Digital Camera and Scanner Performance Metrology: Science, Standards and Software

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IS&T / SPIE Electronic Imaging SCIENCE AND TECHNOLOGY

Updated theory-to-practice course on imaging performance measurement methods for digital image capture devices and systems. We focus on,

- standardized measurement of resolution (ISO 12233, 15529, SMIA)
- speed (ISO 12232),
- image dynamic range/noise (ISO 15739, 21550)
- alternative methods currently under consideration (CIPA DC-003 and polar sine-wave techniques)
- evaluation of capture devices from cell phone cameras to scientific detectors.

We will also address various challenges to reliable evaluation and system comparison using actual test data and software tools.

Required elements of software tools: How to use Matlab software to develop and perform system evaluation using several working examples.

Course Outline

1. Introduction
   – Digital Imaging and Performance Measurement
2. Signal Image Performance Metrics
   – Large area - Opto-Electronic Conversion Function (OECF)
   – Camera speed
   – Color Evaluation

- Break -

   – Spatial detail – Limiting Resolution, SFR/MTF
   – Summary measure: sampling efficiency, and others

- Lunch -

   – Methodologies – ISO, CIPA, CPIQ
   – *Demonstration and examples*
3. Image Noise Measurement
   – Random, fixed pattern, two-dimensional, streaks
   – Standard noise performance measurements and testing
      • Speed, Dynamic Range

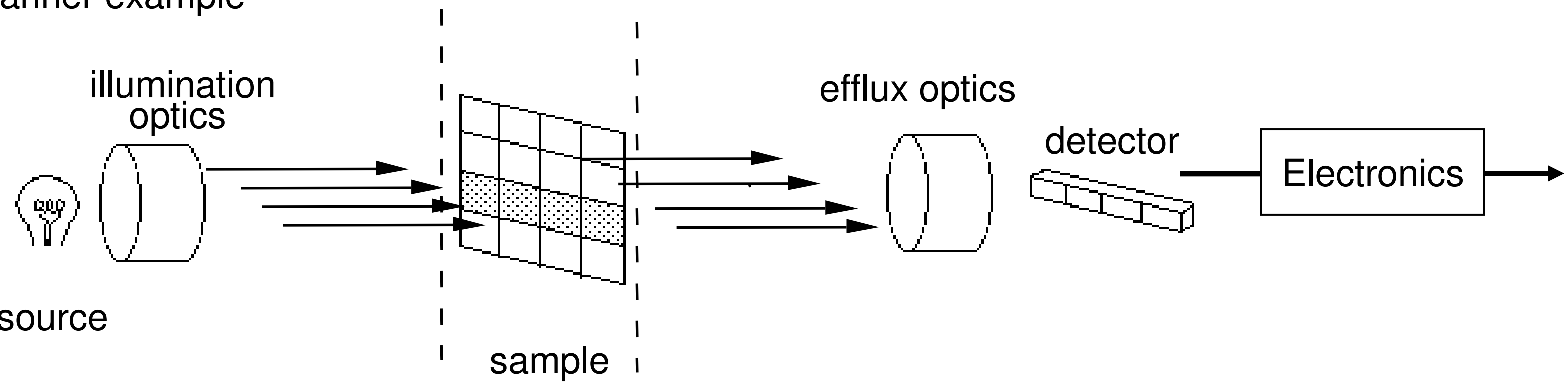
- Break -

   – Why results vary and ways to control variation
   – Requirements for evaluation tools

Introduction: What is a digital imaging system

A collection of optical, software, or electronic functions that convert, encode, or otherwise act upon images or their optical or digital derivatives.

Linear or area array scanner example



Imaging Performance Metrics quantify how an imaging system or component acts on, modifies, or limits the effective optical characteristics of an input scene.

Once digitally captured, the image ceases to exist as light intensities. They are now encoded as N-bit (M channel) digital files. ISO imaging capture performance metrics attempt to trace the data back to the original scene input intensities (input referred).

Digital Capture: *Why measure imaging performance?*

Standard testing, e.g., ISO
- Aimed at hardware evaluation or benchmarking
- Identify the influence of image processing, e.g., sharpening
- Marketing leverage
- Quality control and industry compliance

System testing
- Actual product usage
- Robustness testing – image processing as used, or in default signal path, e.g., sRGB metric
- Scanner as instrument

Metadata population
- Enablement of enhanced product features and ease of use

Image Quality
- Required as input for image quality

and… something to debate at technical conferences

A shopping list of digital camera imaging performance features *

High Priority
- OECF
- White balancing
- Dynamic range (related scene contrast)
- Used digital values
- Noise, signal to noise ratio
- Resolution (limiting resolution center, corner)
- Sharpness

Recommended
- Distortion
- Shading / vignetting
- Chromatic aberration
- Color reproduction
- Unsharp masking
- Shutter lag
- Aliasing artifacts
- Compression rates
- Exposure and exposure time accuracy and constancy
- ISO speed

*From :
"Proposal for a Standard to Test Mobile Phone Cameras"
Dietmar Wueller, Image Engineering,
http://digitalkamera.image-engineering.de/

Optional
- View angle, zoom range (at infinity and shorter distances)
- Hot pixels
- Detailed macro mode testing (shortest shooting distance, max. scale, distortion)
- Flash capabilities (uniformity, guiding number light source etc.)
- Startup time
- Image frequency
- Video capabilities (pixel count, resolution, frame rate, low light behavior)
- MMS capabilities for mobile phone cameras (Resolution, frame rate, compression etc.)
- Display (refresh rates, geometric accuracy, color accuracy, gamut, contrast, brightness, visibility in sunlight)

The following values may be tested if available and applicable.
- Optical stabilization
- Auto focus accuracy and constancy
- Metadata (Exif, IPTC)
- Watermarking
- Spectral sensitivities
- Bit depth of raw data
- Power consumption
- Battery life
- Detailed noise analysis
- Color resolution

How is imaging performance measured?

- **Signal**

Any response that provides valued information

- **Noise**

Any response that detracts from a desired signal

- **Signal-to-Noise Ratio**

A good-to-bad proportionality measure

Important Imaging Characteristics

- an imaging performance taxonomy for classifying the metrics -

<table>
<tr><td>Foundation Attributes</td><td colspan="11">Signal</td><td rowspan="2">Signal-to-Noise Ratio</td><td colspan="11">Noise</td></tr>
<tr><td>Primary Metrics</td><td colspan="5">OECF (Opto-Electronic Conversion Function)</td><td colspan="6">SFR (Spatial Frequency Response)</td><td colspan="6">Radiometric Distortion
NPS (Noise Power Spectrum)</td><td colspan="5">Spatial Distortion</td></tr>
<tr><td rowspan="3">Secondary Metrics</td><td rowspan="3">Linearity</td><td rowspan="3">Sensitivity, Quantum efficiency</td><td rowspan="3">Tone, Exposure</td><td rowspan="3">White Balance/ Neutrality</td><td rowspan="3">Color Rendering or Encoding Accuracy</td><td rowspan="3">Sampling Rate</td><td rowspan="3">Resolution, sampling efficiency</td><td rowspan="3">Sharpening</td><td rowspan="3">Acutance</td><td rowspan="3">Flare</td><td rowspan="3">Depth of Focus</td><td rowspan="3">Dynamic Range
DQE, NEQ, Information capacity</td><td colspan="4">Total Noise</td><td colspan="2" rowspan="2">Chroma Noise</td><td rowspan="3">Micro (deterministic)</td><td rowspan="3">Color Misregistration (deterministic)</td><td rowspan="3">Aliasing (deterministic)</td><td rowspan="3">Spatial SFR Uniformity (deterministic)</td><td rowspan="3">Pincushion/Barrel (deterministic)</td></tr>
<tr><td>Temporal</td><td colspan="3">Fixed pattern</td></tr>
<tr><td>Random (stochastic)</td><td>Banding/Streaking (deterministic)</td><td>Defects (stochastic)</td><td>Vignetting or Shading (deterministic)</td><td>Color Uniformity (deterministic)</td><td>Color SFR Uniformity (deterministic)</td></tr>
</table>

Image Quality vs. Imaging Performance

Subjective Correlates

Sharpness
Acutance
Graininess
Colorfulness
Oversharpness

Objective Utility Correlates

NIIRS
Briggs scores
Resolving power
OCR detection

Performance Metrics

Signal

OECF – tone, color
SFR / MTF

Noise

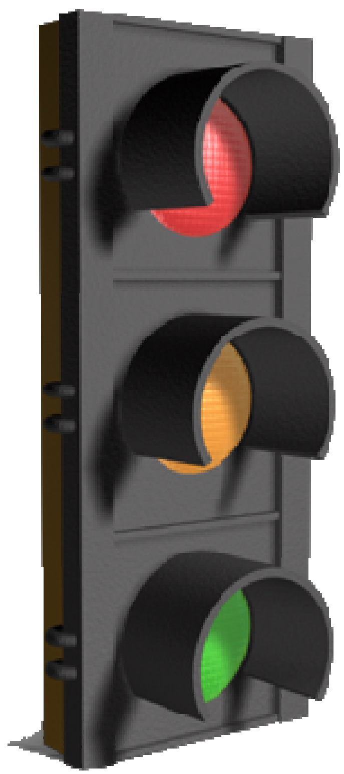
Total RMS noise
Structured noise
Artifacts

Image Quality: Task dependent, but can almost always be correlated to some weighted combination of imaging performance metrics.

- Aerial Reconnaissance – high sharpness and low noise
- Health Imaging – tone control, low noise, sharpness dependent on task
- Consumer Imaging – color and tone, moderate sharpness

Performance metrics are needed for image quality predictions and measurement.

SIGNAL



Signal - Taxonomy

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White Balan
Color Rendering or
Sampli
Resolution, sar
Sharp
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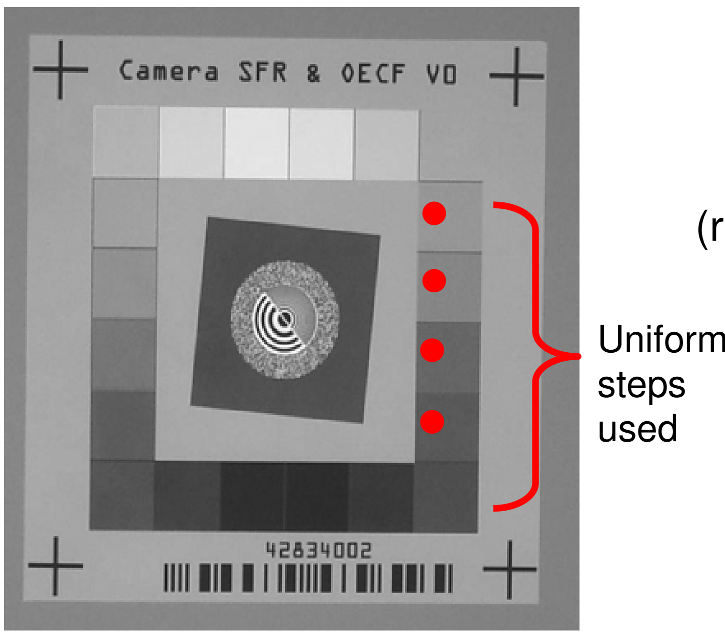
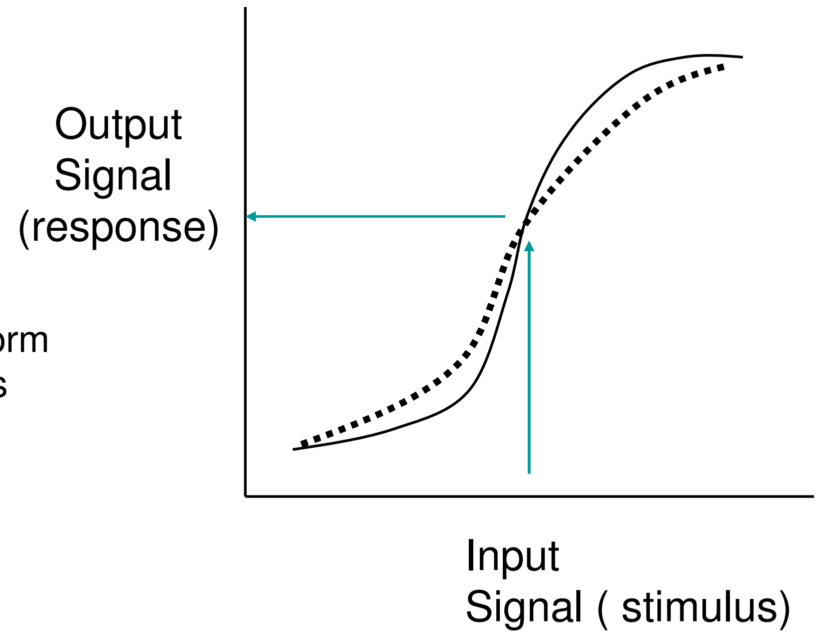
Depth c

Foundation Attributes	Signal										
Primary Metrics	OECF (Opto-Electronic Conversion Function)					SFR (Spatial Frequency Response)					
Secondary Metrics	Linearity	Sensitivity, Quantum efficiency	Tone, Exposure	White Balance/ Neutrality	Color Rendering or Encoding Accuracy	Sampling Rate	Resolution, sampling efficiency	Sharpening	Acutance	Flare	Depth of Focus

Large Area Image Capture – OECF*

- Large area image capture behavior is measured by OECF
- The ***conversion*** relationship between ***optical*** reflectances (gray levels) of a source object and corresponding ***electronic*** (digital) count values in a digitized image file; a luminance-to-signal mapping relation.





*Electro-optical Conversion Function

Some important items to keep in mind on OECF

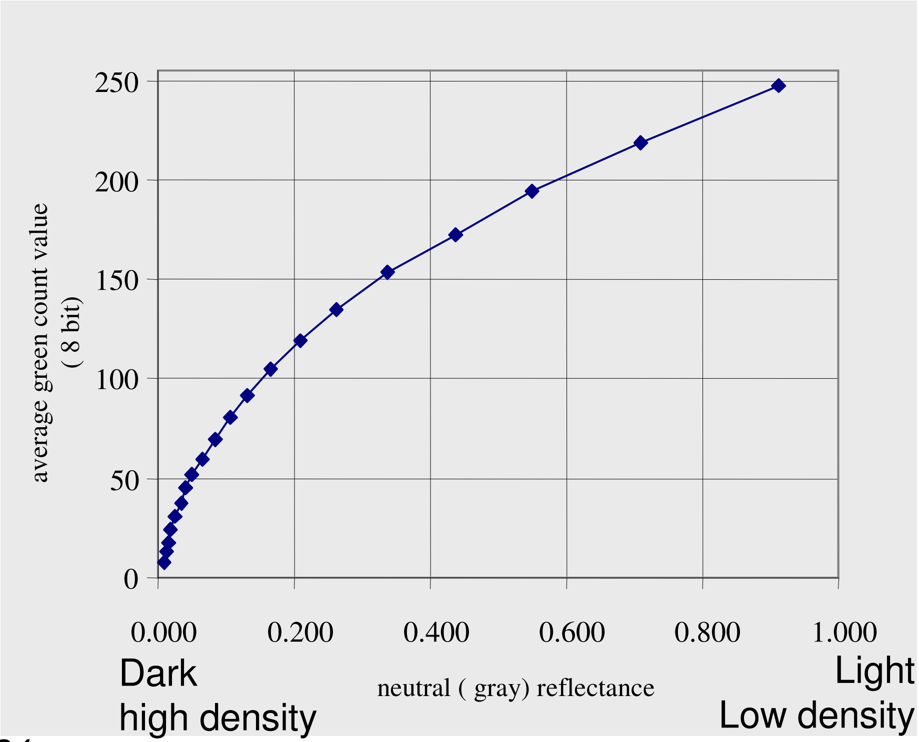
- Important link between the physical characteristics of the source object and its digital image file

- A prerequisite for facilitating image reproduction and image quality and color management tasks.

