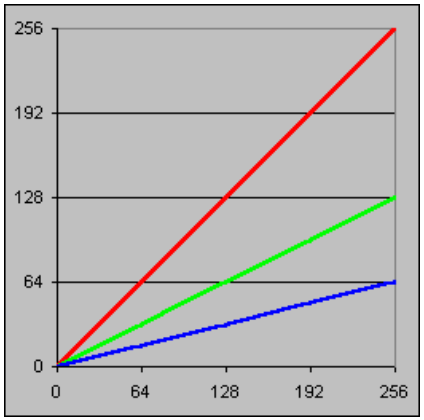
Tone Correction

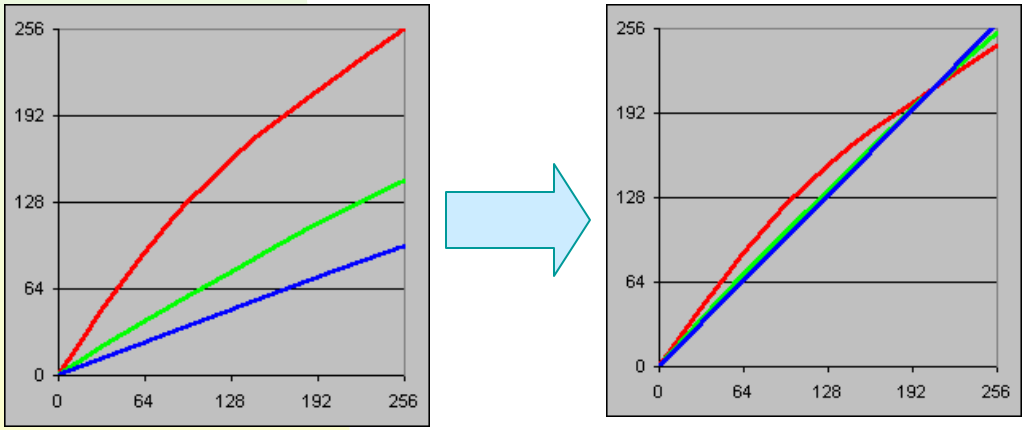
- To linearize image sensor's response curve
  - Foveon X3 has linear log response curve.
  - Analog video source is nonlinear.
- Linearization should be done before further processing
- A nonlinear example:
  - TI CCD sensor

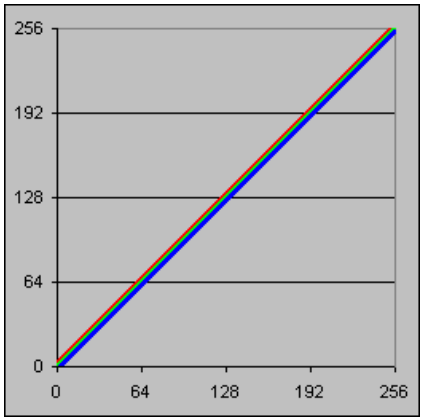


White Balance

- To simulate human eyes white balance
- Adjustable channel gain for each color channel
- General approaches
  - Gray world assumption
  - Perfect reflector assumption
  - Calibration based approaches
- What if data are nonlinear?







Bad Pixel Correction

- Non-perfect image sensors
- More than what the spec. claims
  - Judgment standards are different!
- Must be done in raw data space to prevent bad pixels from polluting neighborhood
- Considering edge and gradient information

Error pixel
(Uncorrected)

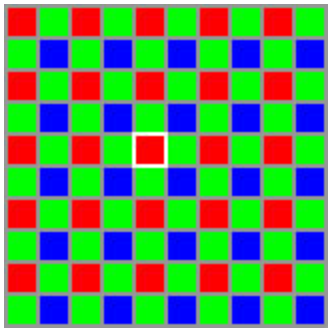
Typical pixel
error correction

NuCORE pixel
error correction

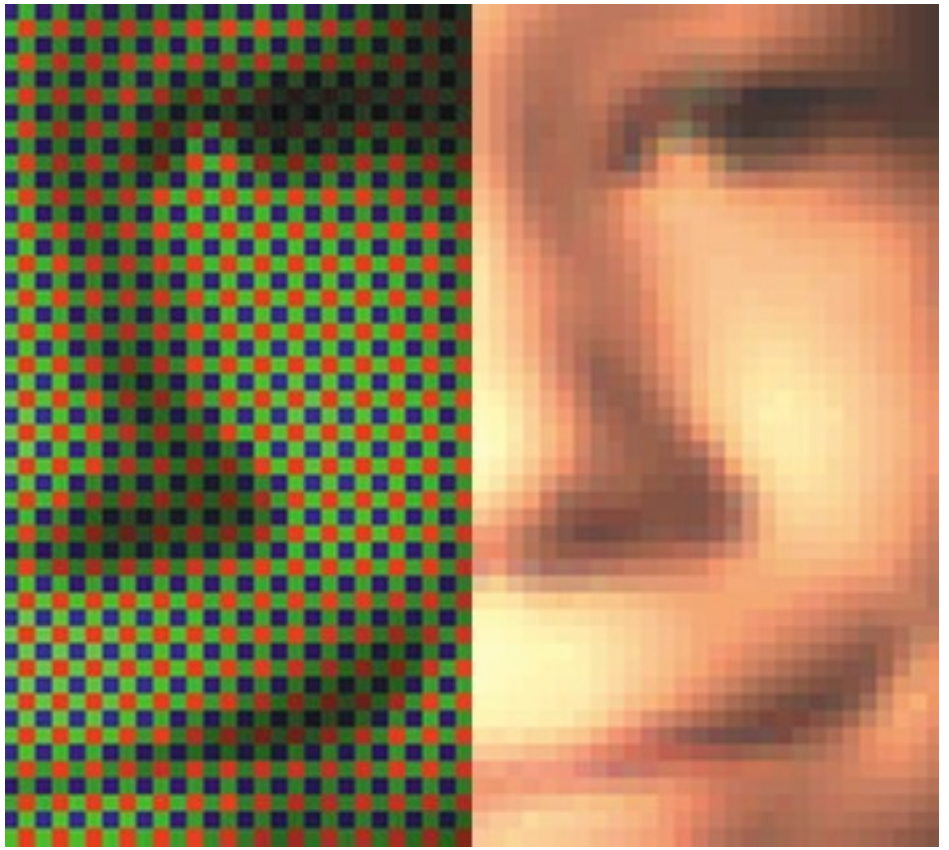
Noise Reduction

- What is noise?
  - Unnatural artifacts: power, readout, flicker...
  - Too many possible noise sources
  - Focus on removing noise sources first
- Should we reduce noise in raw or YUV space?
  - Raw data space
    - Prevent noise from going into remaining steps of image pipeline and being magnified further
  - YUV space
    - More information to reduce noise correctly.

