Image Sensor Noise model for Image System Simulation

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I. Introduction to Simatest camera simulator

Finding the Image sensor noise model from

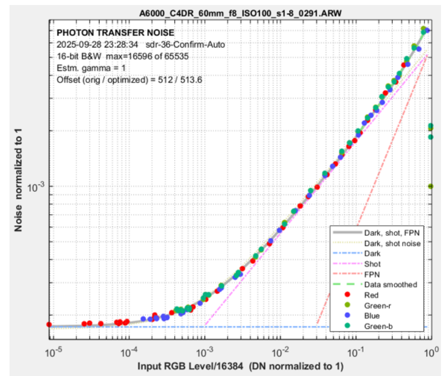
A. Photon Transfer Curve (PTC), measured from a raw (undemosaiced) image of an InfoDR or 36-patch HDR test chart

B. EMVA 1288 results

III. Running Simatest

IV. Brief introduction to Information theory

V. Simatest results



Photon transfer curve (PTC)

Simatest Camera performance simulator

Generate Input image (test chart): same resolution as image sensor

Lens degradation: from lens design program or measurement

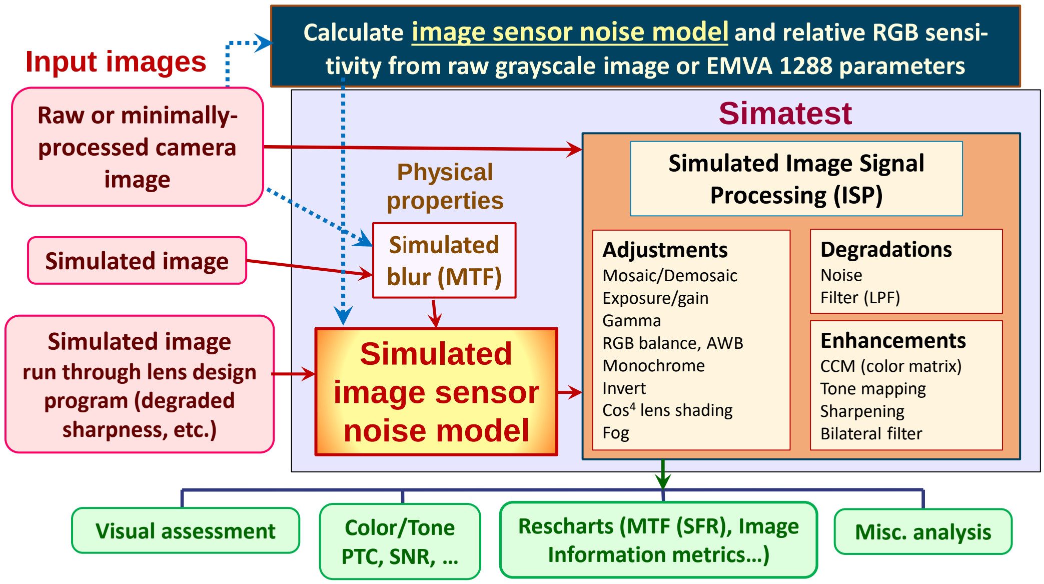
Image sensor noise model: from Photon Transfer Curve or EMVA 1288

ISP: Image Signal Processing: sharpening, bilateral filtering, color correction, *much* more…

Display results: standard and information-based metrics

The effects of illumination level, lens, sensor, and ISP on results, including information metrics, can be predicted and displayed.

Simatest — Camera/Image Signal Processing (ISP) simulator



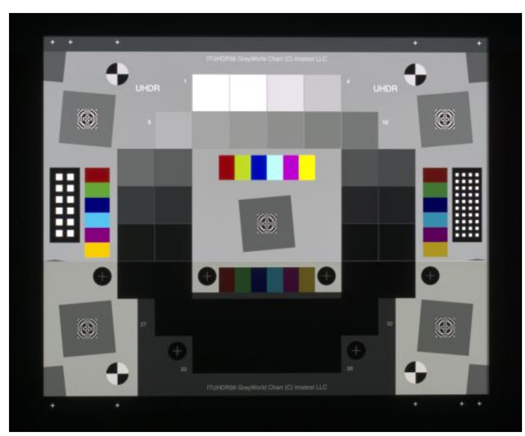
Note: Simulated or acquired Test Chart images are especially valuable, but any image can be used.

Obtaining the Photon Transfer Curve (PTC)

Raw (undemosaiced and unprocessed) images have a remarkable property.

the noise in each patch is a function of the mean digital number (DN), independent of color.

This allows the PTC — a plot of noise as a function of exposure (–chart density) to be measured from a raw image of a High Dynamic Range (HDR) test chart, such as the 36-patch DR chart shown in RGB on the right.