- Allows performance evaluation in a common “input referred” metric* for other metrics like resolution, dynamic range

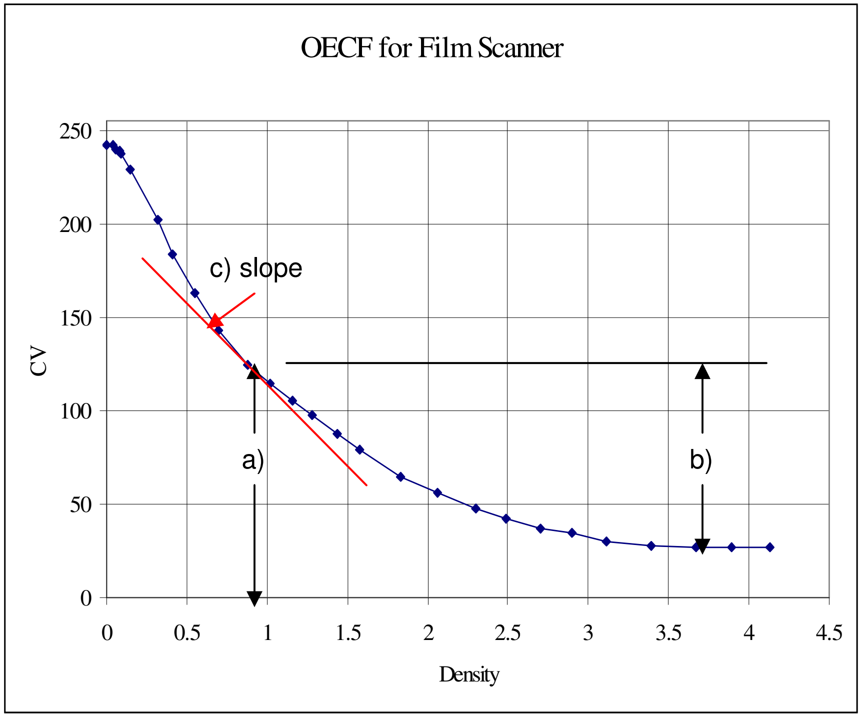
- Measures signal ‘encoding’

- There is no good or bad OECF…. but characteristics like clipping and strong curvatures should be avoided



*ISO 16067-1,16067-2, 21550, 12233, 15739, *14524*

How OECF Measures Signal



*Some ways **signal** is measured:*

a) <u>Peak-to-absolute zero</u> – The *difference between CV of interest and zero.*

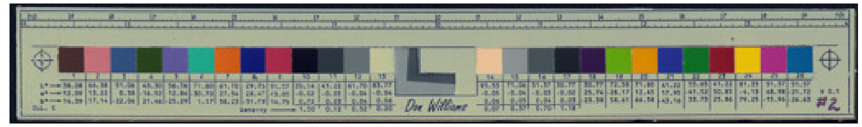
b) <u>Peak-to-peak</u> – Relative difference between the CV of interest and the lowest *effective* CV.

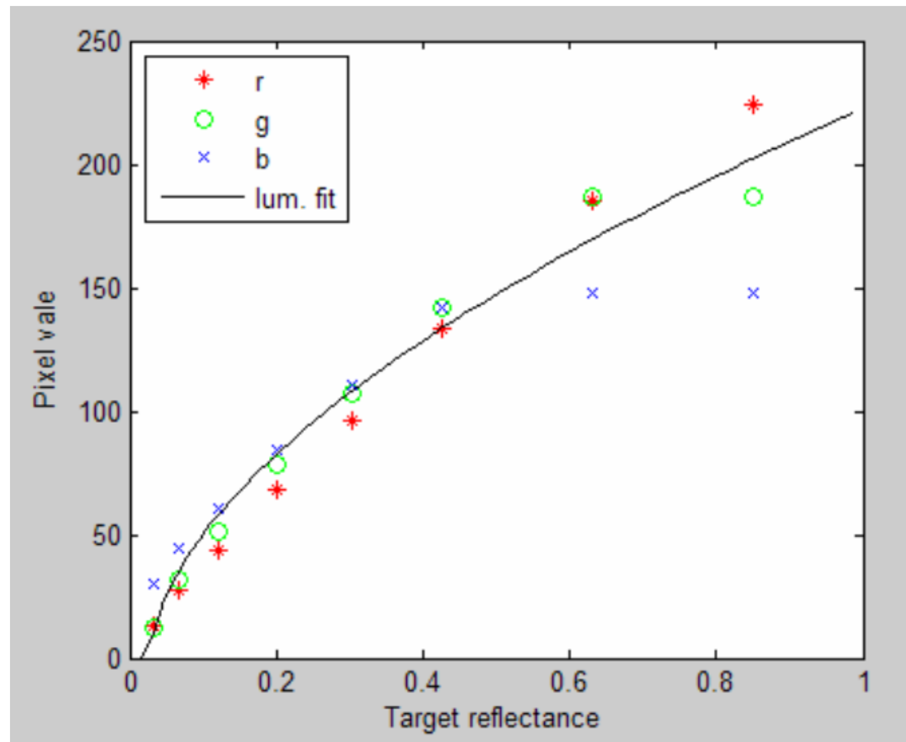
c) <u>Incremental slope</u> – The difference between the CV of interest and the CV of an incrementally small change in density. The slope of the OECF curve for any given density. Indicates how well a device can detect small density differences. (ISO)

Some common input and output OECF variables

Stimulus (Input)	Response (Output)
Photons	Electrons, Current
Reflectance	8 bit Count value (CV)
Density	16 bit Count value (CV)
Exposure (Lux-seconds)	Log CV
Log exposure	
Luminance (L*)	

Color Metrology
- just a three channel OECF -

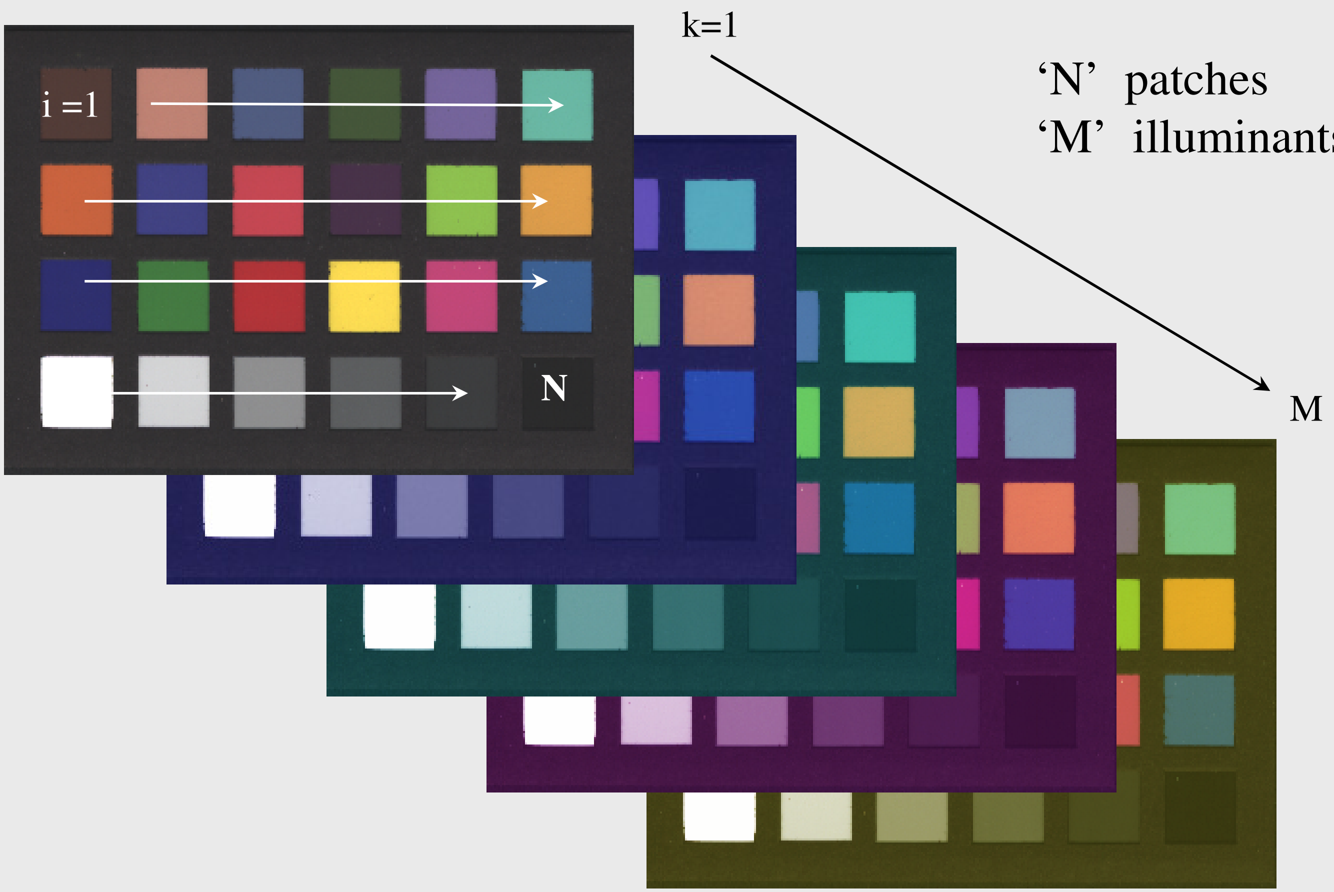




- Keep the neutrals neutral -
85% of good color imaging is maintaining the neutrality of gray patches – white balance

White Balance Tests

Variation with source illumination

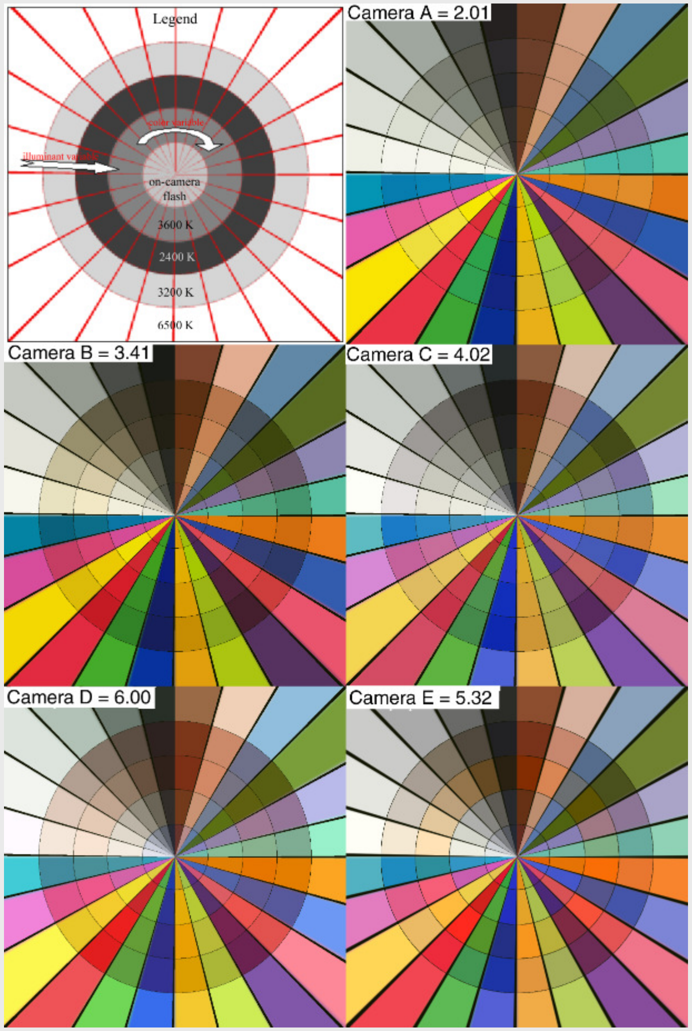


'N' patches
'M' illuminants

Example: testing camera with various illuminants

$$\Delta E^*_{ab} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{(\Delta L^*_i)^2 + (\Delta a^*_i)^2 + (\Delta b^*_i)^2}$$

N color patches



ISO Camera Speed

- Camera speed is intended to indicate the exposure range (or the lower exposure limit) over which a camera can deliver a useful digital image.
- *Useful digital image* can be expressed in terms of
  - Image contrast, i.e, average response. This is similar to photographic film speed
    - Exposure index (EI)
    - Saturation-based speed E_{sat}
  - Noise-based speed (S_{noise})

Exposure Index

$$EI = 10 / H_a$$

$$H_a = (65\ L_a\ t) / (100\ A^2)$$

where: A is the effective *f*-number of the lens
L_a is the arithmetic mean luminance, in candelas per square meter
t is the photosite integration time, in seconds

H_a = Equal 2/10 times the focal plane exposure that would be obtained from a 90% reflectance test card in a statistically average scene (18%).

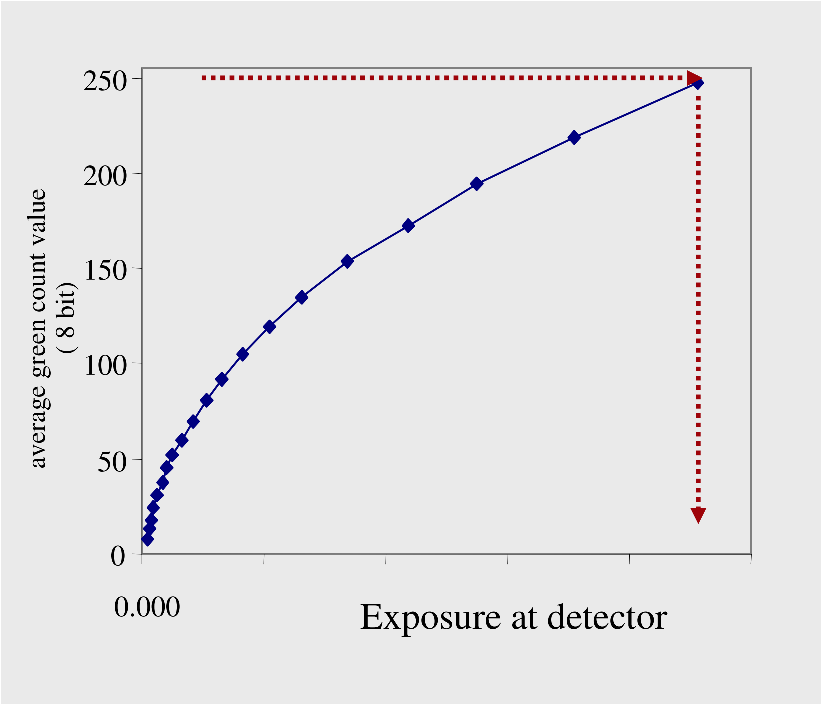
- Using an ISO speed as the exposure index will yield the same camera and resulting focal plane settings as in a film camera or photographic exposure meter. Currently what we think DSCs use when referring to ISO speed.
- ***Unlike photographic film, it makes no presumptions on image quality equivalence between cameras using the same EI. Why is this?***

Saturation-Based Speed, S_{sat}

$$S_{sat} = 78 / H_{sat}$$

where

H_{sat} = Minimum focal plane exposure that yields the highest unclipped output signal (lux-seconds)



- Appropriate for controlled illumination environments where the best possible image quality is desired

- Intended to prevent clipping artifacts associated with image sensor saturation

- ***Correlates the highest exposure to the best SNR and the best image quality for a given camera***

Spatial Resolution

What is it?

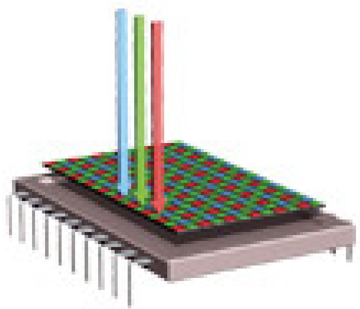
The ability of an imaging component or system to distinguish finely spaced detail. Specifically, the ability to maintain the *relative* contrast of finely spaced detail.

…and what are all these related terms?

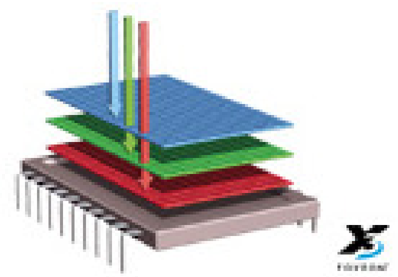
- Number of pixels
- Sampling frequency – dpi, ppi
- Limiting resolution, Resolving power*
- Spatial Frequency Response – SFR*
- Modulation Transfer Function – MTF*

*Related Standards – ISO 16067-1, 16067-2, 12233, & 15529 all employ these metrics.

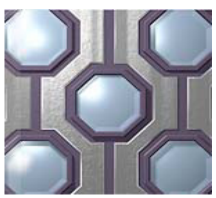
Ways to Count Pixels



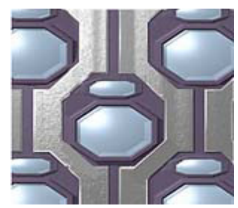
Typical digital sensors have just one layer of pixels and capture only part of the color.



Foveon X3® direct image sensors have three layers of pixels which directly capture all of the color.