Color Interpolation



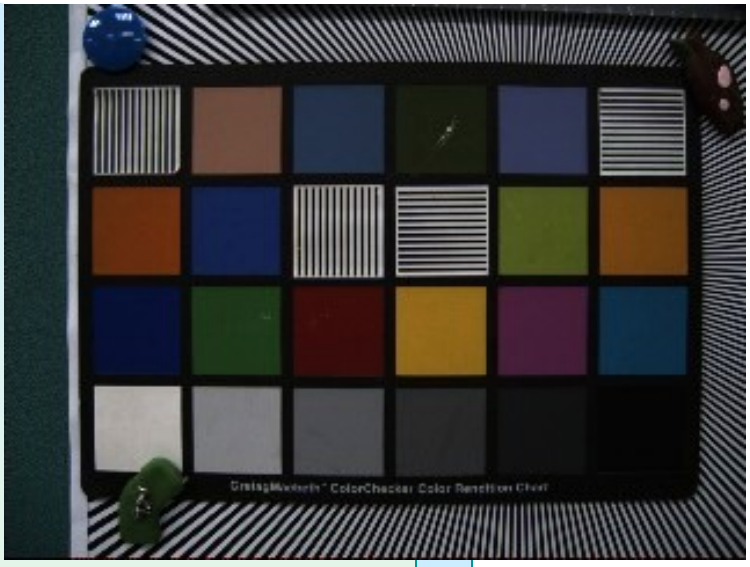
- Also called de-mosaic / raw2rgb...
- Guess missing channels for each pixel by the following:
  - Neighbor pixels
  - Edge
  - Gradient
  - ...
- Avoid zigzag and false color artifacts



Color and Gamma Correction

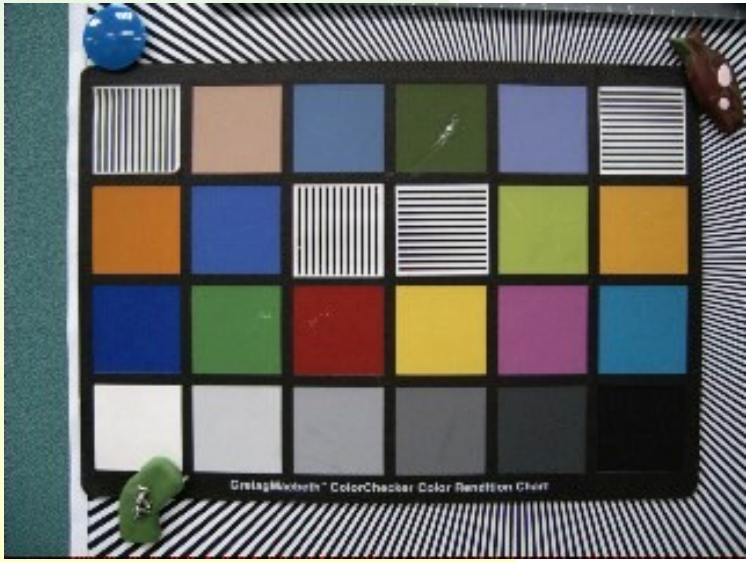
- Image sensor's color sensitivity is different from human eyes.
- A 3x3 matrix multiplication and a nonlinear gamma mapping are used to correct color to match TRUE color. However, there is no TRUE color.
- Color target is used to replace TRUE color.
- Correction means solving best matrix and gamma.
- sRGB assumes 2.2 gamma correction but...
  - No one really cares.
  - Perceptive correctness is the truth.

Influence of Color and Gamma

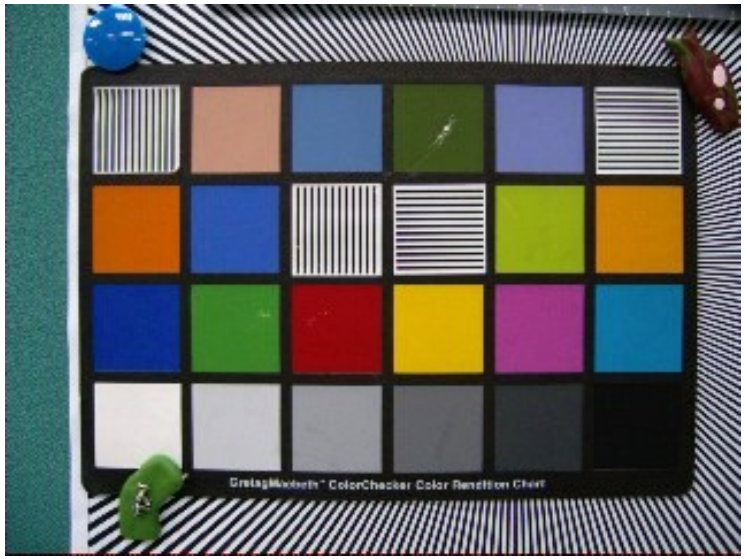


Matrix

Gamma



Gamma



Color Space Conversion

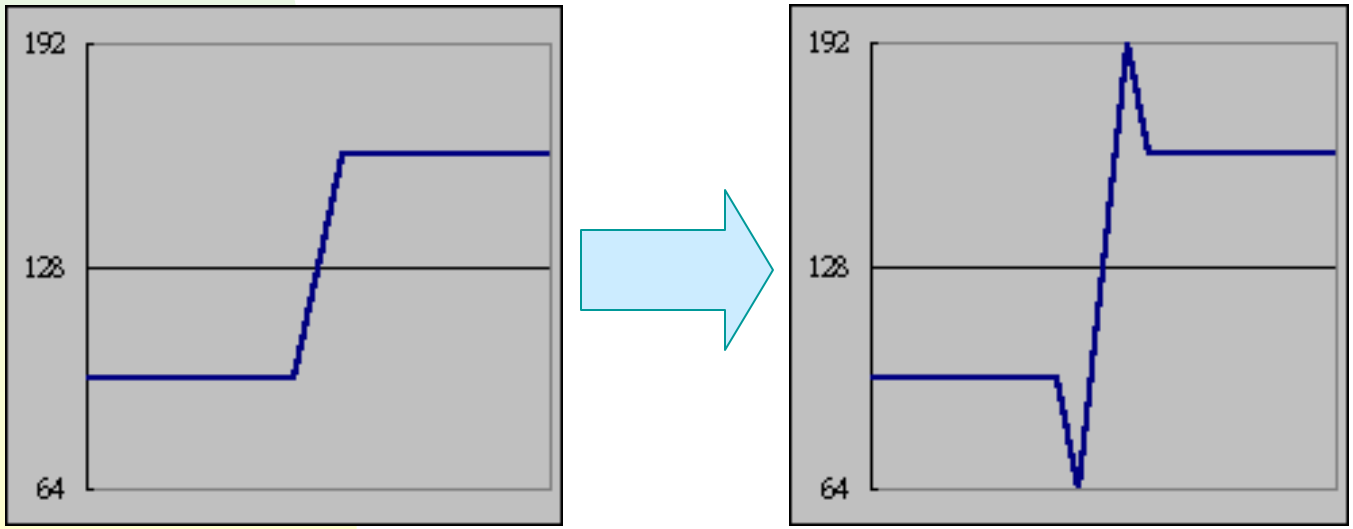
- RGB <-> YUV
- Prepare for brightness/contrast/hue/saturation adjustment and JPEG (Joint Photographic Experts Group) compression
- Typically done by 3x3 matrix multiplication