HDR chart image (RGB)

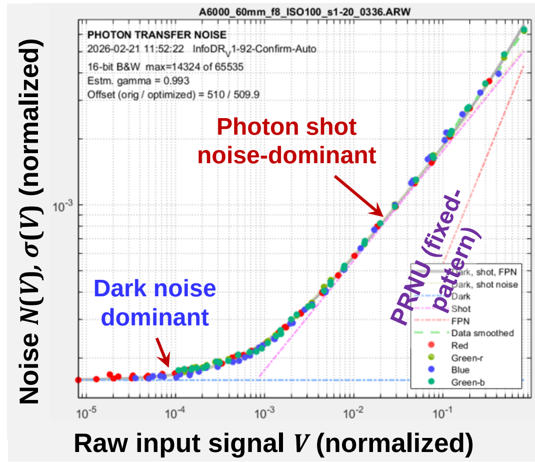
The PTC can be used to derive an *image sensor noise model* that can predict camera performance under a wide variety of conditions

Structure of the Photon Transfer Curve

The PTC — Plot of noise as a function of exposure V (–chart density) combines *three* noise sources.

- **Dark noise k_{Ndark} (fixed)**
- **Photon shot noise $k_{Nshot}\sqrt{V}$: increases with $\sqrt{V}$**
- **Photo Response NonUniformity $k_{PRNU}V$ increases with V.**

$$\sigma(V) = \sqrt{k_{Ndark}^2 + k_{Nshot}^2 V + k_{PRNU}^2 V^2}$$



The heart of the noise model is the three coefficients, k. But before we calculate them, we need to deal with the *signal offset*, DN_{off}, if present.

Photon Transfer Curve – Digital Number Offset

"Raw" images often contain an offset, DN_{off}, (frequently unknown) that must be removed to obtain a correct PTC.

For a chart where the mean (input) *DN* of each patch is V_{input},

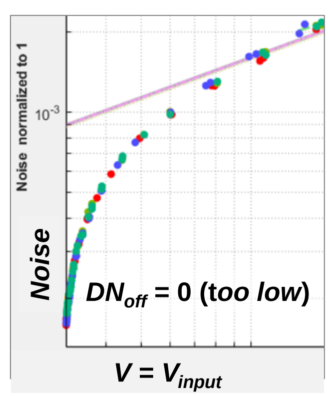
$V = V_{input} - DN_{off}$ should be used to calculate the PTC.

If DN_{off} is known, *use it!* But if DN_{off} is unknown. it can be estimated as DN_{offEst}.

If DN_{offEst} is too high, i.e., if $DN_{offEst} > V_{min}$, some values of $V < 0$, and data will be lost.

If DN_{offEst} is too low (right), the dark noise-dominant region (x-axis) is compressed, and dark noise cannot be obtained.

We have developed an algorithm for finding DN_{offEst} that works well for a wide range of linear cameras.



Estimating the Digital Number Offset, DN_{off}, for the PTC

Let D_{chart} be the set of measured patch densities for the test chart (supplied in a file for film or photomask dynamic range charts). The minimum and maximum values are D_{min} and D_{max}, and the range is $D_{range} = D_{max}\text{-}D_{min}$.

The Luminance ratio of the chart is $L_{ratio} = 10^{Drange} = 10^{Dmax}/10^{Dmin}$.

Let the mean input Digital Numbers for each patch be $DN = V_{input}$, with minimum and maximum values, V_{min} and V_{max}.

The signal V for calculating the PTC is $V = V_{input} - DN_{off}$.

The goal is to find the value of DN_{off} that makes the x-axis signal ratio identical to the luminance ratio.

$$(V_{max} - DN_{off})/(V_{min} - DN_{off}) = \min(L_{ratio}, 10^5) = L_{rTarget}$$

Solving, $$DN_{off} = (V_{max} - V_{min} L_{rTarget})/(1 - L_{rTarget})$$

This gives a reliable estimate of k_{Ndark}, k_{Nshot}, and k_{PRNU}, even though the x-axis (V) may be a little off in the dark (no signal) region.

Finding the PTC coefficients by optimization

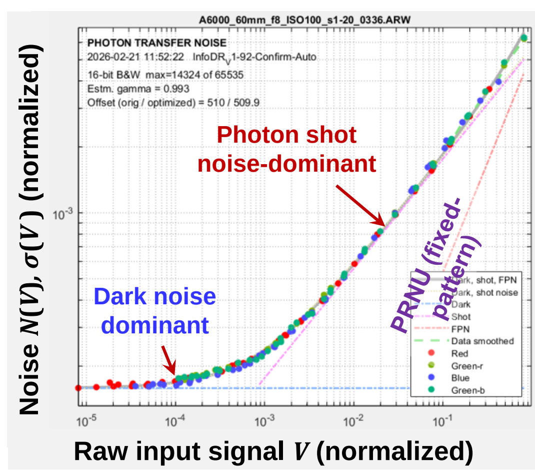
Input data for calculating the PTC consists of the measured patch noise for all channels, $N(V)$, as a function of the mean (corrected) Digital Number ($DN = V$), shown as colored dots, ● ● ● ●).