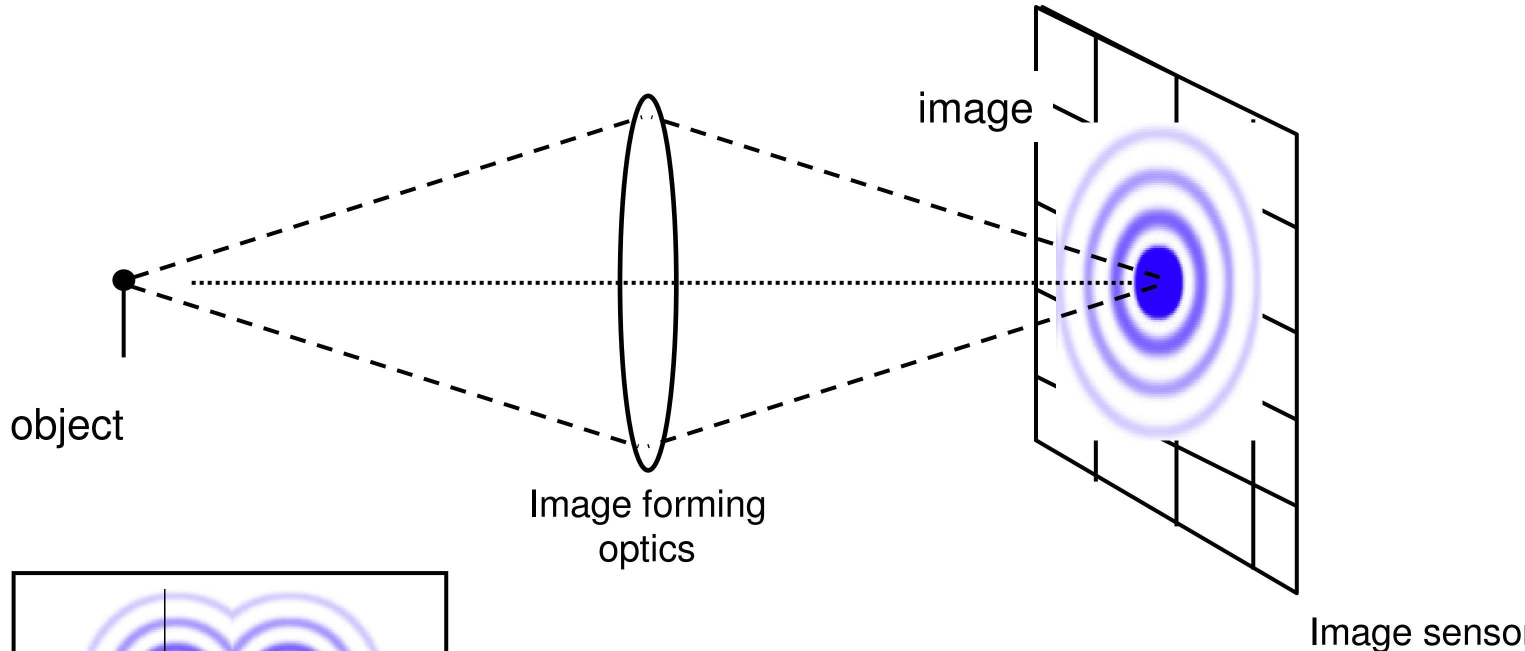
Fuji Standard SuperCCD configuration



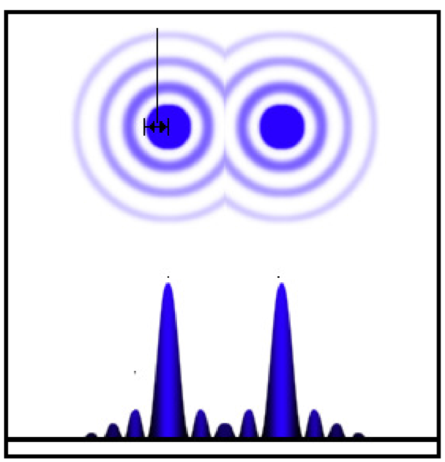
Fuji Dual Element “SR” SuperCCD configuration

None indicate the quality of delivered image detail.

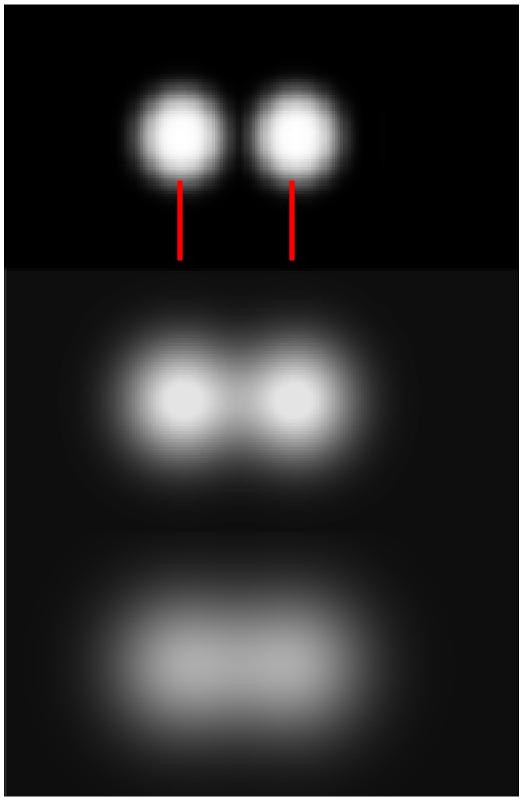
Point Spread Function and image sampling



Airy disk
patterns



Relation between PSF and limiting resolution



$$\frac{\text{peak-to-peak difference}}{\text{peak-to-peak sum}} \equiv \text{modulation} = \frac{1.0 - 0.81}{1.0 + 0.81} = 0.10$$

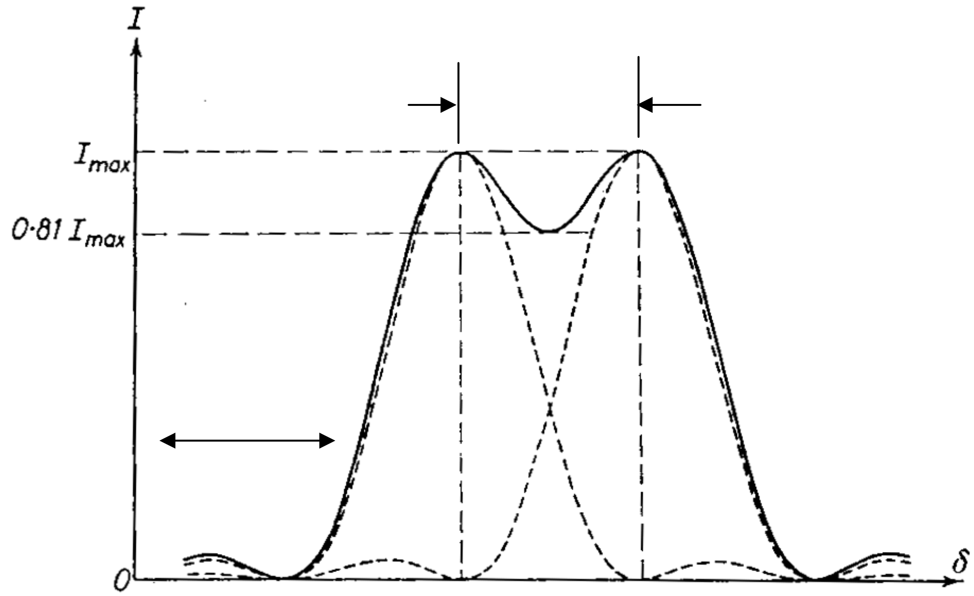


Illustration of two lines just resolved according to the Rayleigh criterion (c. 1879)

Limiting Resolution = Highest spatial frequency at which light and dark parts of image are visually distinguishable.

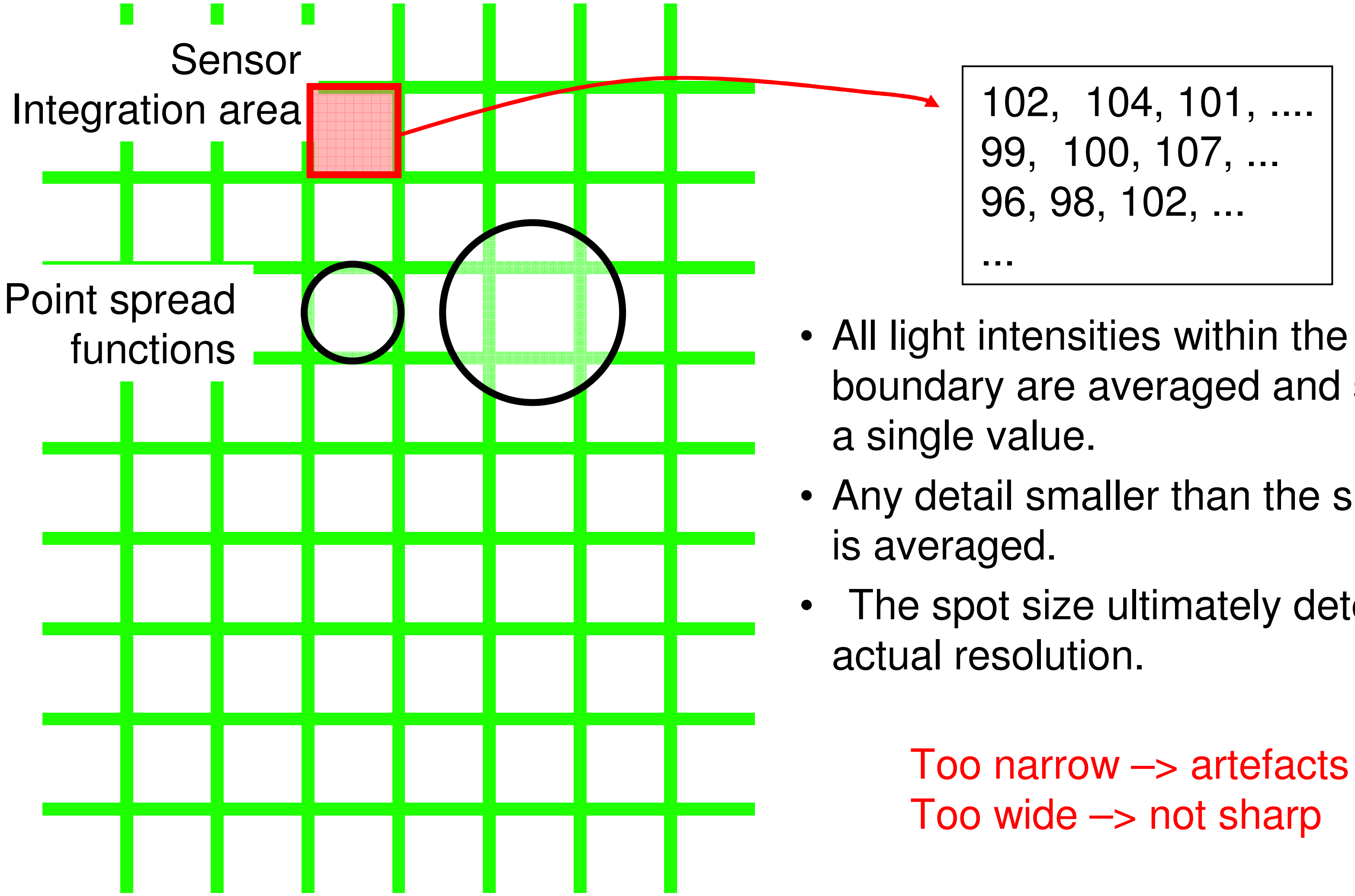
Spread Functions
- influencing components -

- Several *imaging mechanisms* influence spread function descriptions
  - Optical – focus, diffraction, aberrations, radiation scatter, filters
  - Mechanical – sampling aperture size, vibration, motion
  - Digital filtering – de-screening, unsharp masking

- Some do not*
  - Image noise, film grain, detector noise
  - Sampling artifacts
  - Signal quantization and clipping (thresholding)

- *...but make spread function and SFR measurements difficult

Digital image capture involves sampling the optical image



- All light intensities within the pixel boundary are averaged and stored as a single value.
- Any detail smaller than the spot size is averaged.
- The spot size ultimately determines actual resolution.

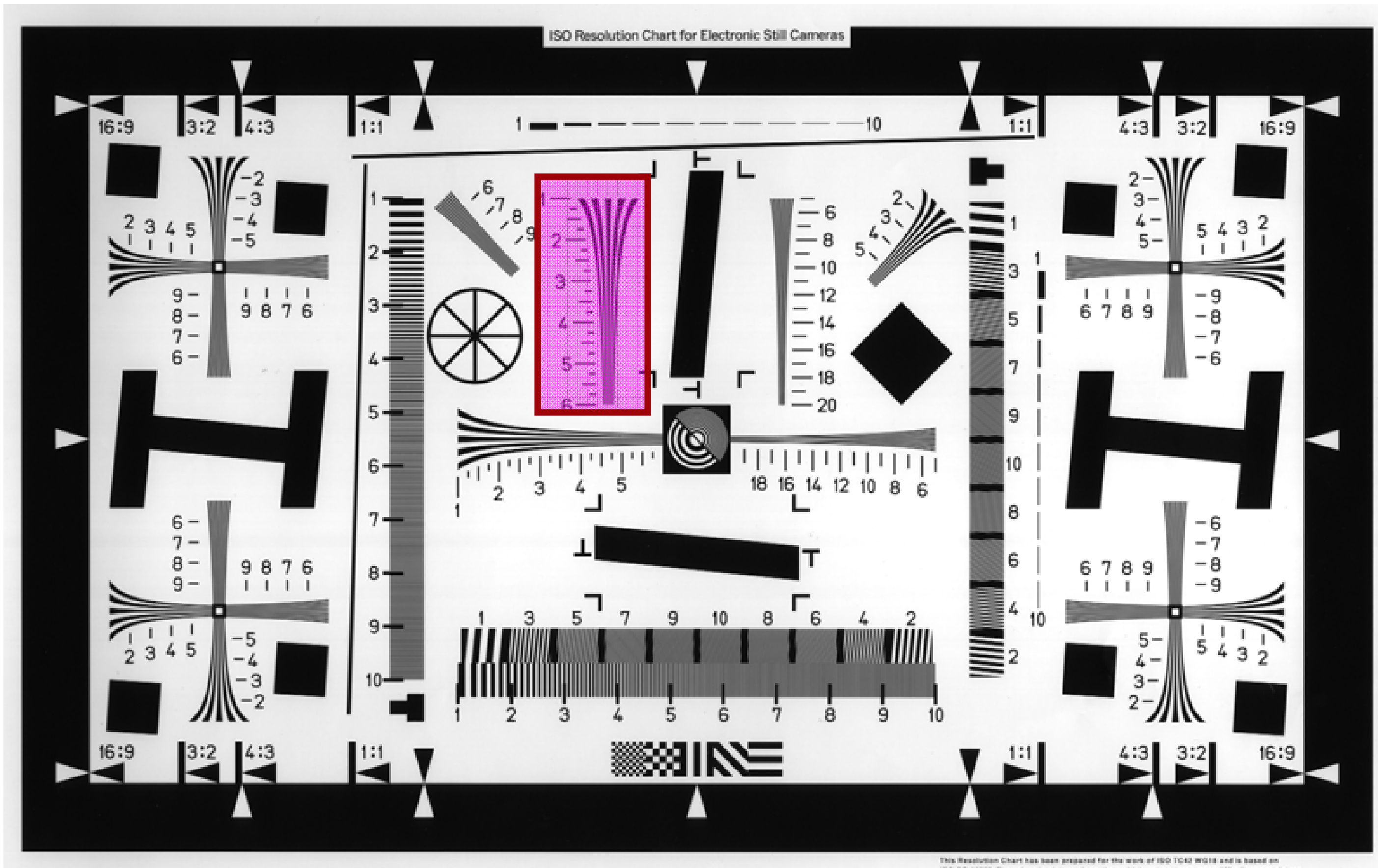
Too narrow –> artefacts
Too wide –> not sharp

Limiting Resolution

- Highest frequency (lowest period) at which light and dark parts of image are distinguishable
- Usually defined for a periodic signal (sine wave or repeating bars)
- Evaluation can be by visual inspection or instrument
- Units: line-pairs/mm, cycles/mm, line-pairs/picture height

The apparent sharpness of a displayed digital image can generally be improved using a digital sharpening filter but at the expense of image noise.