Tone Mapping

- Map tone curve to get better image
- Similar to histogram adjustment or Photoshop's curve function
- For Y channel only

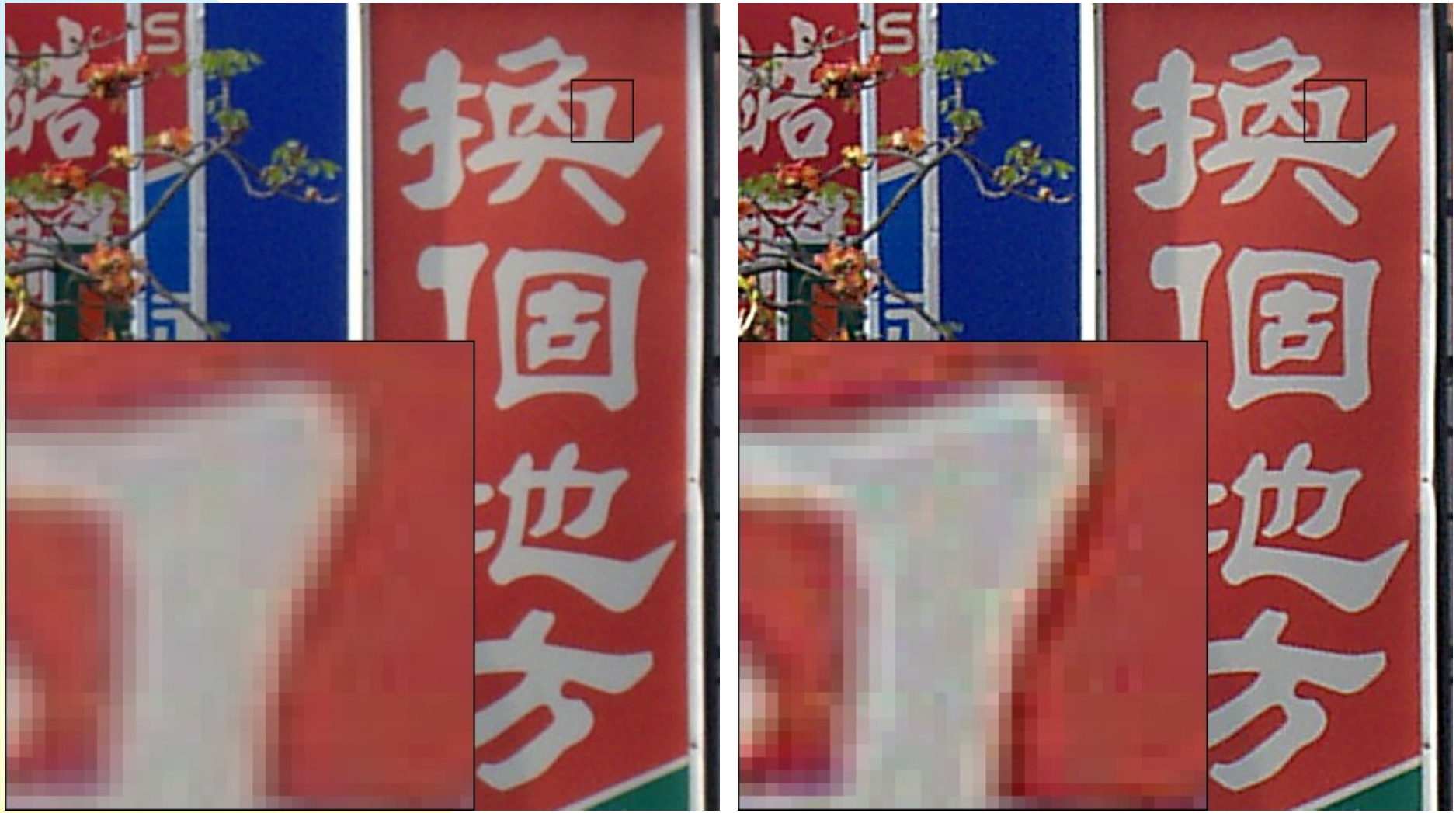
Edge Enhancement

- A must - all cameras add edges
- General approaches
  - Edge filter: NxN, 1xN+Nx1
  - Edge gain control
  - Edge detection module
- Noise should not be enhanced



Edge Enhancement

- Normal and strong edge enhancement



Resizing and Cropping

- Preview display
  - Sensor lines number doesn't match with LCD.
- Video capture
  - Sensor lines number doesn't match with output.
- Digital zoom
  - Crop smaller area centered at original center
- Raw data space or YUV space
- Performance vs. quality
  - Dropping or duplication, bilinear interpolation, bicubic interpolation

AE / AF / AWB (I)

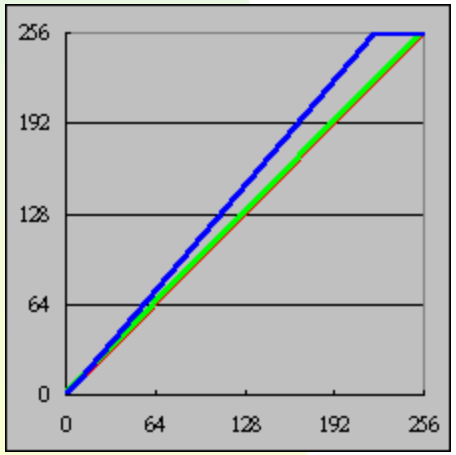
- Closed loop controls for passive 3A (active 3A are totally different)
  - Data collecting + control mechanism + converging algorithm
- AE (auto exposure)
  - Collect luminance before gamma correction
  - Control exposure time, analog gain, iris,...
  - Converge luminance to AE target

AE / AF / AWB (II)

- AWB (auto white balance)
  - Collect color statistic after white balancing
  - Control color gain
  - Converge color average to white target
- AF (auto focus)
  - Collect focus value before edge enhancement
  - Control image plane position via AF motor
  - Find position with maximum focus value

More Processing (I)

- To avoid false color
  - Color clamping
  - False color suppression
  - Color noise reduction
- Lens shading correction
- Lens distortion correction



More Processing (II)

- Skin-tone detection

More Processing (III)