The Levenberg-Marquardt optimizer finds the values of k that minimizes

$$Error = (N^2(V) - \sigma^2(V))/N^2(V)$$

where

$$\sigma(V) = \sqrt{k_{Ndark}^2 + k_{Nshot}^2 V + k_{PRNU}^2 V^2}$$



Division by $N^2(V)$ is critical to obtaining good results. Without it, large values of N have excessive weight, and k^2_{Ndark} cannot be accurately estimated.

PTC from the 36-patch Dynamic Range chart

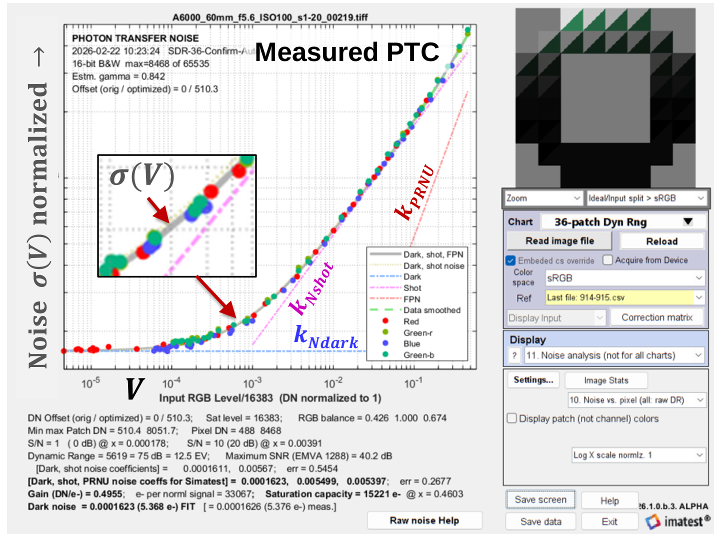
For the camera under test (24MP APS-C; pixel pitch = 3.9 μm)

k_{Ndark} = 0.0001623
Dark noise (total)

k_{Nshot} = 0.005499
Photon shot noise

k_{PRNU} = 0.005397
PRNU fixed-pattern noise

Gain (DN/e-) & RGB balance (0.426 1 0.674)also important



Photon Transfer Curve (PTC) & results

PTC from new InfoDR chart

Taken about three months after the DR36 image. Same camera.

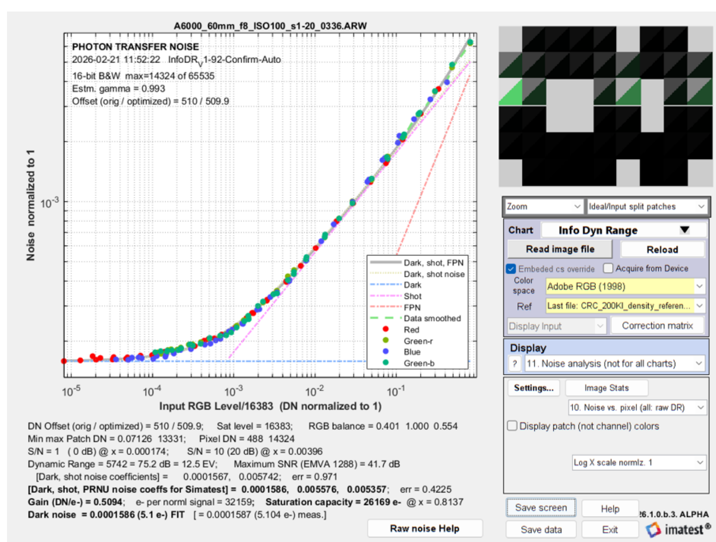
k_{Ndark} = 0.0001568 Dark noise (total) — Slightly lower: *tempera-ture-sensitive* (was 0.0001623)

k_{Nshot} = 0.005576 Photon shot noise — Close (was 0.005499)

k_{DSNU} = 0.005367 PRNU fixed-pattern noise (was 0.005397)