Lab Using CIPA Target – Limiting Resolution

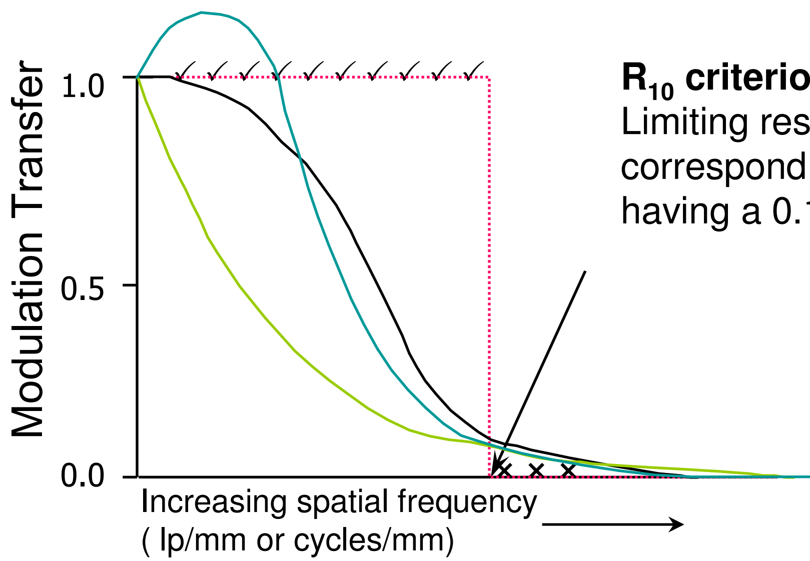


Current ISO 12233 digital camera resolution target

SFR: *The Better Alternative*

Instead of using a subjective YES/NO criterion along the vertical axis, an objective contrast (i.e., modulation) transfer ratio is adopted. The SFR it is an indicator of contrast loss as a function of spatial frequency.

$$\text{Modulation Transfer} = \frac{\text{Target feature modulation } \textbf{after} \text{ being imaged}}{\text{Target feature modulation } \textbf{before} \text{ being imaged}}$$



R_{10} criterion
Limiting resolution will generally correspond to the spatial frequency having a 0.10 modulation transfer value

*Spatial Frequency Response

MTF/SFR Measurement Techniques

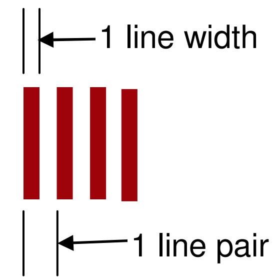
	Pro	Con
Direct		
Sine waves	Simple, intuitive analysis	Large spatial extent Limited sampling Costly capture targets
Indirect		
Point/Line Spread Function	Fundamental features	Low signal strength
Square Waves	Simple targets	Large spatial extent
Edge gradients	Compact features Simple targets	Noise sensitive
Noise fields	Small signal	Spectrum estimation

Spatial Frequency Units

- *there are several* -

1 - cycles/mm, cy/mm, mm^{-1} - *Engineering, film photography*

2 - line-pairs/mm - *Graphics*



lines/mm = $\dfrac{l}{mm} = \dfrac{lp}{2mm} = \dfrac{cy}{2mm}$ **or** $\dfrac{lp}{mm} = \dfrac{cy}{mm}$

3 – cycles/pixel – *digital processing, filter design*

4 - line-pairs/picture height – *Video, digital systems*

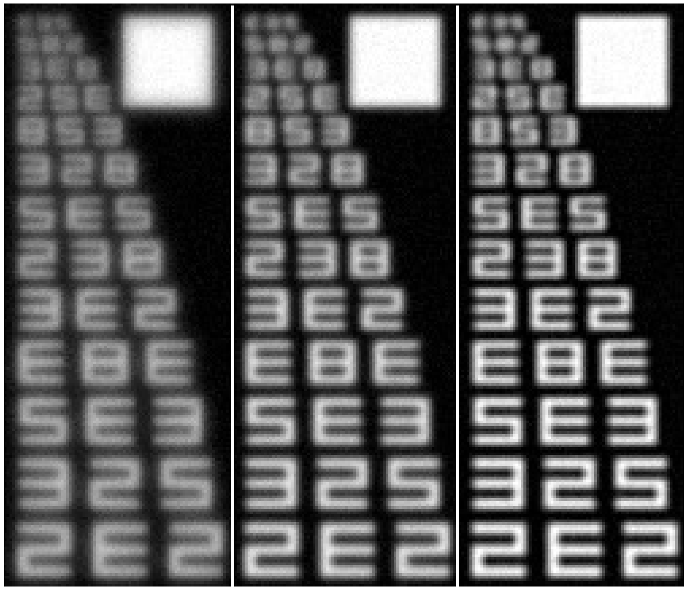
$$\frac{lp}{ph} = \frac{cy}{pixel}\frac{pixel}{ph} = N\frac{cy}{pixel} \qquad ph = Npixels$$

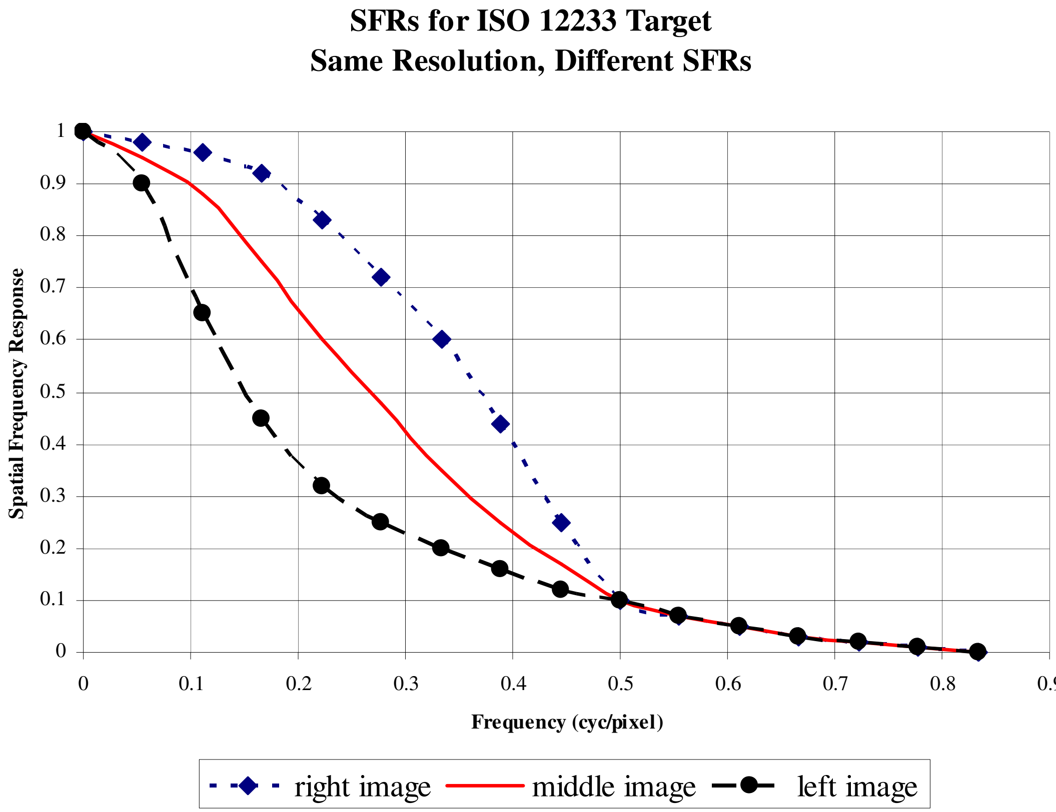
5 – line widths per picture height, LW/PH – *Video,12233 standard*

6 – cycles/degree (CPD) – *visual acuity, image quality*

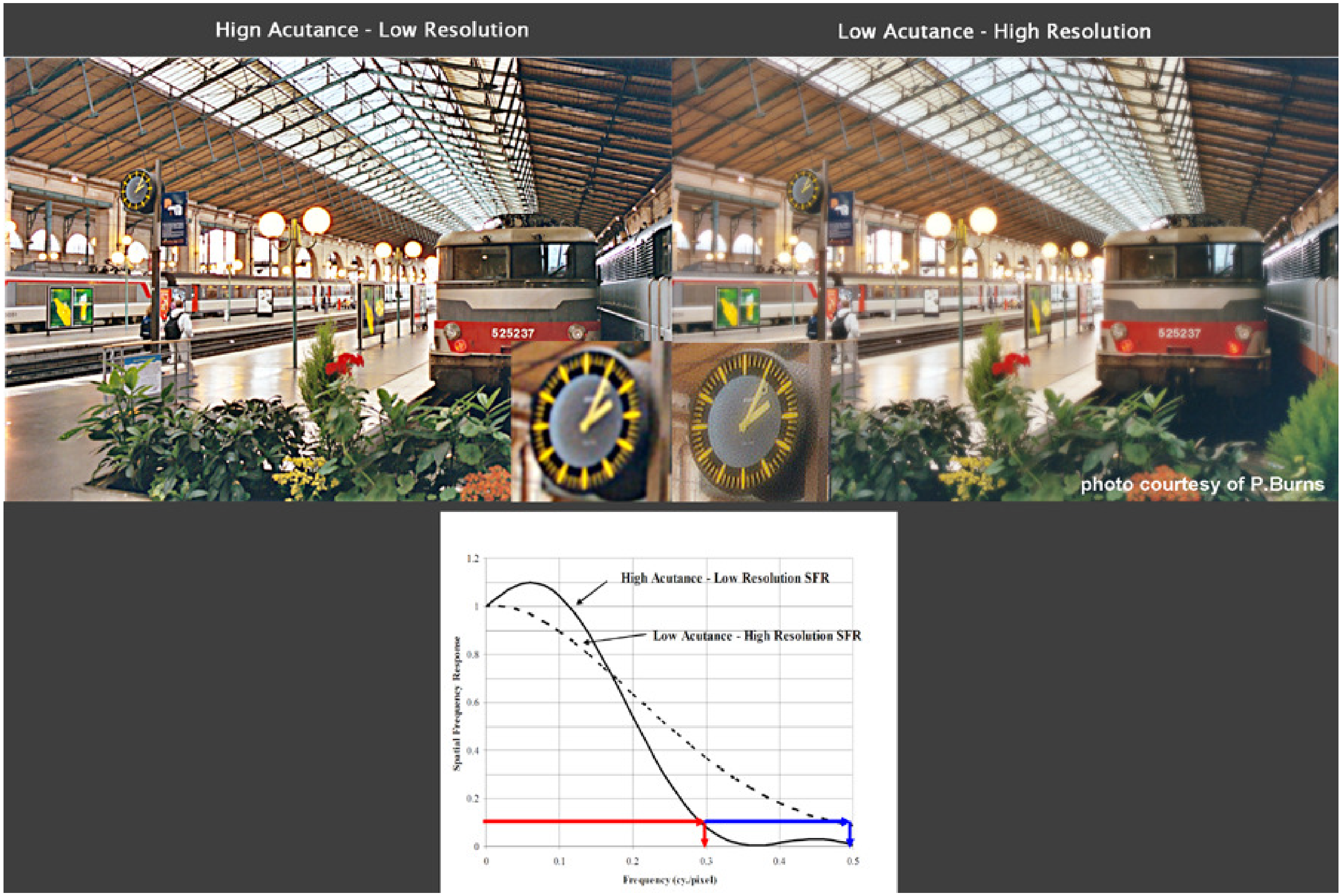
See last page of notes for conversion table

How limiting resolution can fail to predict quality and why the SFR is better.



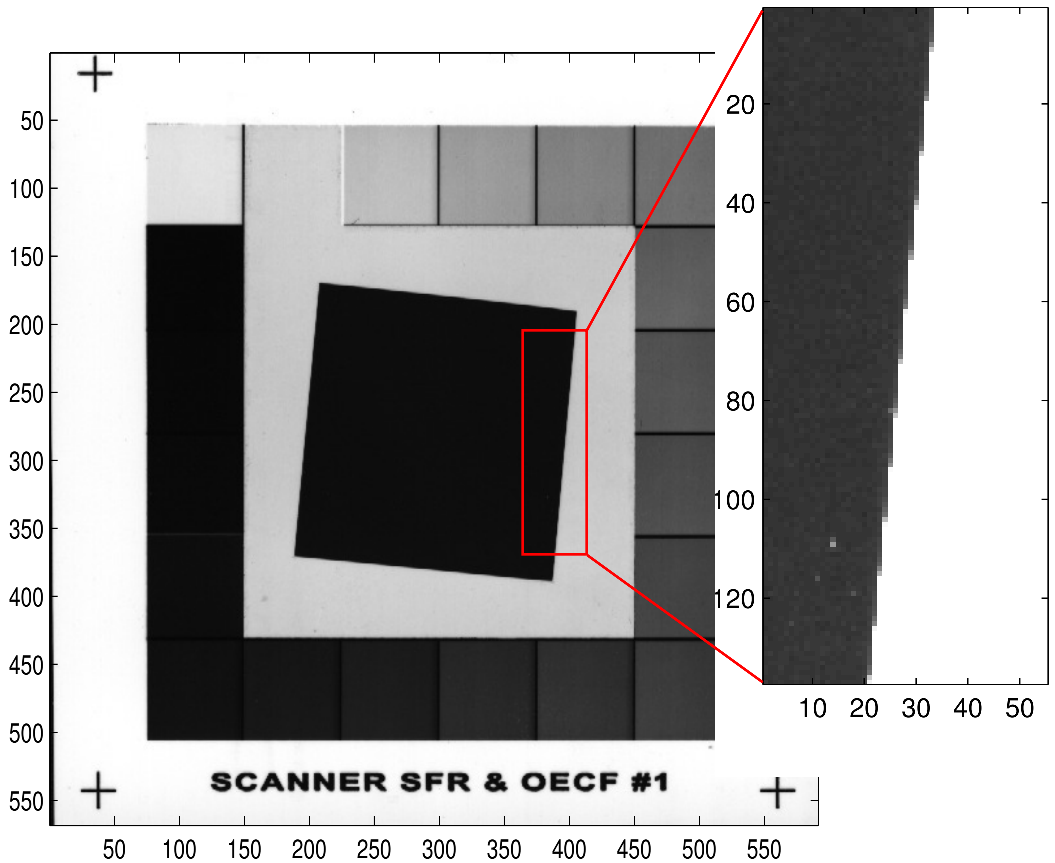


How SFR can predict image quality ?

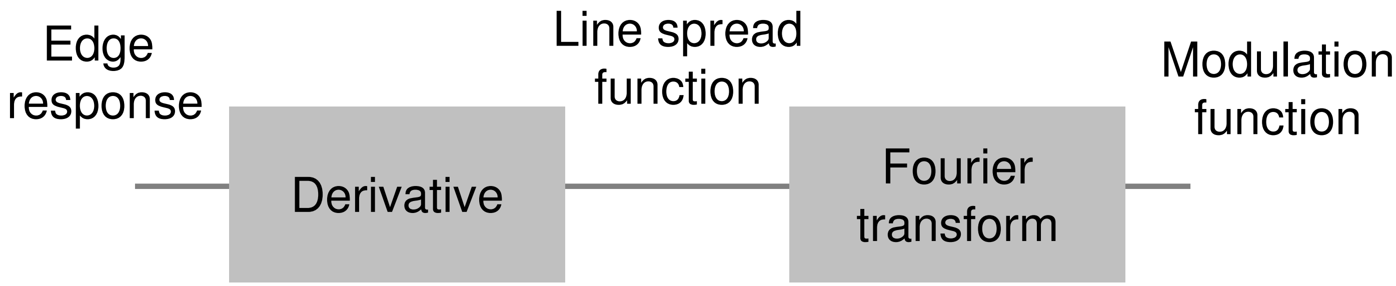


How is SFR measured for digital capture?

All you need is an image of a good slanted edge target.



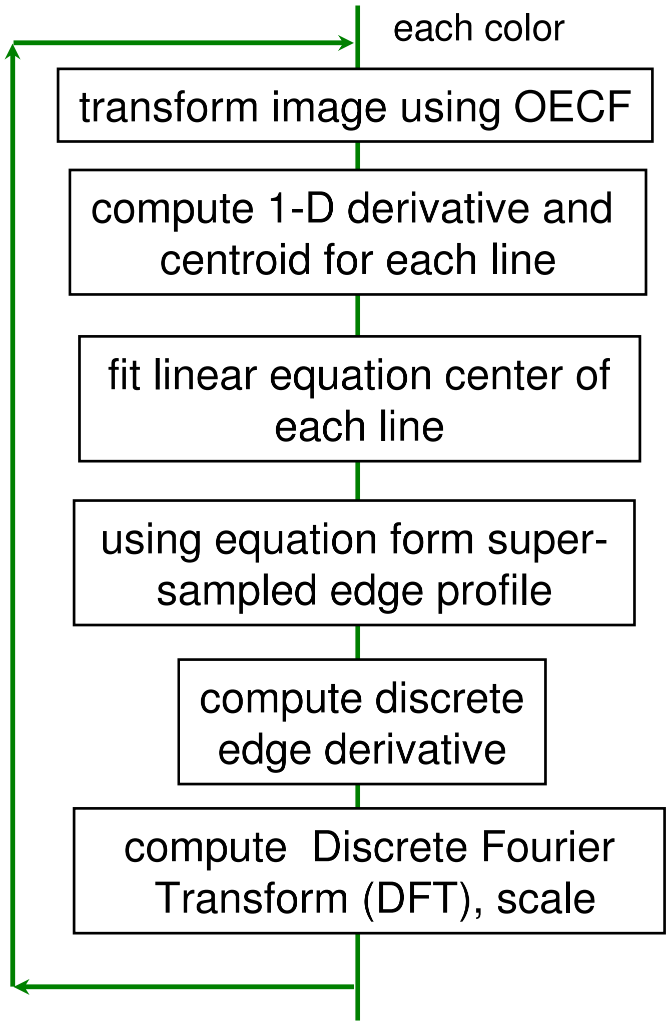
Theory: Frequency response by edge-gradient analysis