- Digital flash (local contrast normalization)
  - Improve the contrast on dark area like a flash light
  - http://www.ukapical.com/products_DSC_inter.htm

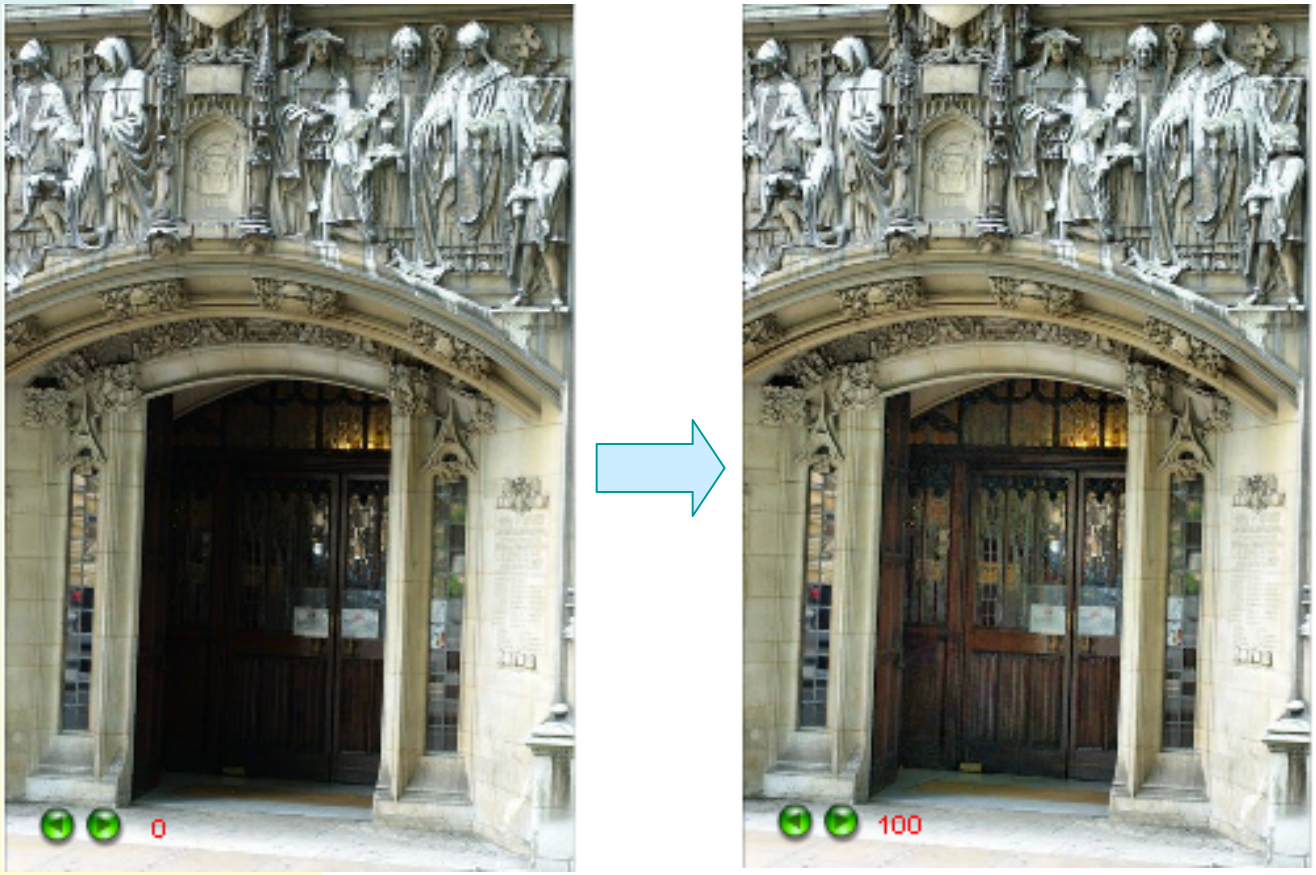


Image Details Degradation

- Image process harms image details
  - Increasing noise
  - Accumulating rounding error
  - Overflow and underflow
- Less processing is better

Image Pipeline Noise (8-bit, δ=0)