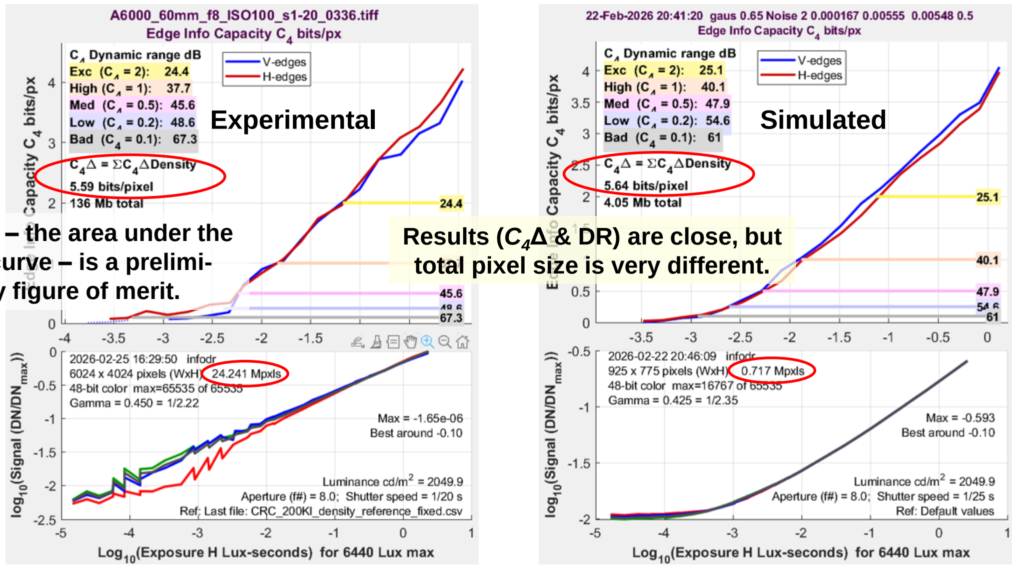
***RGB* = (0.401 1 0.554)**

Results are virtually identical, even though the charts are different.



Photon Transfer Curve (PTC) & results

Comparison of InfoDR C_4 plots: Experimental and Simulated

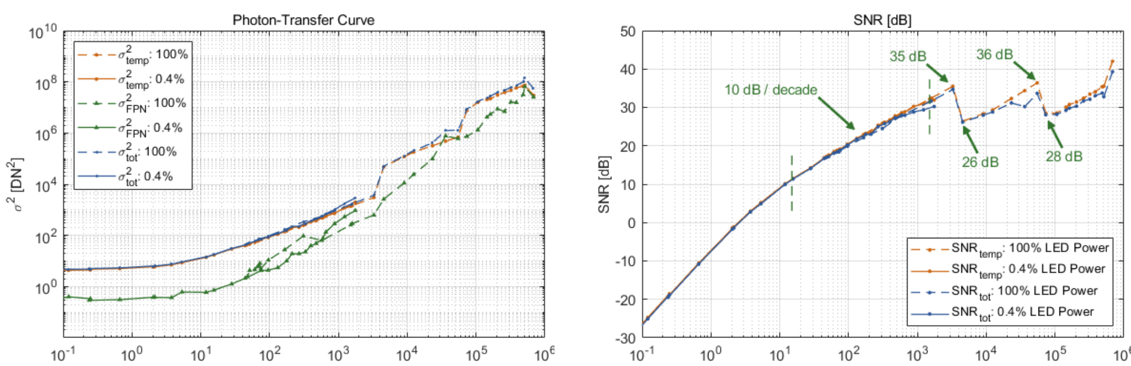


$C_4\Delta$ – the area under the C_4 curve – is a preliminary figure of merit.

Results ($C_4\Delta$ & DR) are close, but total pixel size is very different.

Unfinished work: modeling High Dynamic Range (HDR) sensors

SNR Curves: PTC and SNR Curves



from IEEE P2020 Noise Metrics – A Review
Orit Skorka and Paul Romanczyk (2022)

HDR sensors have steps in noise and SNR.

Key EMVA 1288/ISO 24942 measurements

The key EMVA 1288 results needed to model noise are

Measurement	EMVA symbol	Units
Temporal dark noise	σ_d *or* σ_{Dark}	e-
Dark Signal Nonuniformity DSNU	$DSNU_{ISO}$	e-
Dark current (noise)	μ_C *or* i_{Dark}	e-/s
(Photon shot noise = $\sqrt{K/DN_{max}}$)		
Photo Response Nonuniformity PRNU	$PRNU_{ISO}$	%
Gain (DN/e-)	K	DN/e-
Saturation capacity	$\mu_{e.sat}$	e-
From ISO 24942, section 15.2 and Annex A or EMVA 12288 4.0, section G.		