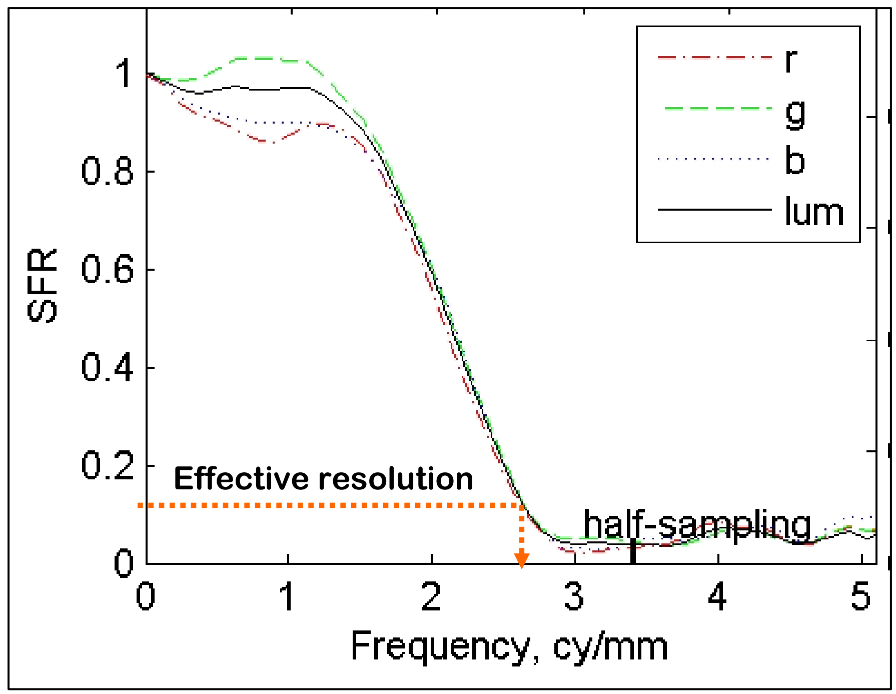


Theory: Estimate the line spread function from an ideal edge measurement

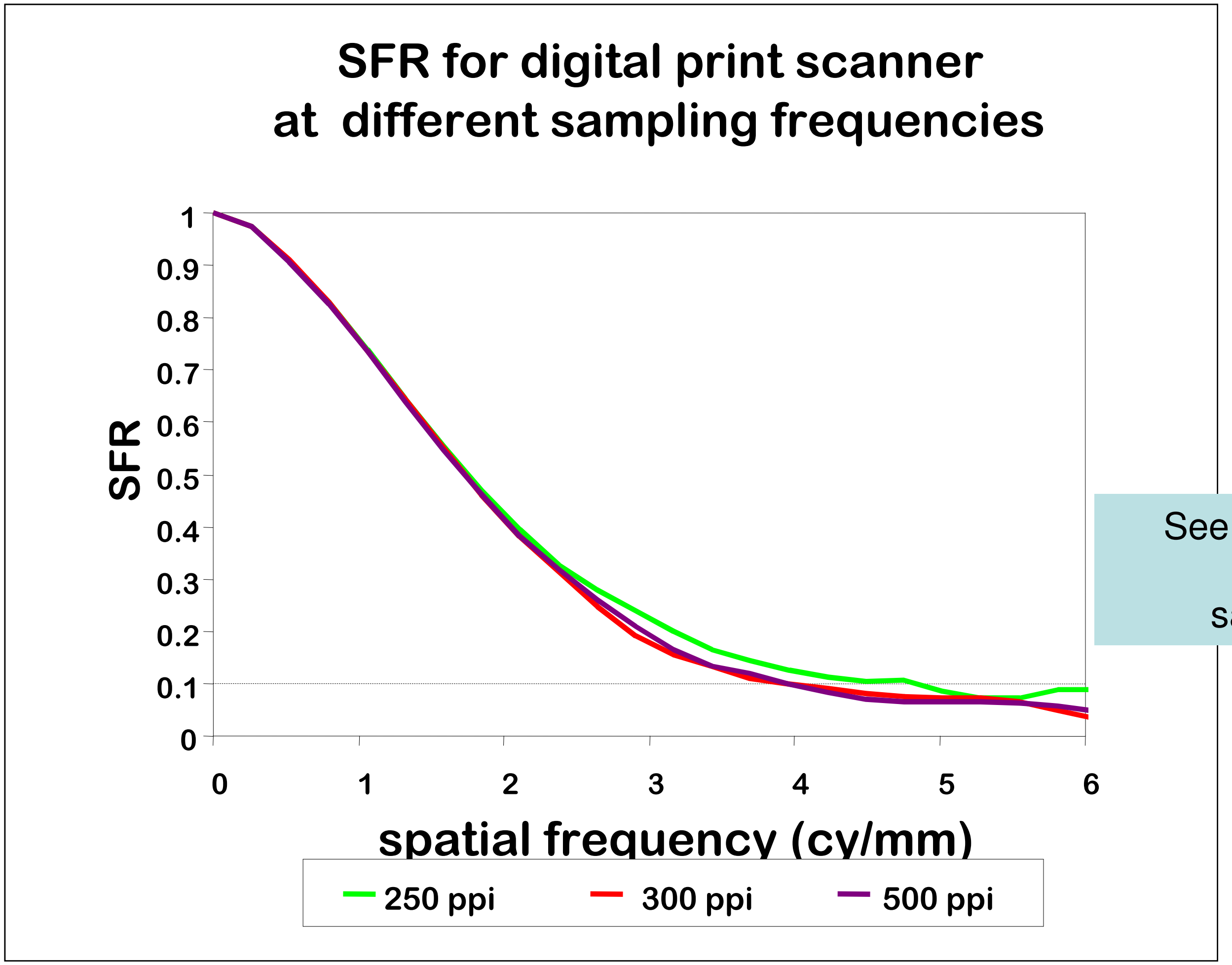
ISO 15529 Method: Principles of measurement of MTF of sampled imaging systems

Practice: ISO12233 SFR using slanted edges





Interpreting scanner resolution a real example



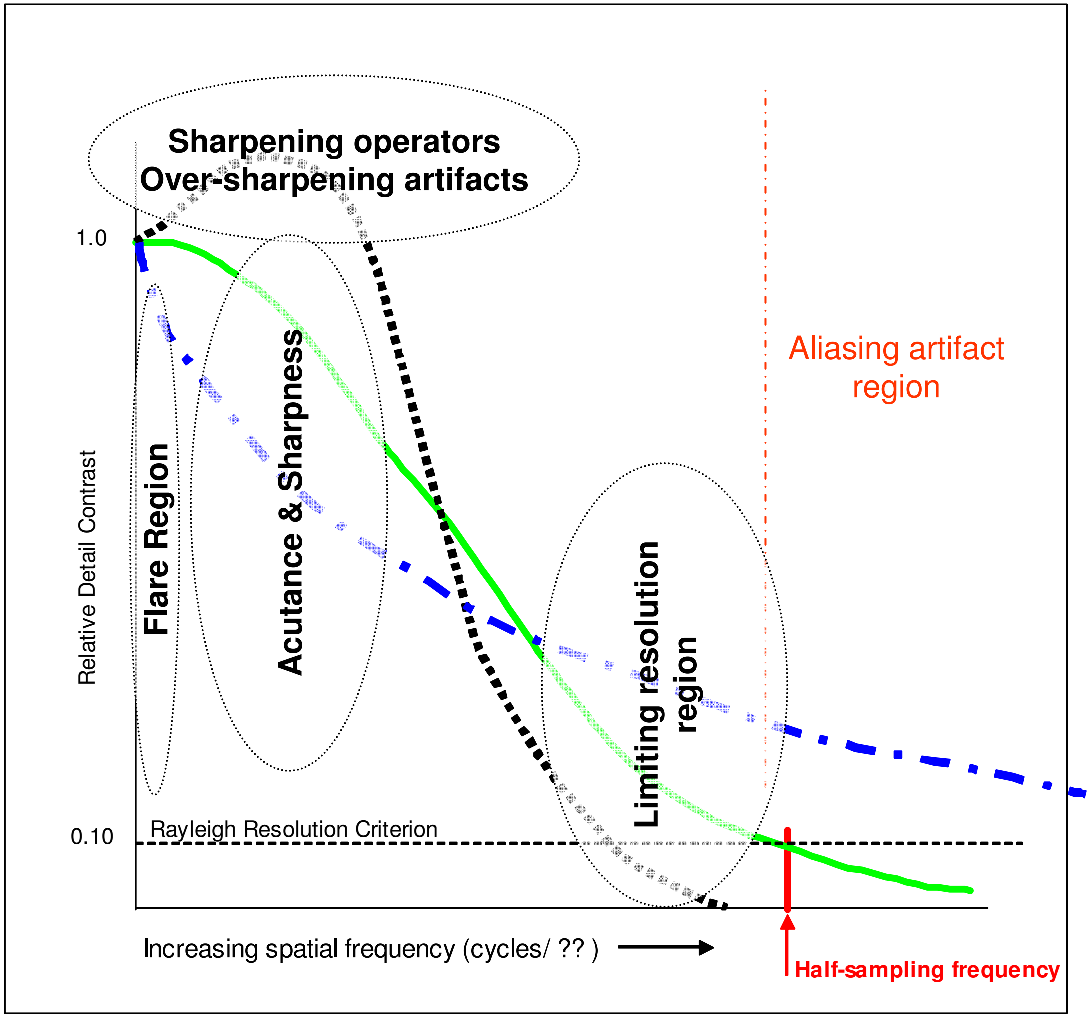
See Appendix on limiting resolution,
sampling efficiency

Derivative Measures of SFR

- Color fringing vs. misregistration
- Sharpening
- Acutance
- Aliasing
- Flavors of resolution
- Flare

Anatomy of the SFR

- regions of behavior -



Summary

ISO SFR Method

- Based on edge-gradient method
- Intended for digital capture devices
- Alignment immunity
- Localized features
- Open source software
- Extendable to any angular direction
- Ease of target generation; several imaging mechanisms or steps can be described in terms of spread functions

MTF and SFR

- Spread functions and MTF indicate the imaging or transfer of signal detail and sharpness
- Slanted-edge SFR method is a form of edge-gradient analysis, applied to electronic image acquisition

SFR in Review

- *What is it?*
  - Descriptive plot that measures the extent to which image detail contrast (*modulation*) is maintained by an imaging component or system. It characterizes the spatial interaction of neighboring signals whether they are in remote (low frequency) or close (high frequency) proximity.

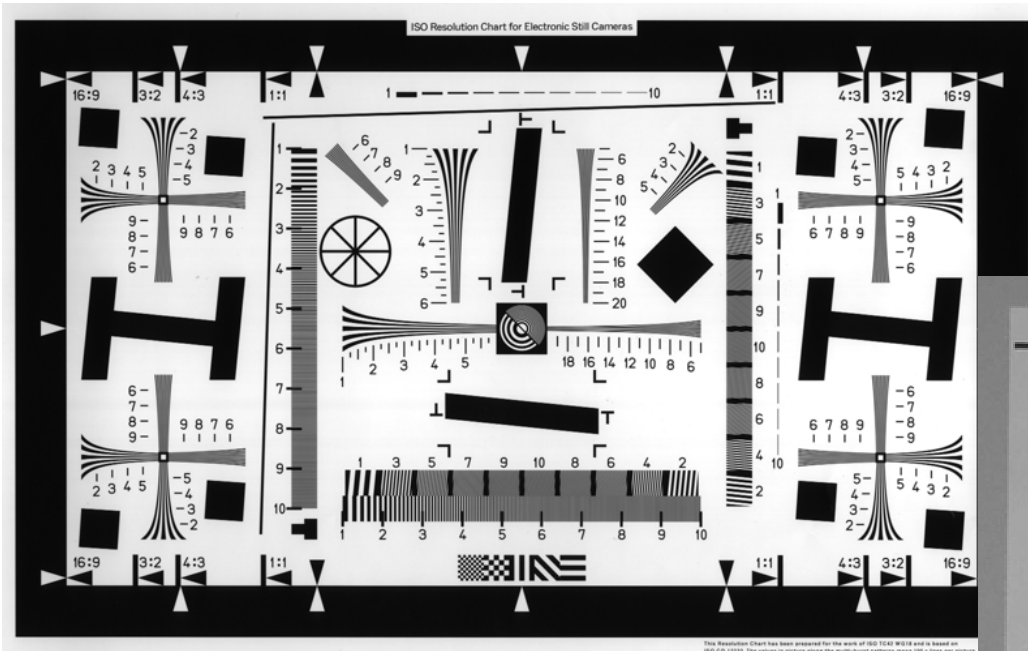
- *What it is not?*
  - Same as “resolution”
  - Sampling frequency or number of pixels
  - Complete descriptor of image quality (noise, color, …)

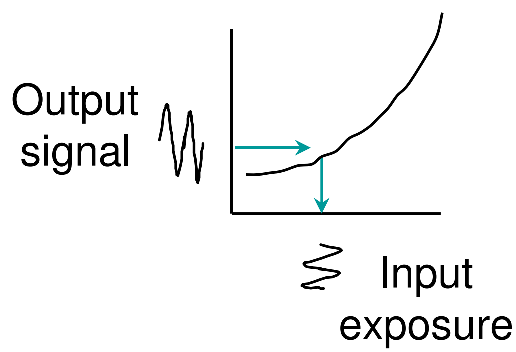
- *What good is it?*
  - It is a primary engineering metric that provides a way to analyze the influence of imaging components on the retention and reproduction of *image detail.* It provides means to derive a number of single valued metrics such as acutance, flare, sharpening, aliasing, and color fringing.

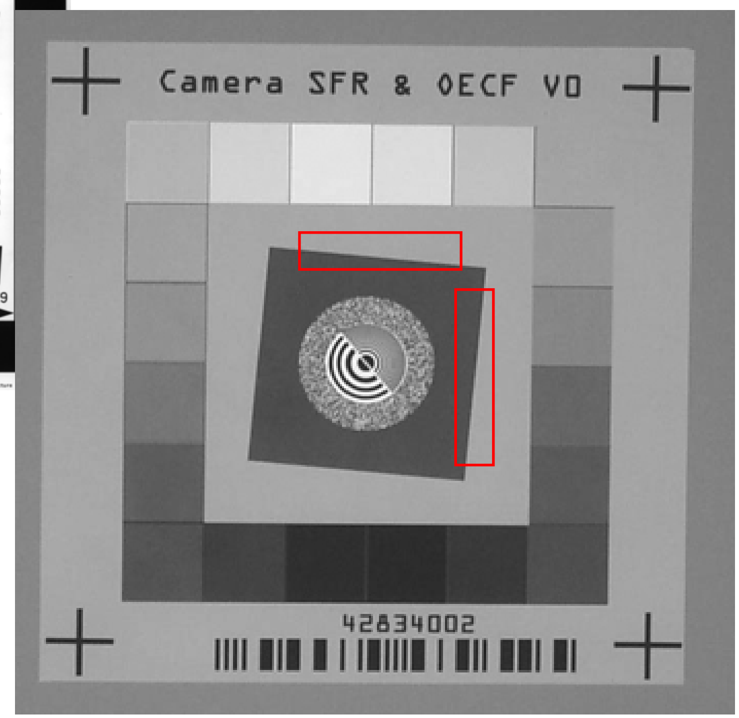
- *Which digital imaging standards address it ?*
  - ISO 16067-1: Resolution for digital print scanners
  - ISO 16067-2: Resolution for digital film scanners
  - ISO 12233 : Resolution for digital still cameras
  - ISO 15529 : MTF for sampled imaging systems

ISO Method: Resolution Charts

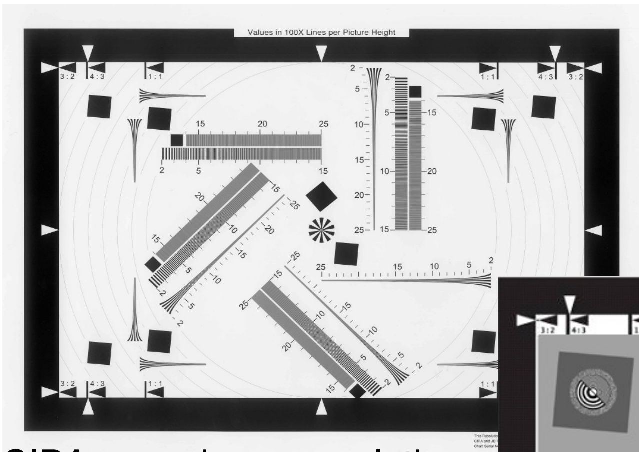
- OECF
- SFR



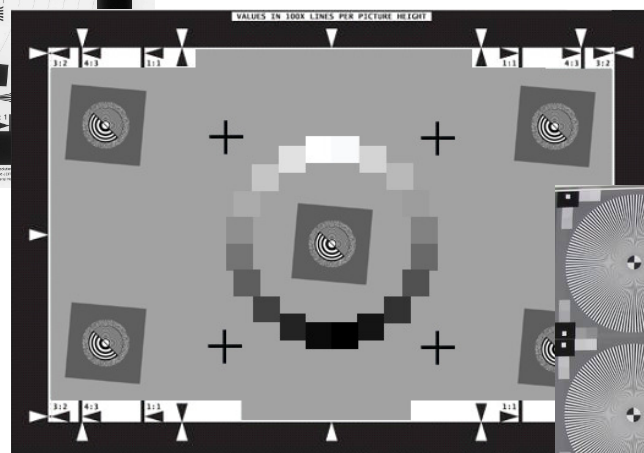




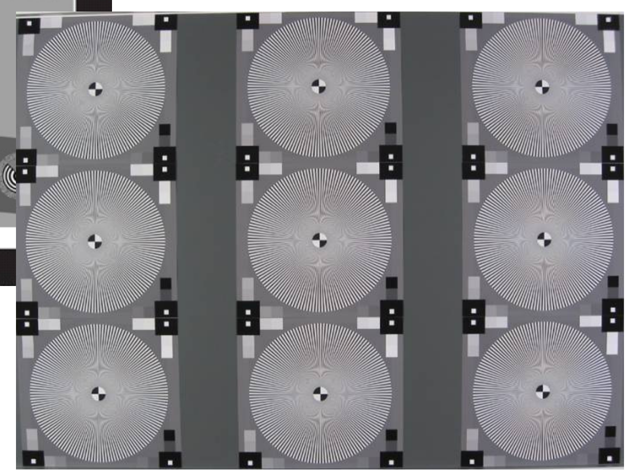
Proposed New ISO 12233 Resolution Targets – Rev. 2