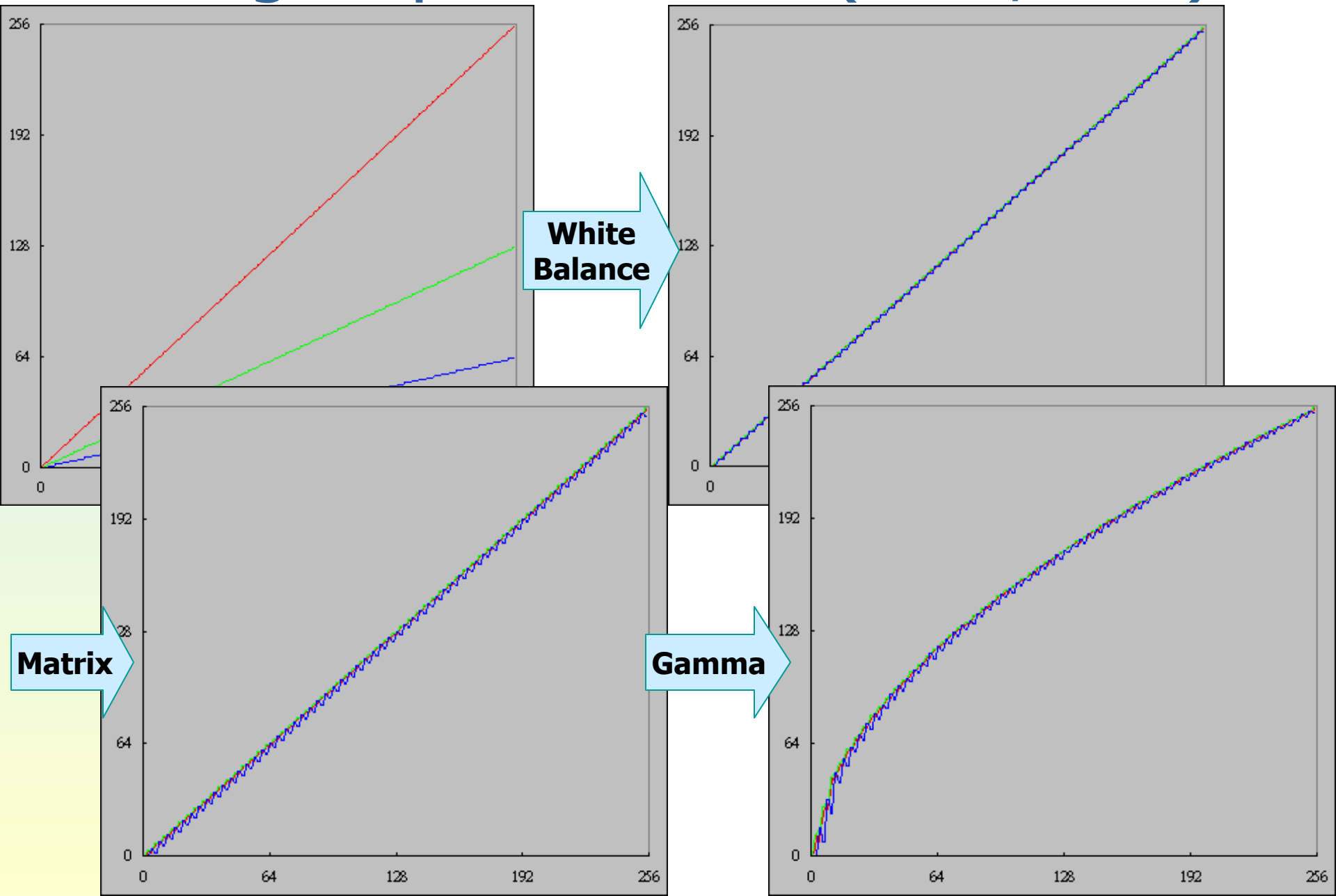
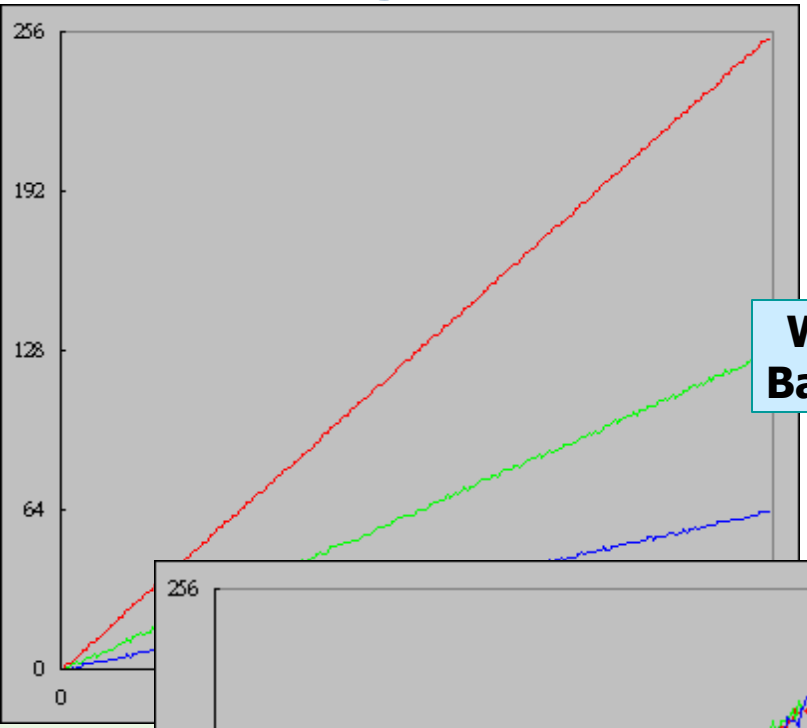
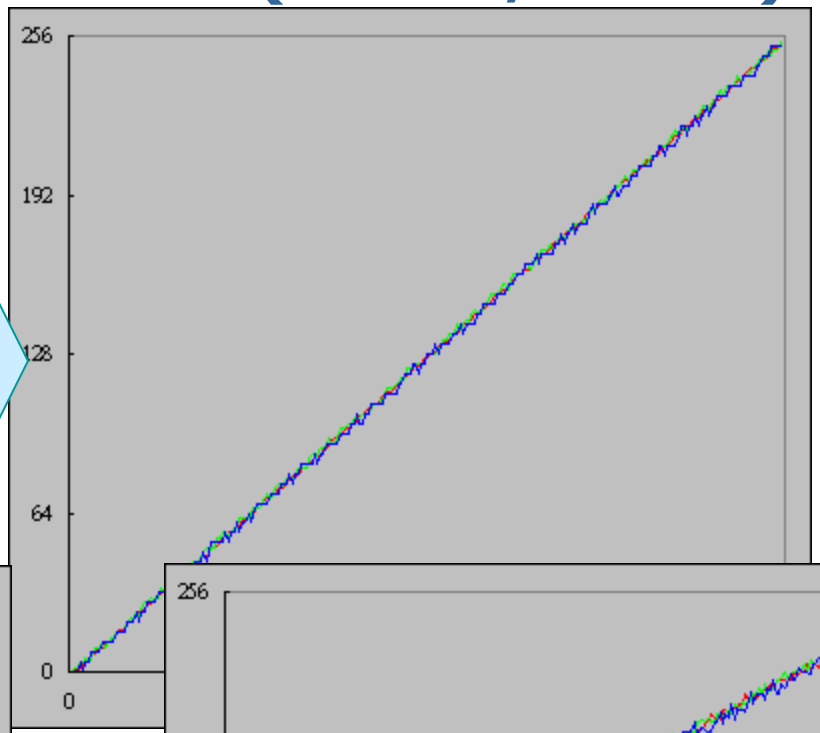


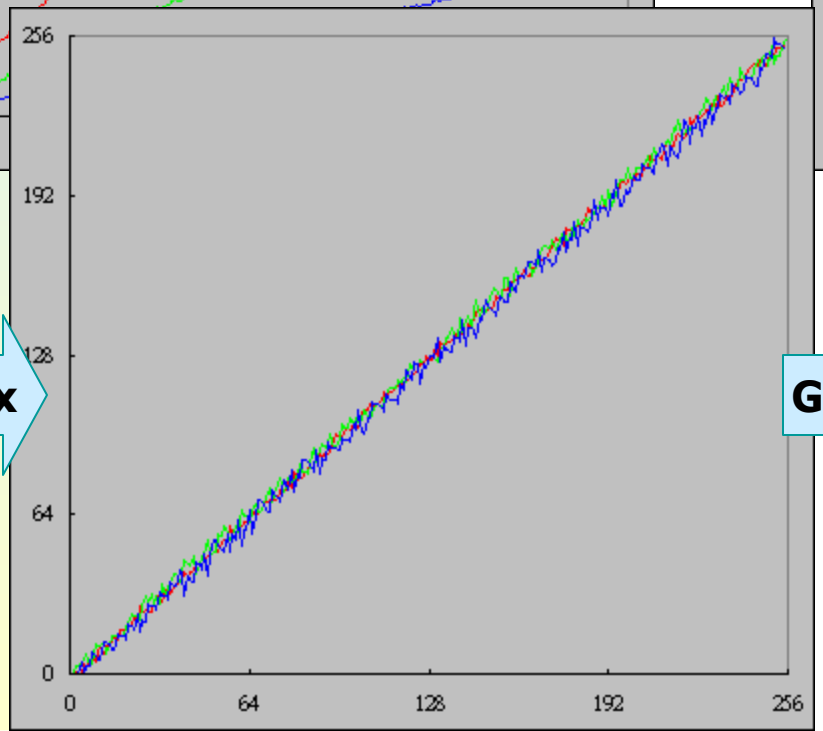
Image Pipeline Noise (8-bit, δ=2)