DN = Digital Number; e- = electrons; s = exposure time (seconds)

EMVA 1288 measurements for the noise model

For *DN* = Digital Number and *e-* = electrons, and *s* = exposure time, where

V = normalized amplitude $= DN/DN_{max}$ **where**

DN_{max} **is the maximum *DN* for the system, typically $2^{N\text{-}1}$ for bit depth = *N*,**

The key EMVA 1288 measurements for Simatest input are

$$k_{NDark} = \text{total dark noise} = \sqrt{\sigma_d^2 + DSNU^2 + (i_{Dark}\, s)^2} \times \text{Gain}(V/e-)$$

$$k_{Nshot} = \text{photon shot noise} = \sqrt{\frac{\text{Gain}(DN/e-)}{DN_{max}}} = \sqrt{\frac{K}{DN_{max}}}$$

$$k_{PRNU} = \text{PRNU Fixed Pattern noise} = PRNU(\%)/100$$

www.imatest.com/imaging/image-sensor-noise/#emva

EMVA 1288 vs. Imatest PTC measurements — summary

EMVA 1288 measurements are

- **well-established and documented: ISO 24942 standard.**
- **highly accurate and detailed: temporal noise and fixed pattern noise (DSNU, PRNU) sources are kept separate. Valuable for image sensor designers.**
- **time-consuming to acquire. 30+ images of a dark field and a flat field (around ½ saturation illumination) are required.**

The Imatest Photon Transfer Curve (PTC) method is

- **new and relatively unfamiliar (though the PTC has been around for a while).**
- **a subset of EMVA 1288 with less detail. Fixed pattern and temporal dark noise are combined, BUT it is sufficient for modeling camera performance.**
- **fast and convenient. One or at most two images are required.**

EITHER measurement provides input for Simatest simulations.

III. Running Simatest

Characterize the image sensor noise

- **Acquire a raw image of an HDR test chart and calculate the key parameters — k_{Ndark}, k_{Nshot}, k_{DSNU}, Gain (DN/e-), and relative RGB amplitudes — from the PTC — or —**
- **Convert EMVA 1288 measurements to the key parameters.**

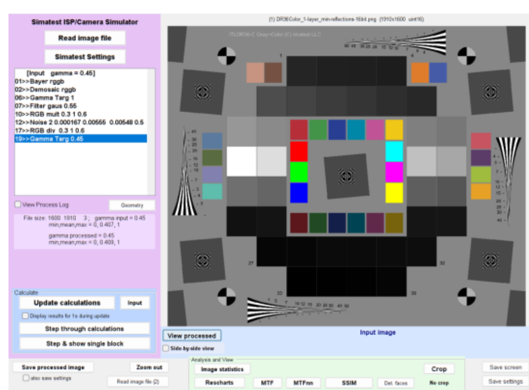
Open Simatest.

Open an ideal test chart image: HDR chart with grayscale at least one slanted edge recommended.

Enter the key parameters in the settings window, then update the calculation. You can use different settings to

- **Simulate the PTC by converting the image into pseudo-raw, or**
- **Simulate the camera for normal operation, including low light.**

Open the simulated image in an Imatest analysis module to measure performance.



New DR test chart designed to minimize ghost images

Simulated Photon Transfer Curve

Read an ideal image in Simatest.

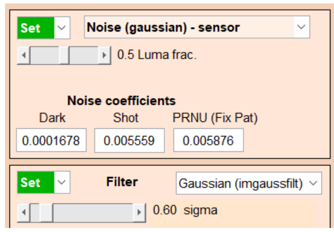
Enter parameters obtained by analyzing the raw HDR chart.

k_{Ndark}, k_{Nshot}, k_{PRNU}

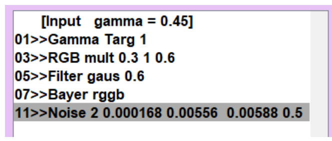
Gain (DN/e-)