CIPA – maximum resolution
Not recommended for SFR

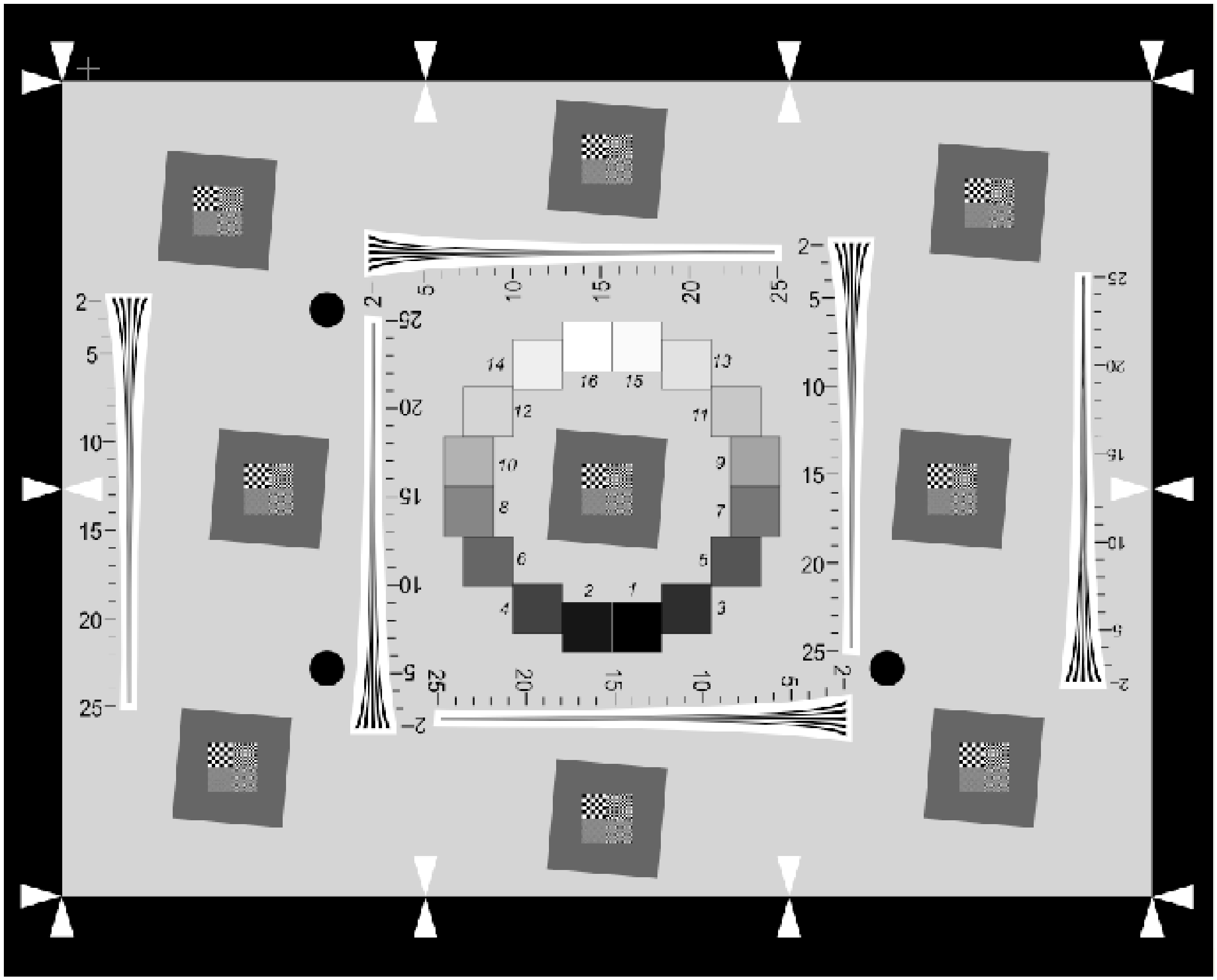


OECF, Slanted Edges
Edge-based SFR

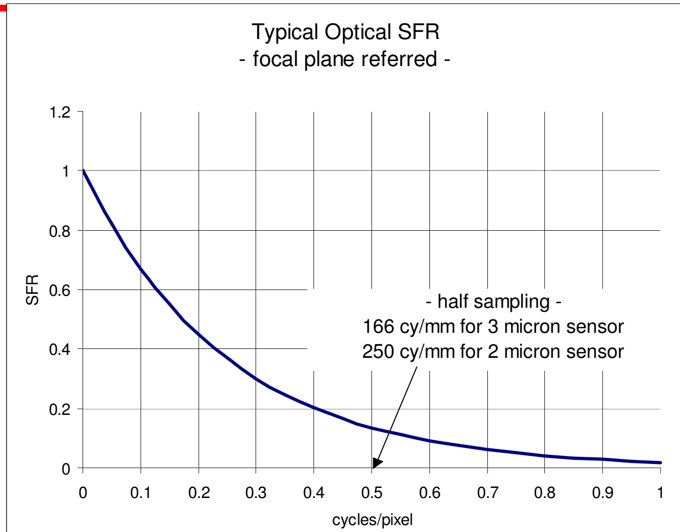


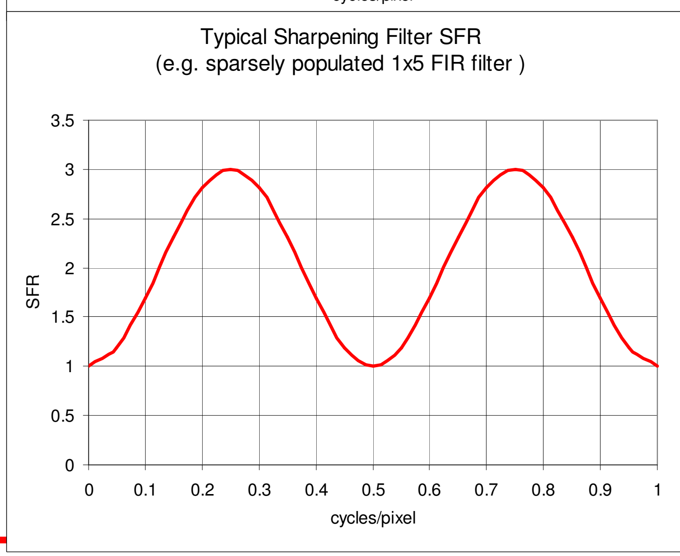
Polar sine waves
Sine-based SFR

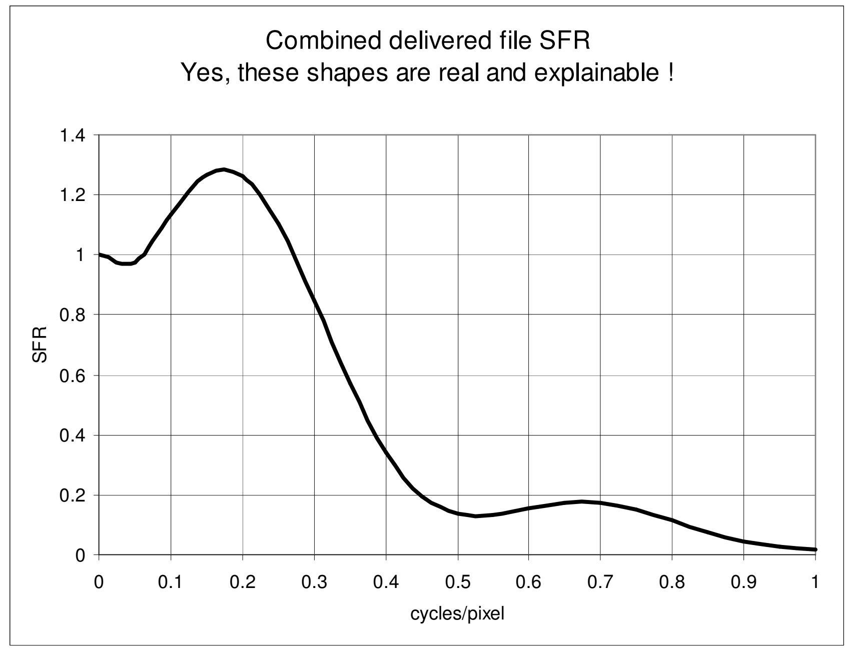
Proposed Cell Phone Resolution Target



Anatomy of the SFR
- strange, but explainable, shapes -

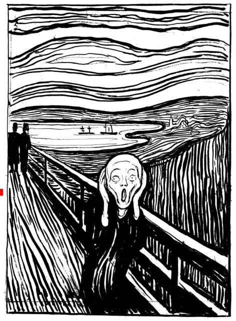


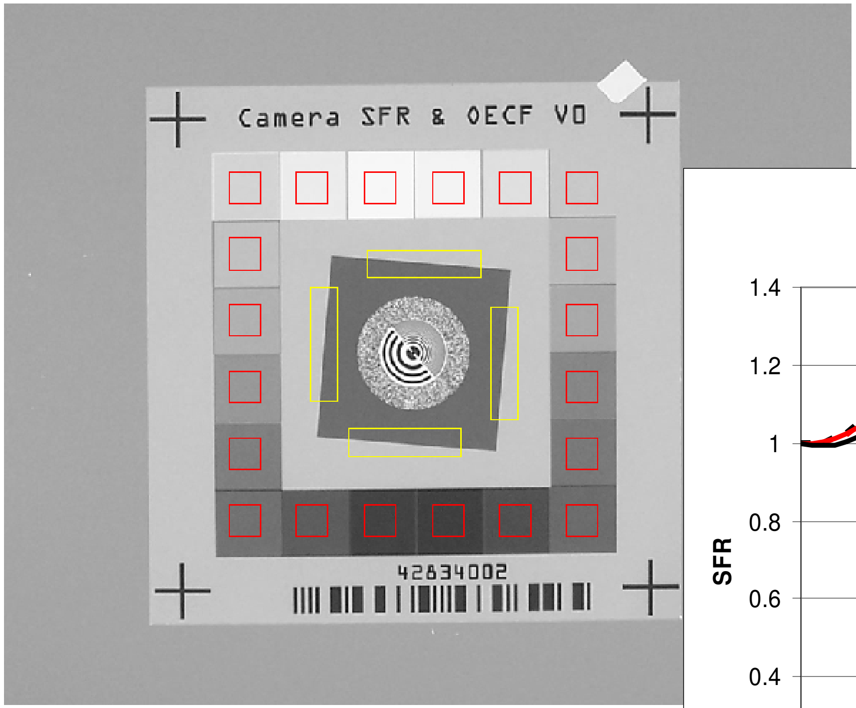


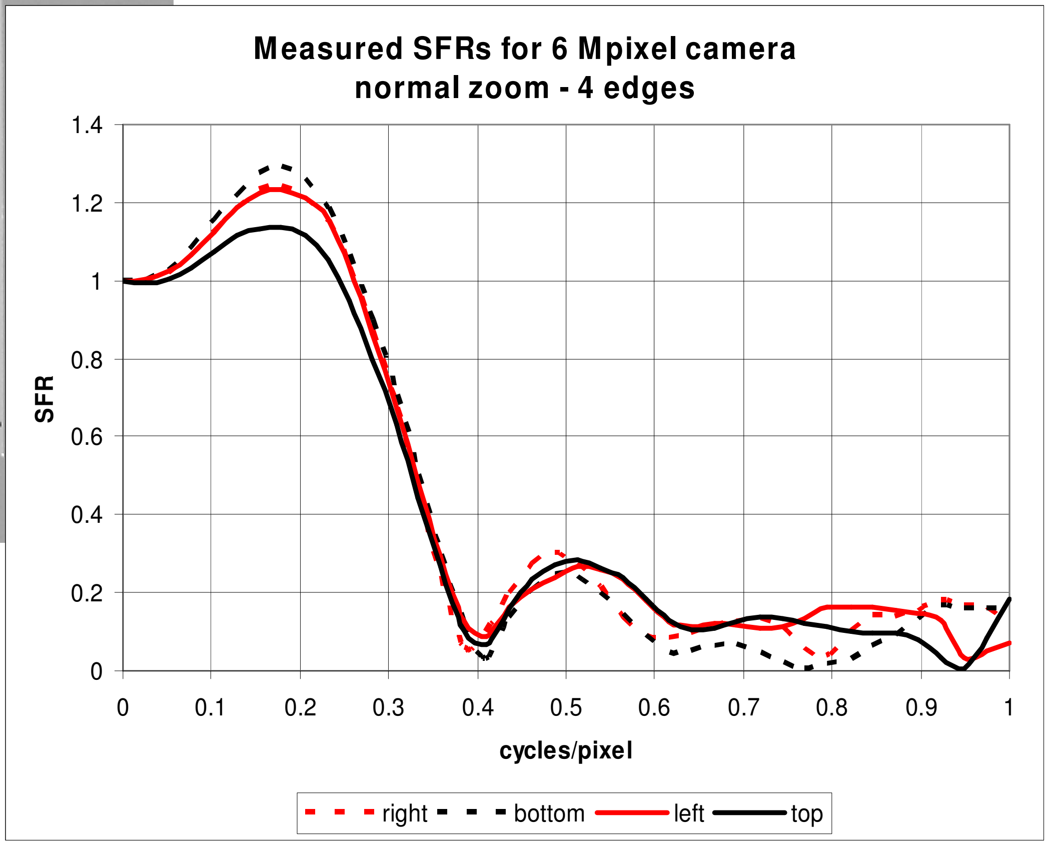


Anatomy of the SFR

- strange, but explainable, shapes -

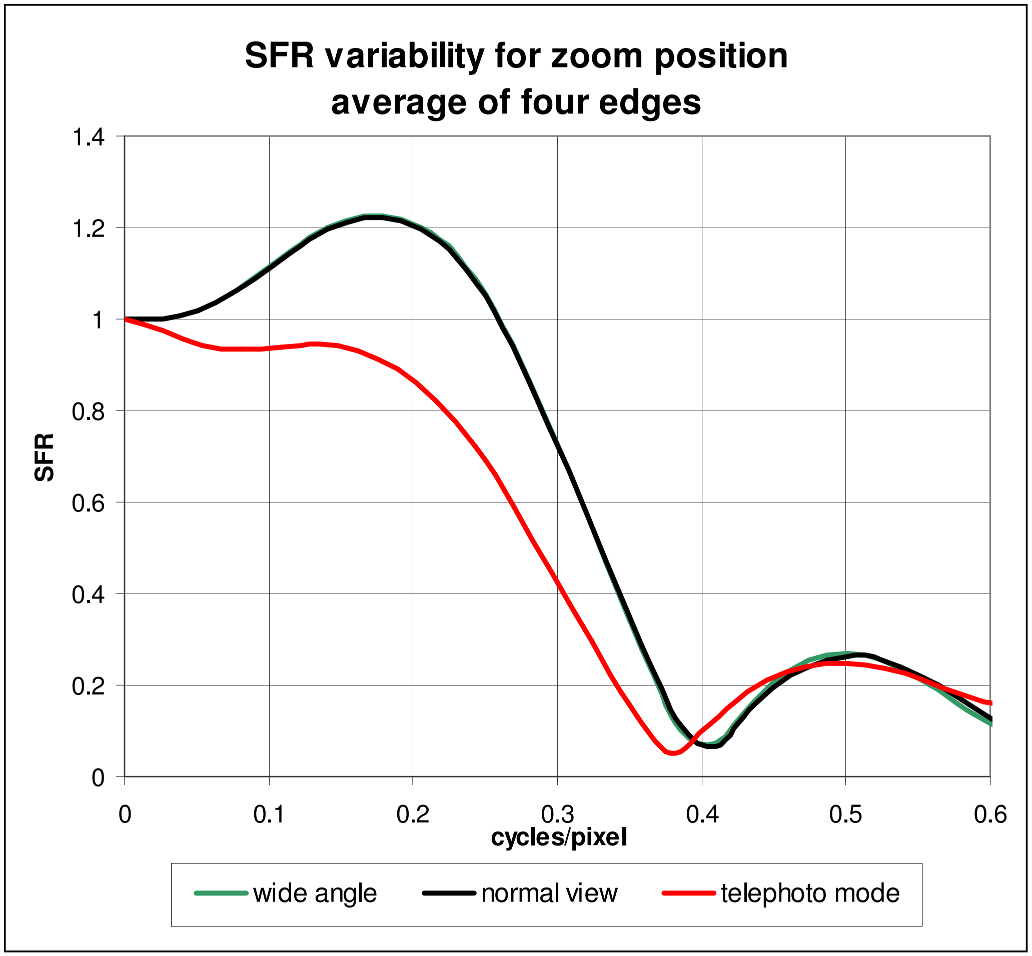




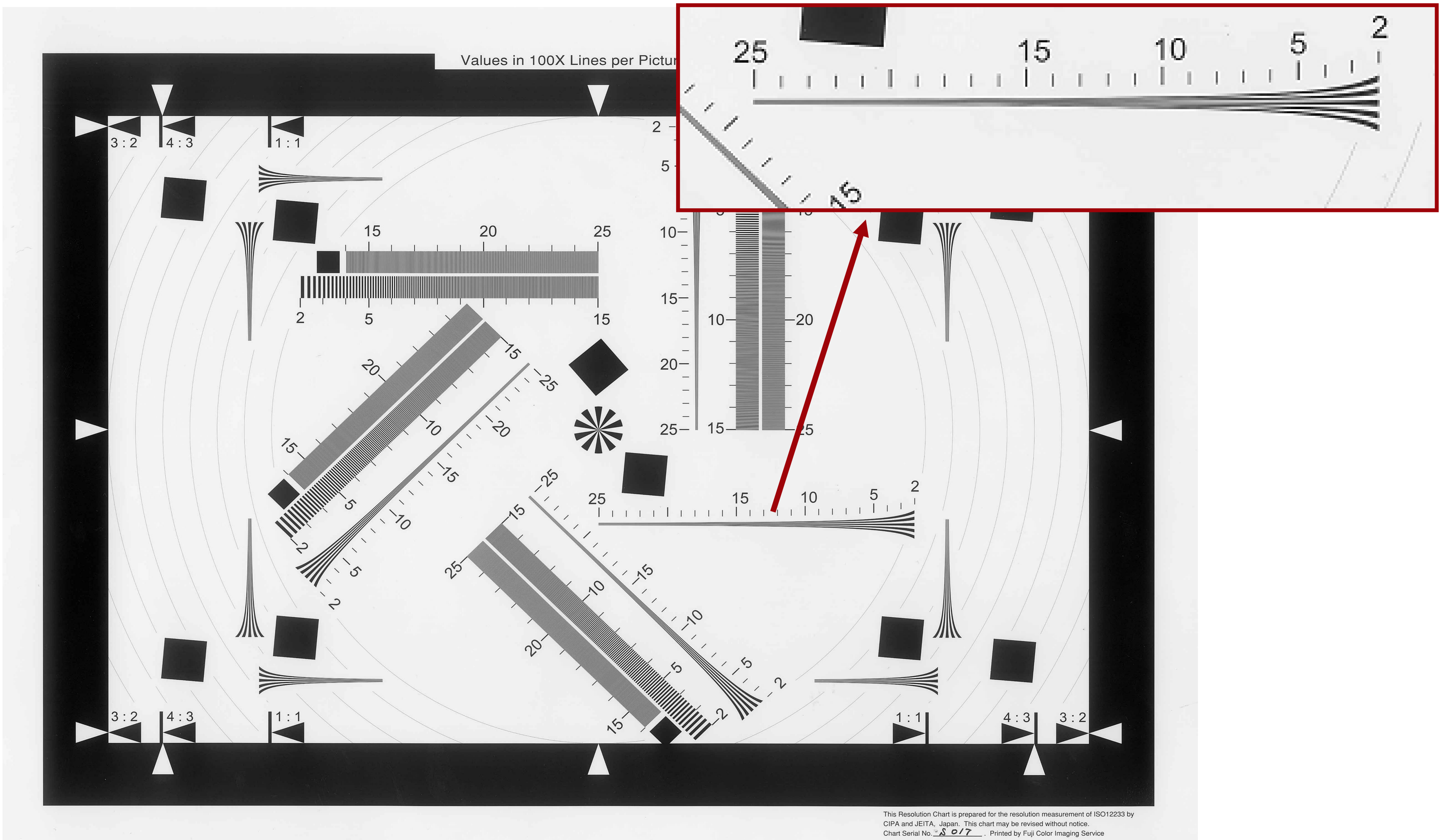


Evaluating multiple SFRs

SFR variability as a function of zoom level



CIPA Target


Values in 100X Lines per Pictur
3 : 2
4 : 3
1 : 1
This Resolution Chart is prepared for the resolution measurement of ISO12233 by
CIPA and JEITA, Japan. This chart may be revised without notice.