White Balance



Matrix



Gamma

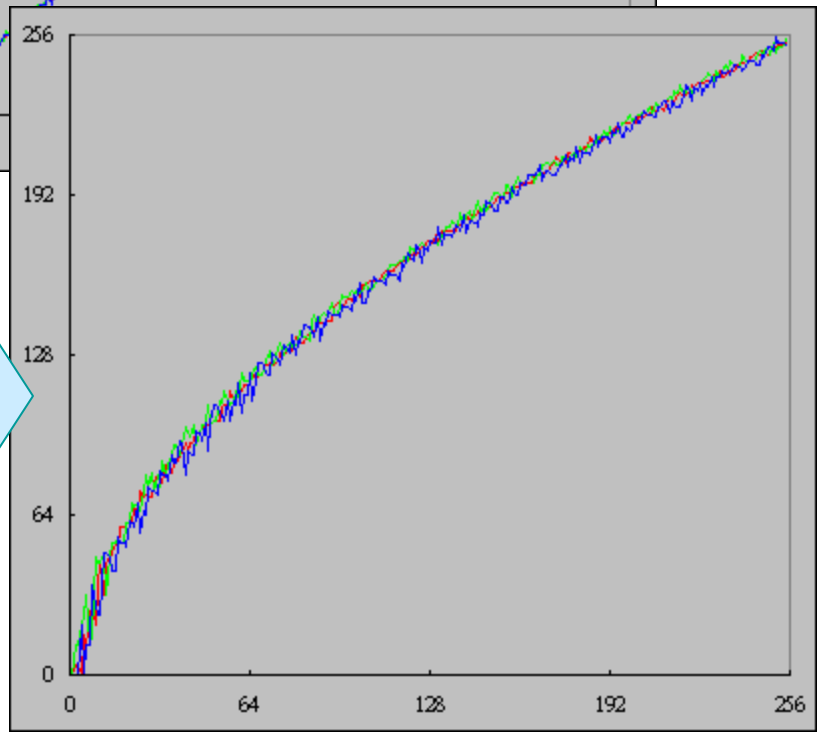
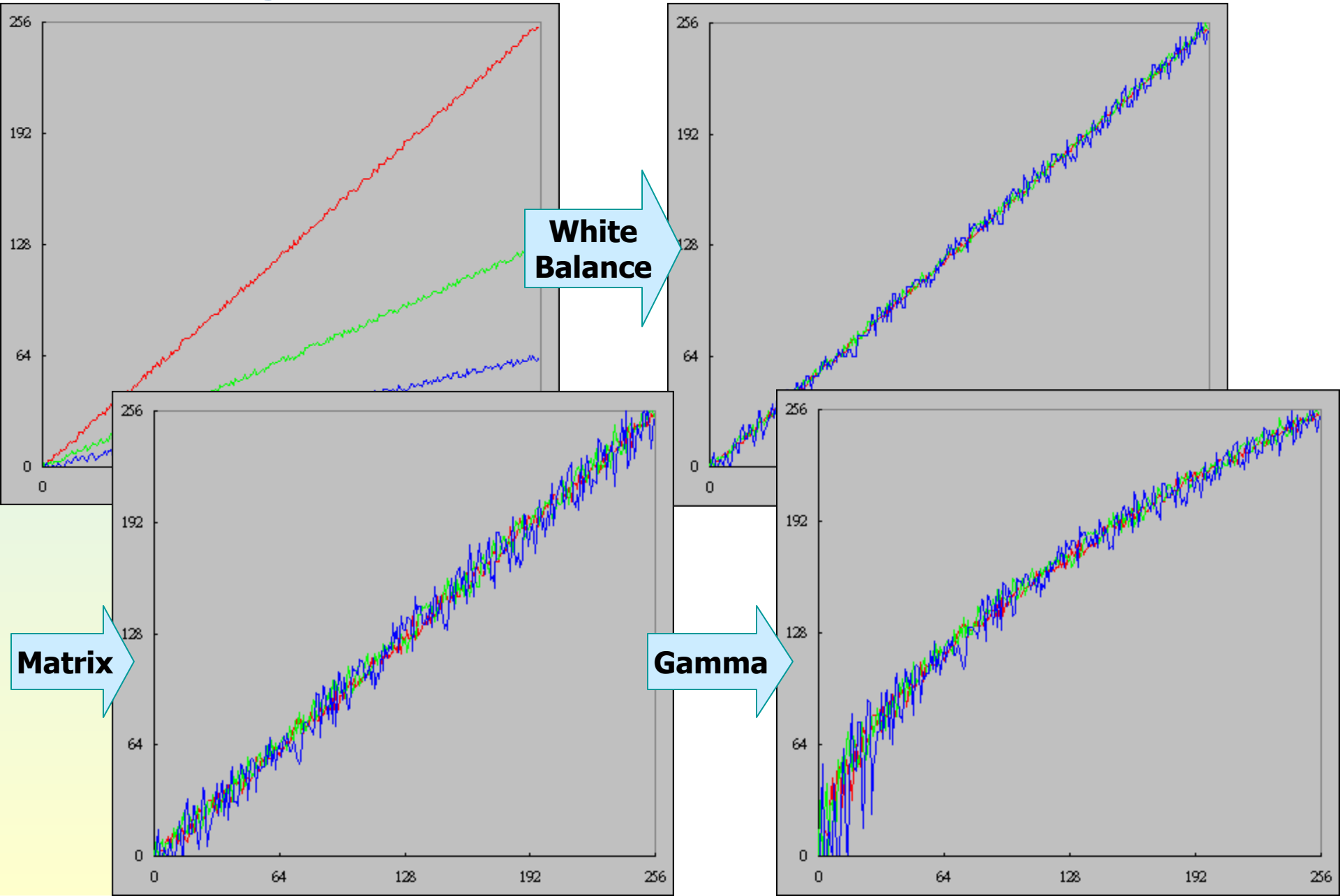


Image Pipeline Noise (8-bit, δ=4)



Performance & Resource Consideration

- Memory buffer size
- DRAM bandwidth
- Computing complexity
- Pipelining: overlapping operation