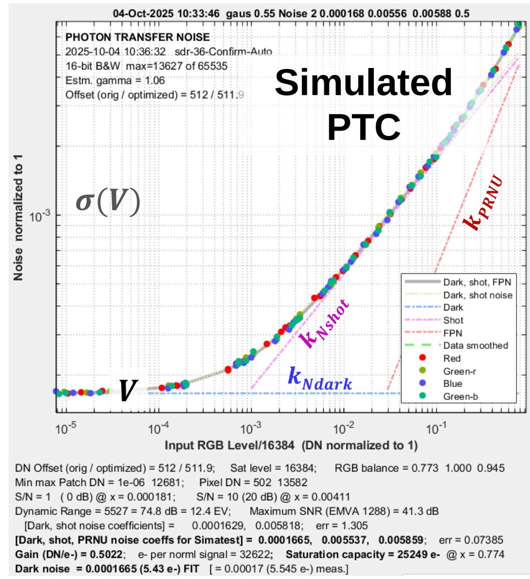
RGB balance

Noise and filter settings



Simatest processing steps

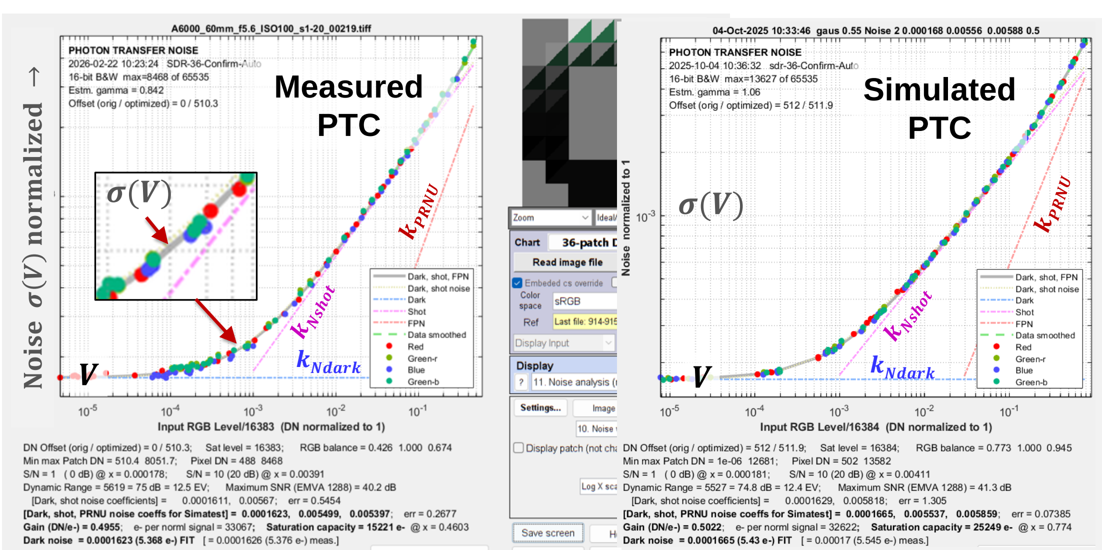




Convert the RGB image to pseudo-raw (Bayer rggb).

Open Color/Tone to obtain the PTC (right).

Measured and simulated PTC: side-by-side



Photon Transfer Curves (PTCs)

Simatest settings

To change a setting

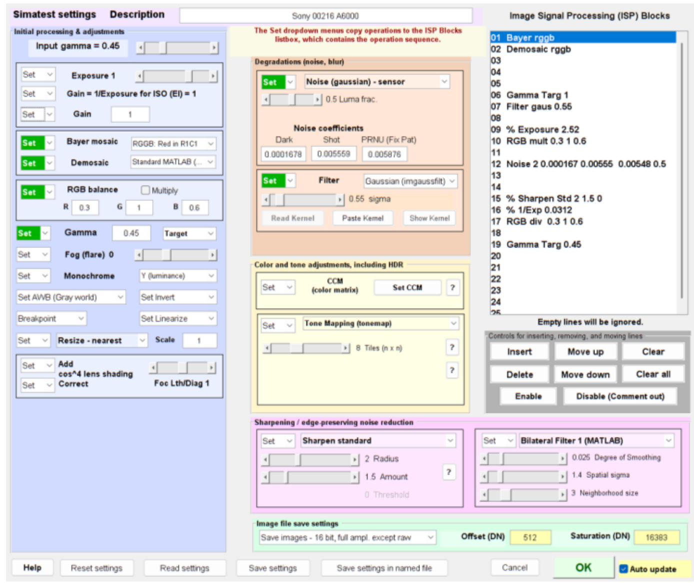
Choose a processing block.

Adjust its parameters.

Use the Set dropdown menus to copy it to a line in the ISP blocks box (right). (Empty lines & comments (%) are ignored.)

The contents of the ISP Blocks box can be edited (moved, deleted, disabled, etc.) using the buttons below the window.

Pressing OK updates the Simatest calculations if Auto update is checked.



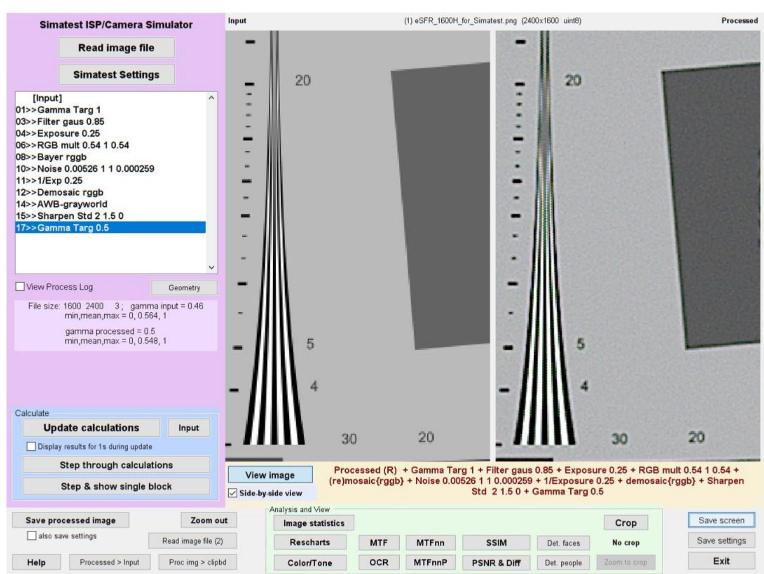
Simatest — Results: Side-by-side view

The original simulated image is on the left.