Chart Serial No. S 017 . Printed by Fuji Color Imaging Service

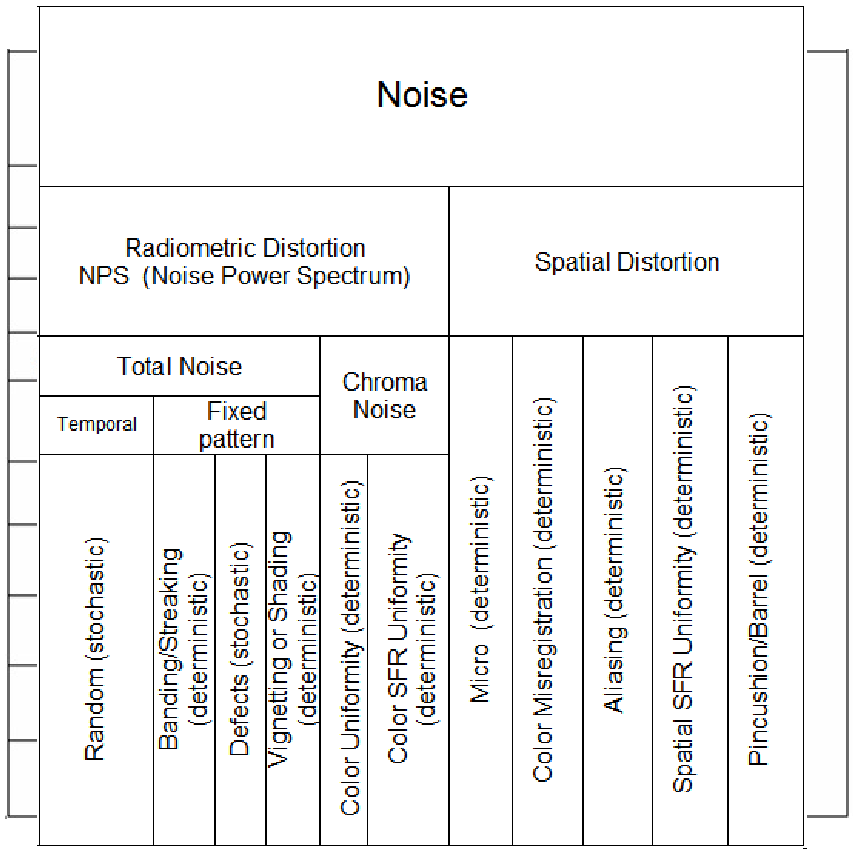
NOISE

Image Noise

Noise is a general term applied to error or unwanted fluctuations in images. Given that it can have many sources, it can take several forms.

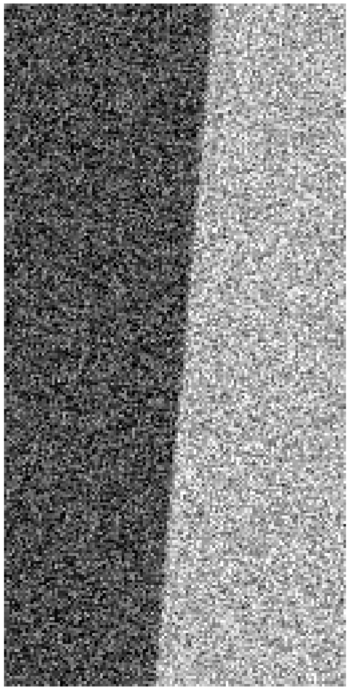
- Random noise due to film grain or low exposure to a detector. Often looks like “salt and pepper” noise.
- Often reported as an RMS number (*standard deviation*)
- Structured banding
- Compression artifacts

Taxonomy - Noise



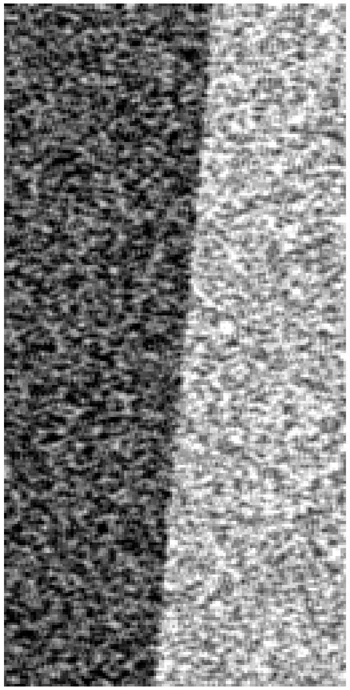
Two-Dimensional Random: Example

Fine-grain noise ->
high frequency fluctuations



$\sigma_R = 0.025$

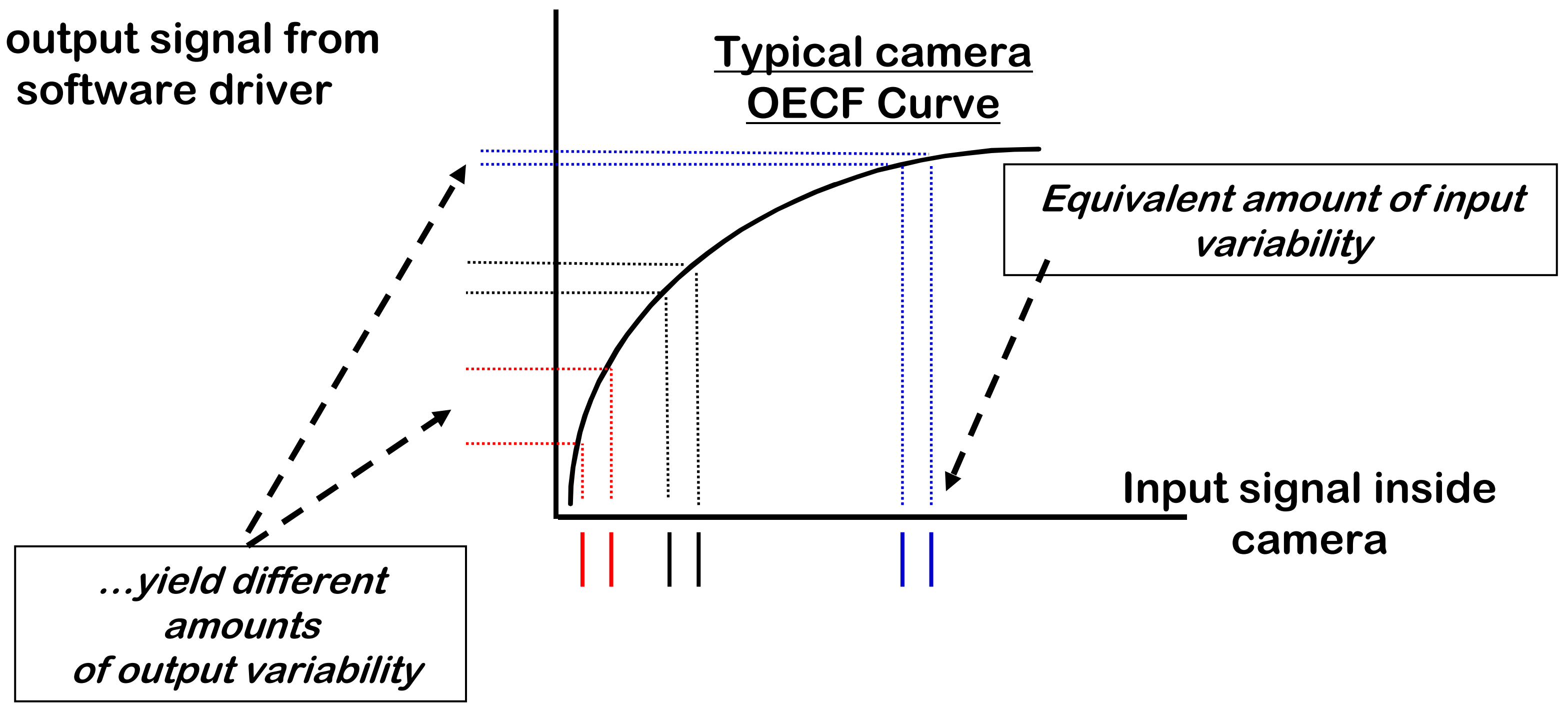
Course-grain noise ->
low frequency fluctuations



$\sigma_R = 0.025$

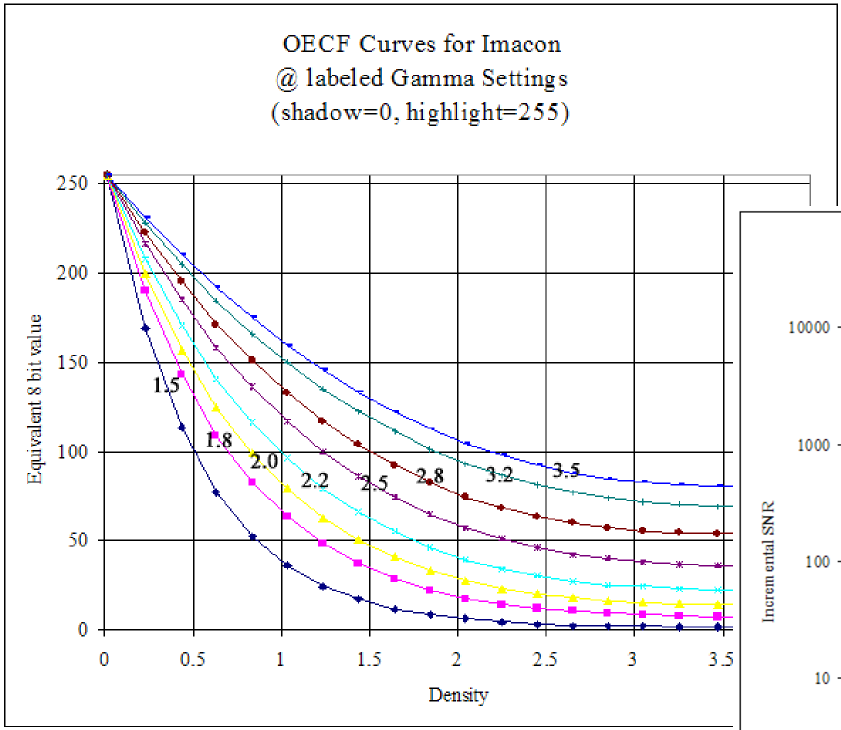
R = print reflectance [0-1]

Noise Changes with Look-Up Table

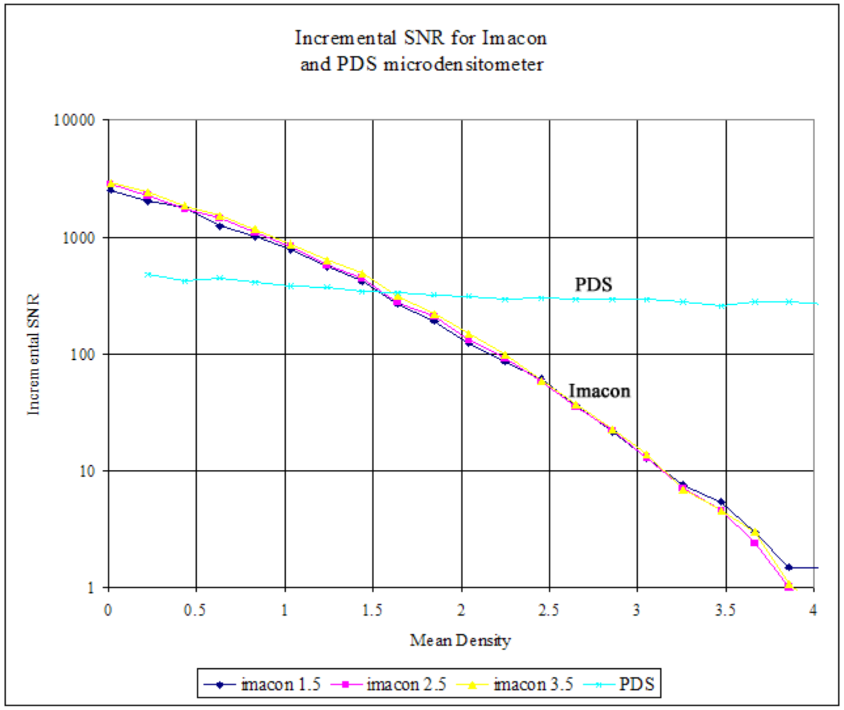


RMS is multiplied by the local slope of the transformation.