Image Pipeline Fine-tuning

- From beginning of pipeline
- Step by step
- Back and forth

Zoran COACH 6

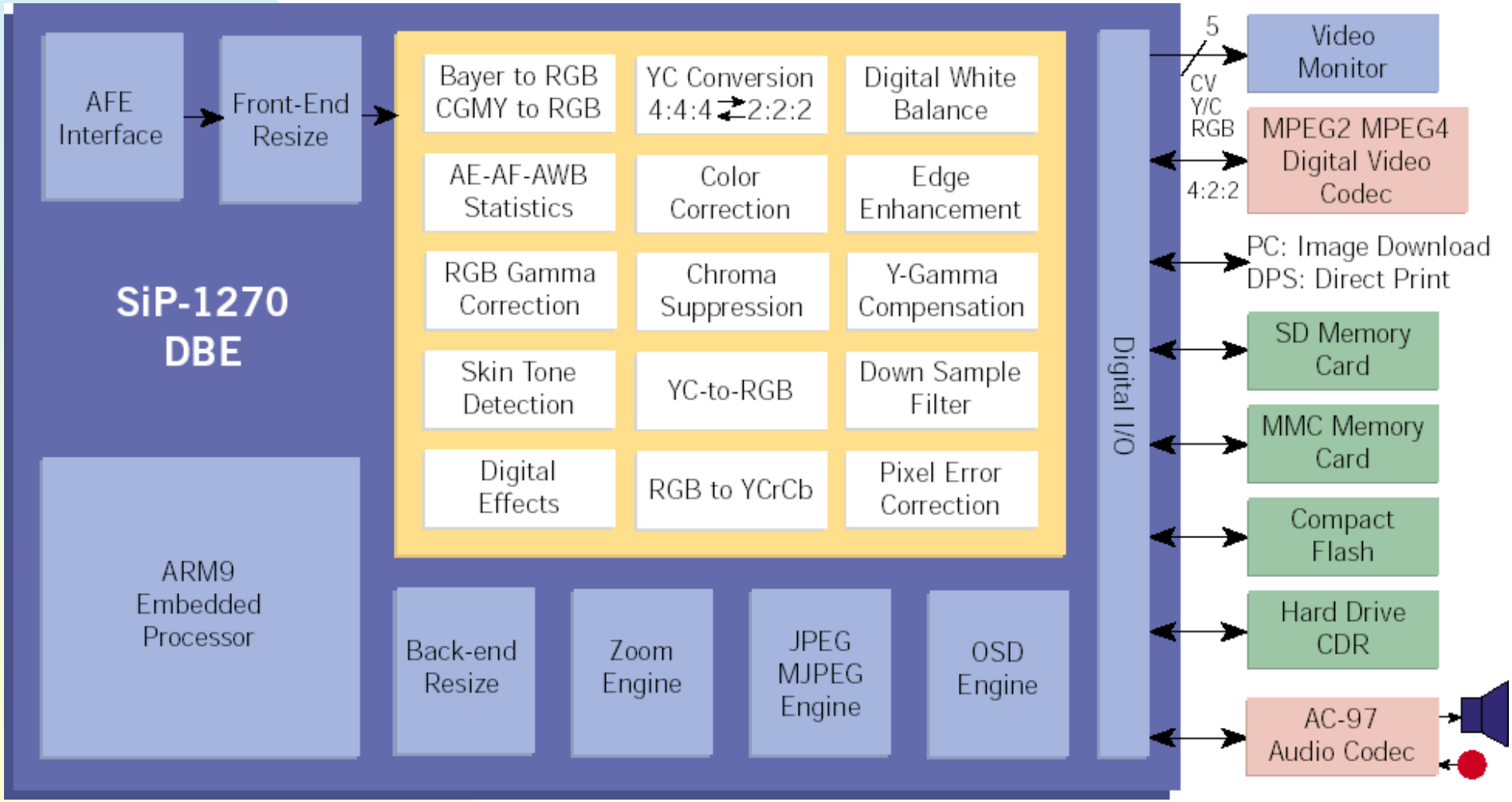
Features

- Direct glueless interface to multiple-field & progressive CCD and CMOS sensors
- Supports image resolutions up to 3 Megapixels for COACH 6e and up to 16 Megapixels for COACH 6p
- Enhanced CCD signal processing with
  - 12-bit processing for high dynamic range
  - Color interpolation and conversion
  - HW based Image scalers (zero penalty on click-to-click times)
  - Automatic White Balance (AWB)
  - Automatic Exposure (AE)
  - Edge enhancement
  - Programmable Lens Shading (Patent Pending) compensation
  - Performance enhancement when using Zoran's CMOS sensor

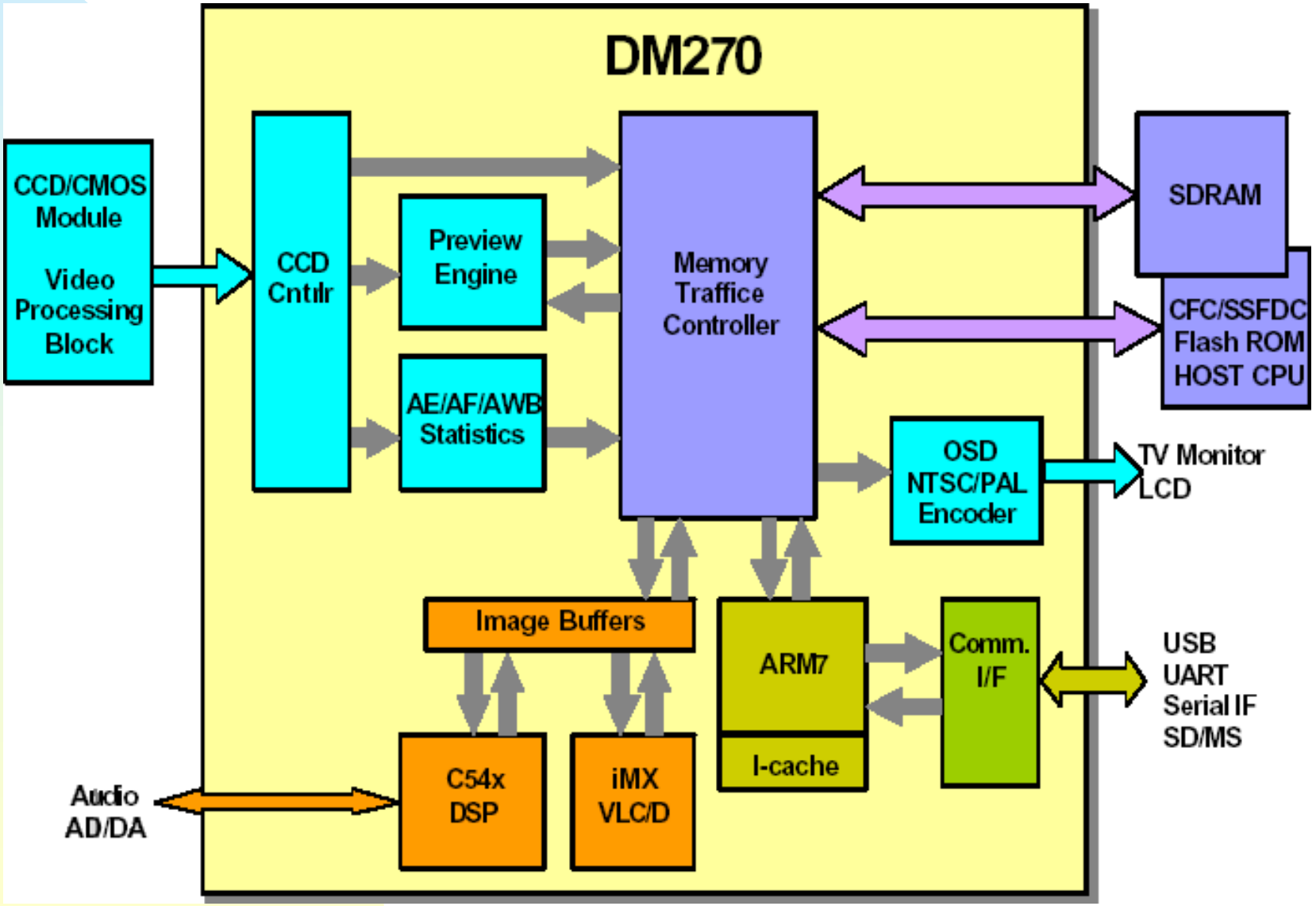
- Programmability for image processing algorithms
- Smooth Digital zoom – complete emulation of optical zoom (view, capture and clip recording)
- Real-time JPEG compression with advanced bit rate control
- Capture of a sequence of still images
- Movie (AVI, with compressed audio) capture and playback to the Flash card, at a rate of up to 30 frames per second (CIF & VGA)