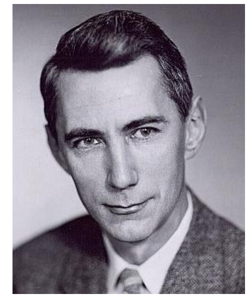
The processed image with blur, noise, sharpe-ning, etc., is on the right.

Processing steps are displayed on the left.

Buttons on the bottom let you select the results display or send results to *Imatest* modules for further analysis.



IV. Information theory & metrics – Introduction



Developed by Claude Shannon at Bell Labs in 1948-9.

Information is the amount by which uncertainty is resolved. Classic example: The result of a "fair" coin flip (*P*(*head*) = *P*(*tail*) = 0.5) has one bit of information. Lower for a biased flip.

Widely used in electronic communications, where channels are characterized by information capacity C in bits/second.

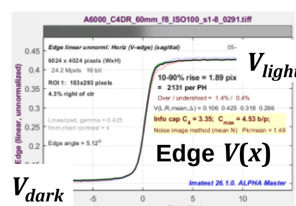
Images are communication channels where C has units of bits/pixel or bits/image.

***Imatest* has developed a method to conveniently calculate C by measuring signal power, $S(f)$, and noise power, $N(f)$, at the *same* slanted-edge location.**

C_4 is the amount of information a 4:1 object can convey. It is measured directly from 4:1 contrast slanted edges. C_{max} is the maximum information the image can convey. Its calcu-lation involves extrapolation — not valid for HDR sensors.

Shannon-Hartley equation for C_4

4:1 contrast edges are specified by ISO 12233 and widely used for practical measurements.



$$S(f) = \left(\left(V_{light} - V_{dark}\right) SFR(f)\right)^2 / 12$$

is the mean signal power derived from the edge, *V*(*x*): includes sharpness (*SFR*(*f*)).

$$C_4 = \int_0^W \log_2\left(1 + \frac{S(f)}{NPS(f)}\right) df$$

C_4 is the amount of information that can be conveyed in a 4:1 contrast edge. It is sensitive to exposure.

W is always the Nyquist frequency, 0.5 Cycles/Pixel.

$NPS(f)$ is the Noise Power Spectrum, from the noise image

C_4 is a *complete* pixel-level performance metric that combines *partial* metrics: Signal amplitude, sharpness, and Noise.

C_4 vs. Exposure ($\log_{10}(H)$) from the new InfoDR chart

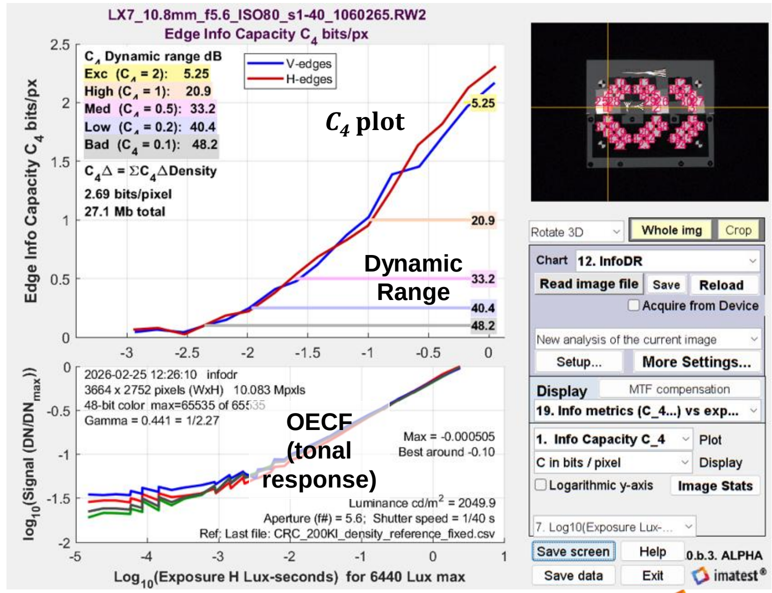
***C* is relatively unaffected by reversable image processing.**

***C_4* is a compromise.**

Contrast is

- ***typical of objects of interest.***
- ***Low enough to easily avoid saturation.***
- ***High enough to have decent SNR.***

Also: *SNRi* (ideal observer SNR quanti-fies object detectability



A few more notes on information

(a big subject — new and unfamiliar in imaging science.)

Information capacity *C* is (relatively) unaffected by *reversable* image processing (linear with no response nulls for $f < f_{Nyquist}$).