NuCORE Sip-1270

- Work with their AFE NDX-1260



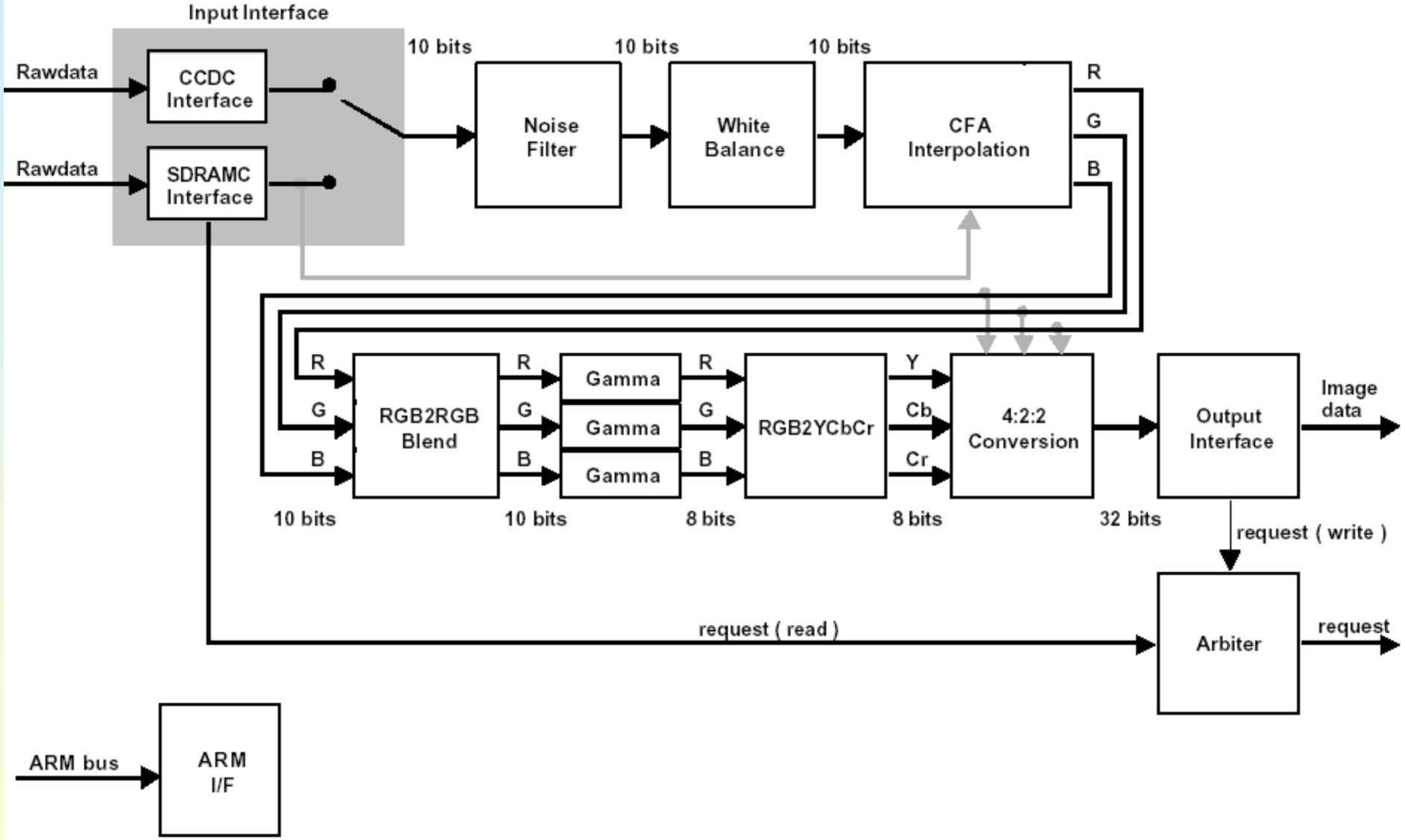
TI TMS320DM270



DM270 CCD Controller

- Digital clamping
- Black level compensation
- Median filter
- Gain and offset
- Output formatter

DM270 Preview Engine



DM270 AF/AE/AWB Statistics Engine

- AE / AWB
  - Up to 192 windows
  - Configurable rows and columns number
  - Configurable window size and position
  - Output R, Gr, Gb, B accumulation
- AF
  - Up to 36 windows
  - Configurable window size and position
  - Output G accumulation and focus value (result of two filters for green pixels)

Reference

- NuCORE Technology Inc., Sip-1270 CleanCapture™ Image Processor, 2003.
- NuCORE Technology Inc., The CleanCapture™ NDX-1260 Analog Image Processor - A No-Compromise Approach to Image Quality and Performance, 2003.
- NuCORE Technology Inc., Sip-1270 CleanCapture™ Image Processor - A No-Compromise Approach to Image Quality and Performance, 2003.
- Texas Instruments, TMS320DM270 System Spec, 2002.
- Texas Instruments, TMS320DM270 CPU and Peripherals - Technical Reference Manual Version 1.0, 2003.
- Texas Instruments, TC255P 336-x244-PIXEL CCD IMAGE SENSOR, 2002.
- Zoran Corporation, COACH™ 6 Digital Camera Processor, 2003.