***C* cannot be increased by image processing, but *bilateral filters*, which sharpen edges but smooth low contrast areas , can falsely increase the measured value of *C*. They are nearly universal in JPEG files from cameras.**

Several metrics derived from C_4 are affected by image processing, which can be optimized with an approximate matched filter.

The most important is ideal observer SNR (SNRi), which is a metric for object detectability, affected by image processing, image contrast and object size.

Information capacity and the new metrics are the basis of the proposed ISO 23654 standard.

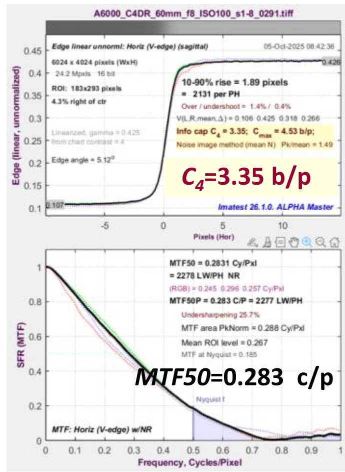
Full description: Image information metrics from slanted edges

V. Simatest results: acquired vs. simulated image

Edge rise distance, *MTF50*, *MTF Area PkNorm*, and **Information capacities** are similar.

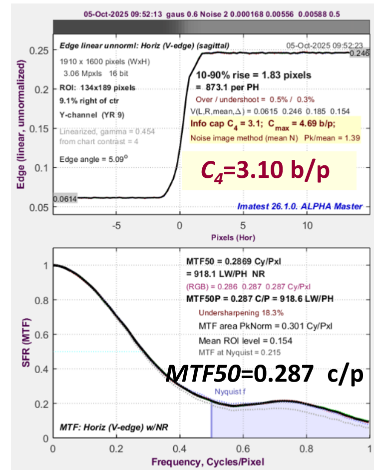
The shapes of the MTF curves are somewhat different.

Using parameters from the PTC or EMVA 1288, simulated results from Simatest are close to experimental results.



Acquired image

(demosaiced raw with minimal processing)



Simulated image

Noise model from undemosaiced raw image. Filter blur set to match MTF50 (demosaiced).

Simulating low light (high ISO speed) performance

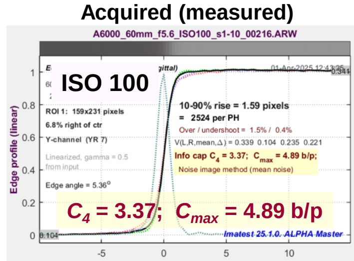
Simulated image from an ideal edge with blur added to match MTF50 of demosaiced acquired image.

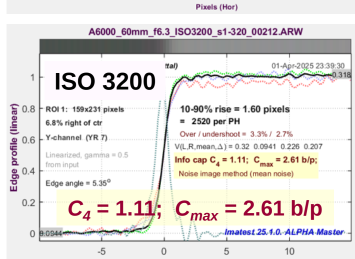
Noise model was calculated from an ISO 100 raw image.

High ISO speed (equivalent to low light) was simulated by attenuating the signal, adding the modeled noise, then restoring the signal.

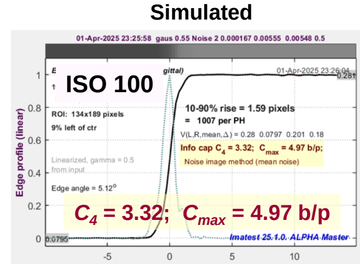
Simatest can predict system performance for a wide variety of conditions, including low light and ISP tuning.

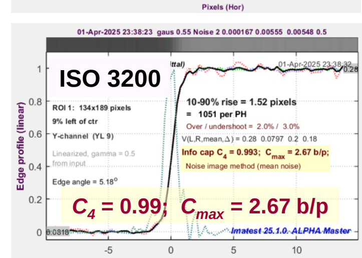
Acquired (measured)





Simulated





www.imatest.com/imaging/Simatest-overview/

Image sensor noise model — Summary

We have described an image sensor noise model for use in camera simulations that can also predict the effects of lens blur and ISP on camera performance over a wide range of conditions — most importantly, for low light.

The image sensor noise model derived from either

- **Photon Transfer Curve (PTC) measured from a raw test chart image, with coefficients calculated by an optimizer, or**
- **EMVA 1288 measurements**

The simulation can display information capacity and related metrics, which are superior to sharpness and noise or SNR as predictors of system performance.

The *Simatest* camera performance simulator allows camera designs to be soft-prototyped and low light performance to be simulated, saving development time and money.

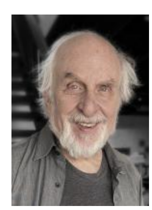
Thank you.

Contact me at norman@imatest.com.

Documentation is linked from

image information metrics **Simatest**

Please visit the *Imatest* booth. I'll be happy to answer questions.



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