SNR_{inc} Example – Gamma Function Influence



PDS = reference instrument



ISO/TC42 Standards for Digital Imaging Noise Metrology

ISO 15739 – Noise for Digital Still Cameras
ISO 21550 – Dynamic Range for Digital Film Scanners

Commonalities

- Assume an additive noise model; $\sigma^2_{total} = \sigma^2_{fixed\ pattern} + \sigma^2_{temporal}$
- Attempt to discriminate noise contributions with replicate images
- Requires OECF measurement for scene referred metrology
- Dynamic Range reported as a linear ratio, not decibels (dB)

Differences

15739

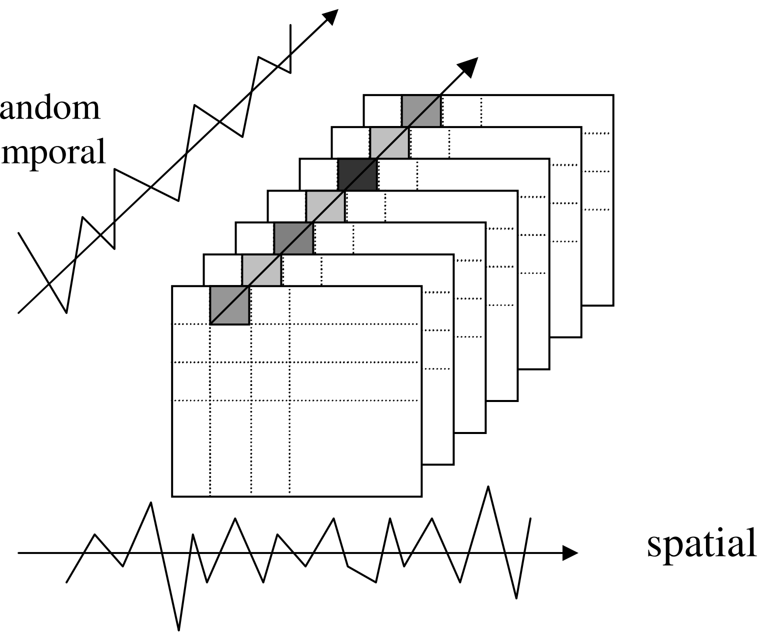
- Focuses on noise metrology
- Uses peak-to-peak definition of signal for dynamic range
- Provides for frequency weighted visual noise output (informative)
- Assumes 140% luminance_{max}
- Photoshop plug-in available at http://www.i3a.org

21550

- Focuses on dynamic range metrology
- Uses Incremental signal definition for dynamic range calculation
- Assumes 100% maximum transmission

Fixed-Pattern Noise Separation

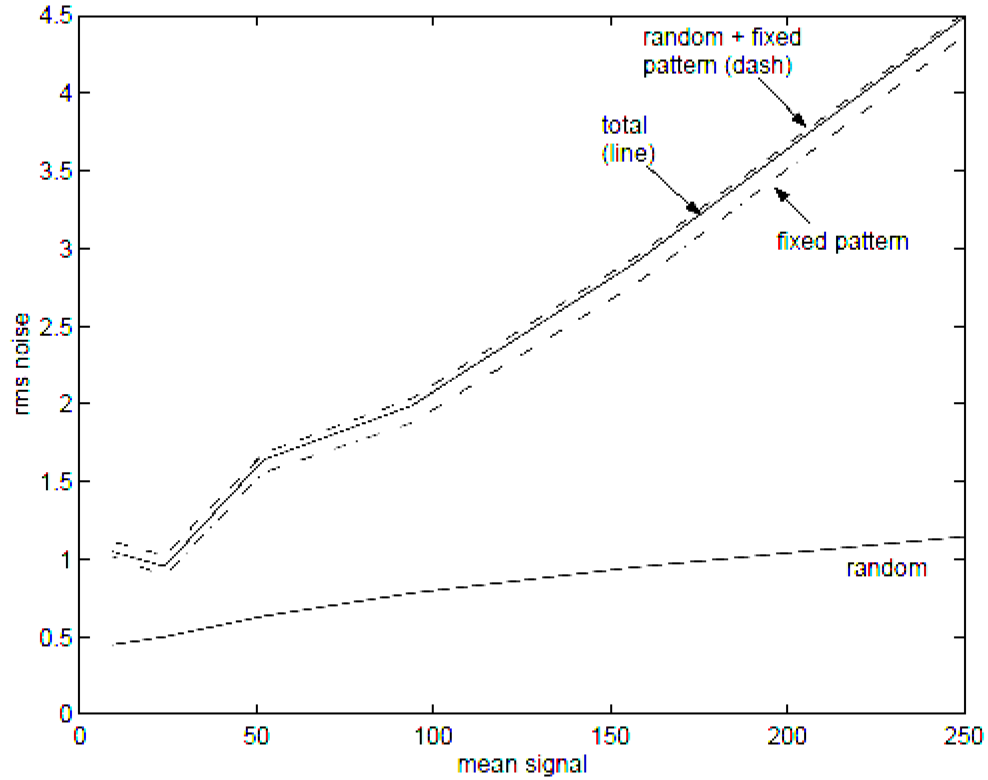
- We are interested in statistics of the noise components
- System evaluation/verification
  - Testing conditions
  - Targets
  - Analysis
- *Effective* contributions
- We can use replicate image



$$\sigma^2_{total} = \sigma^2_{random} + \sigma^2_{fp}$$

$$\sigma^2_{fp} = \sigma^2_{target} + \sigma^2_{imager}$$

Fixed-Pattern Noise Removal: Scanner



Dynamic Range – Cameras and Scanners*

The extent of energy over which a digital capture device can ***reliably detect*** signals: reported as either a normalized ratio (xxx:1) or in equivalent optical density units, $D = -\log_{10} R$, R= reflectance.

<u>Signal Detection → OECF</u>

The mean (average) change in count level associated with a particular input density level.

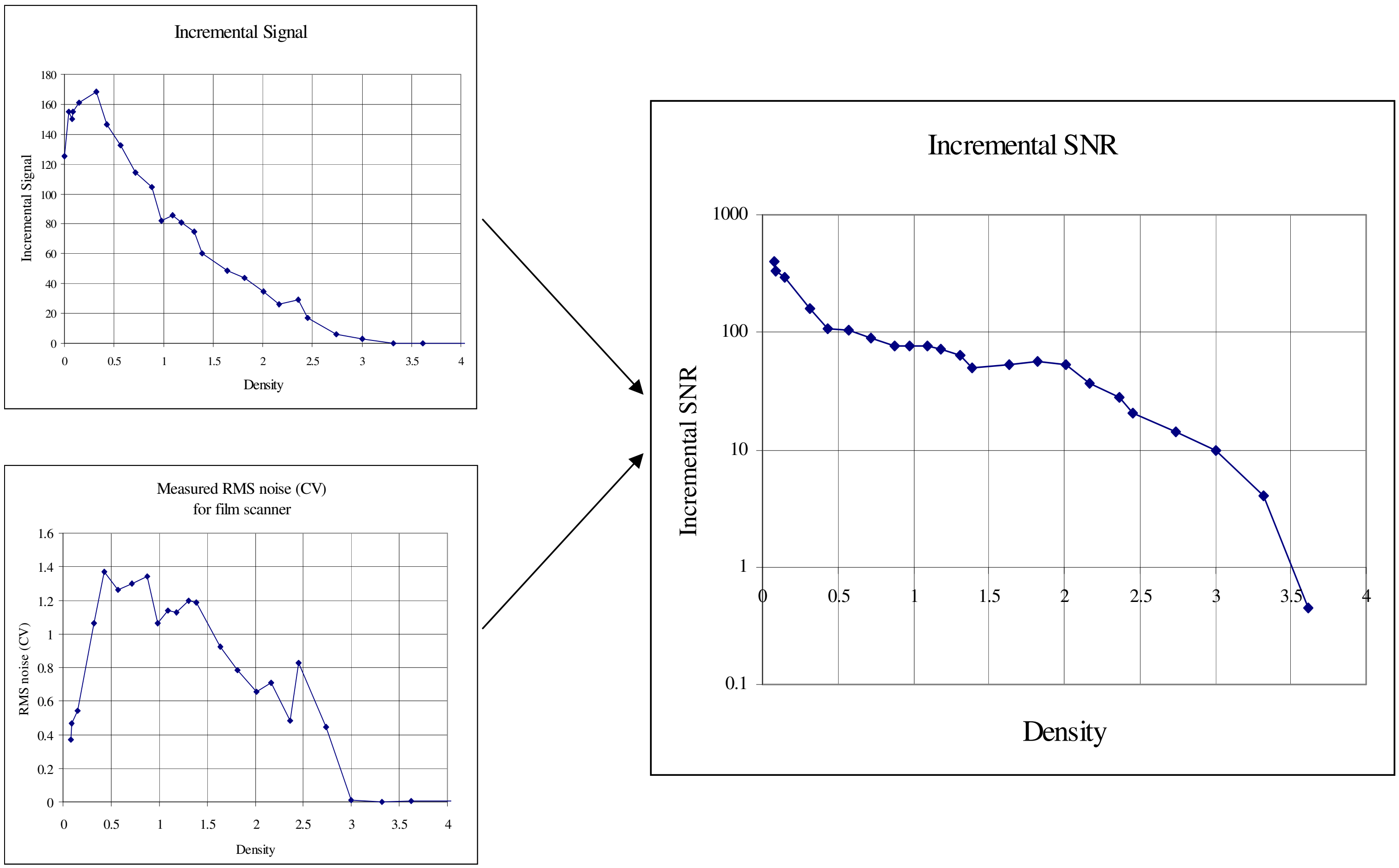
<u>Reliability of Detection → Noise</u>

The root mean square (std. dev.) count level associated with a particular input density level
High noise ≡ low reliability

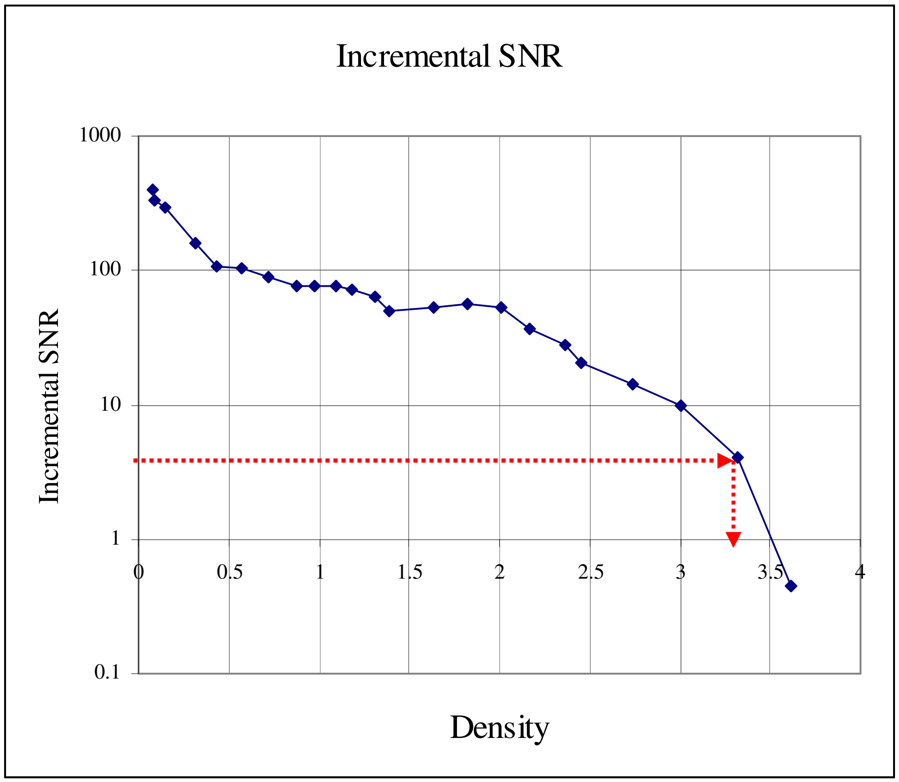
$$\frac{\textit{Signal}}{\textit{Noise}}$$

- ISO 21550 – Dynamic Range for Digital Film Scanners
- ISO 15739 – Noise Measurement for Electronic Still Pictures Cameras

Incremental Signal-to-Noise Ratio – Scanners



Determining Camera Dynamic Range from SNR_{inc}



Generally, the density level corresponding to a SNR_{inc}= 4 to 6 defines the dynamic range of a scanning device. For this device, the dynamic range would be 3.32

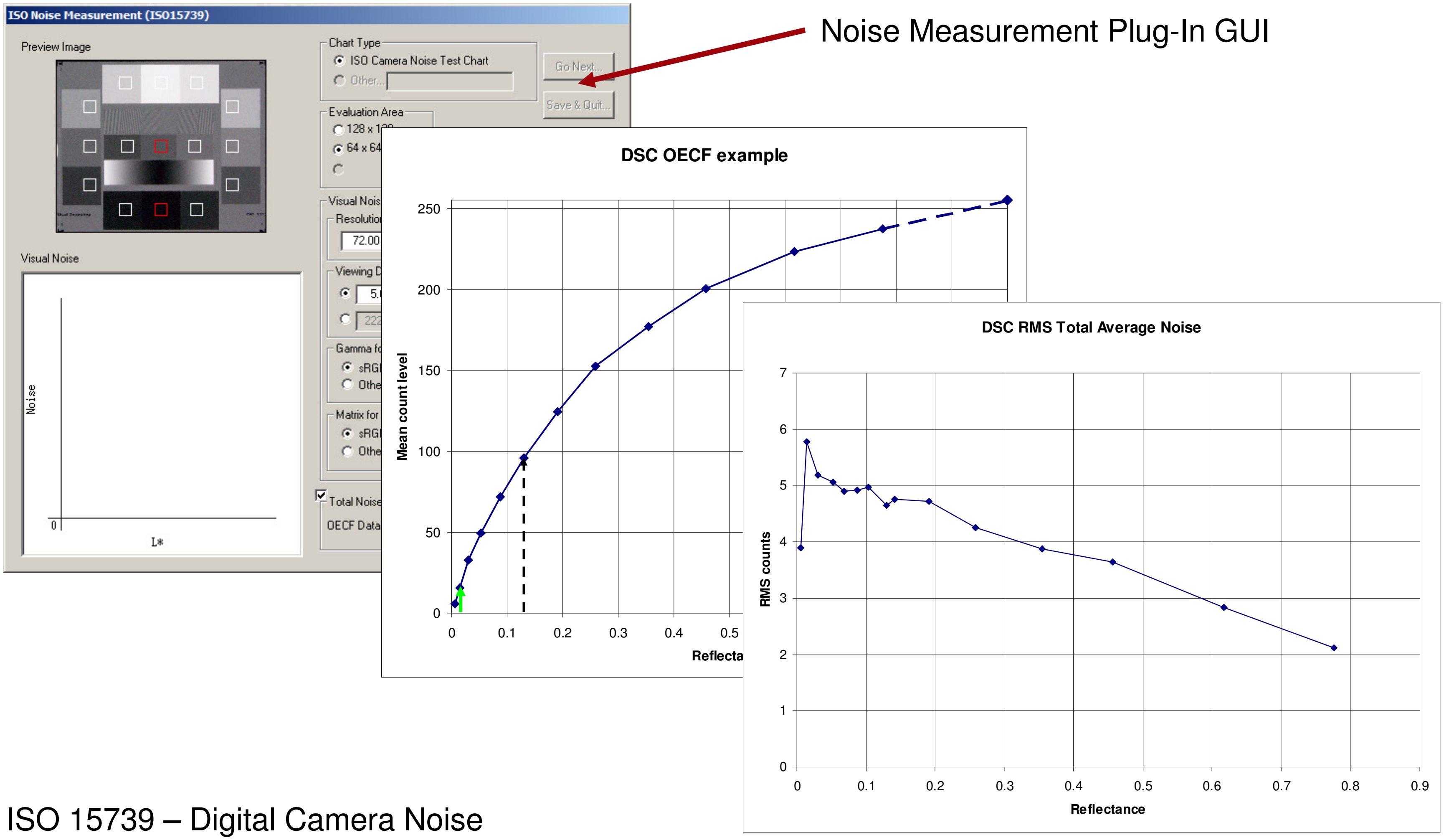
Compare this to simple bit depth methods, e.g., for a 14- and 8-bit scanner. It would be

$$DR = -\log\left(\frac{1}{2^{(\#bits)}}\right)$$

14 bits = 4.2
8 bits = 2.4

The advantage of using SNR_{inc} as a metric for dynamic range is its insensitivity to camera function settings like gamma.

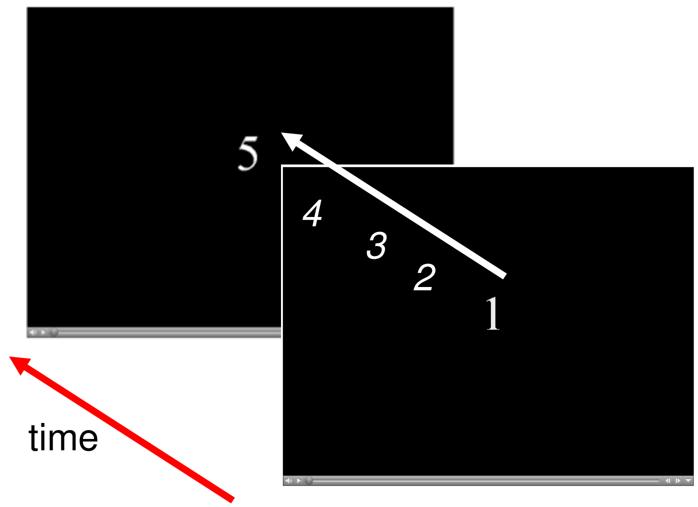
Camera SNR and Dynamic Range – Example



ISO 15739 – Digital Camera Noise

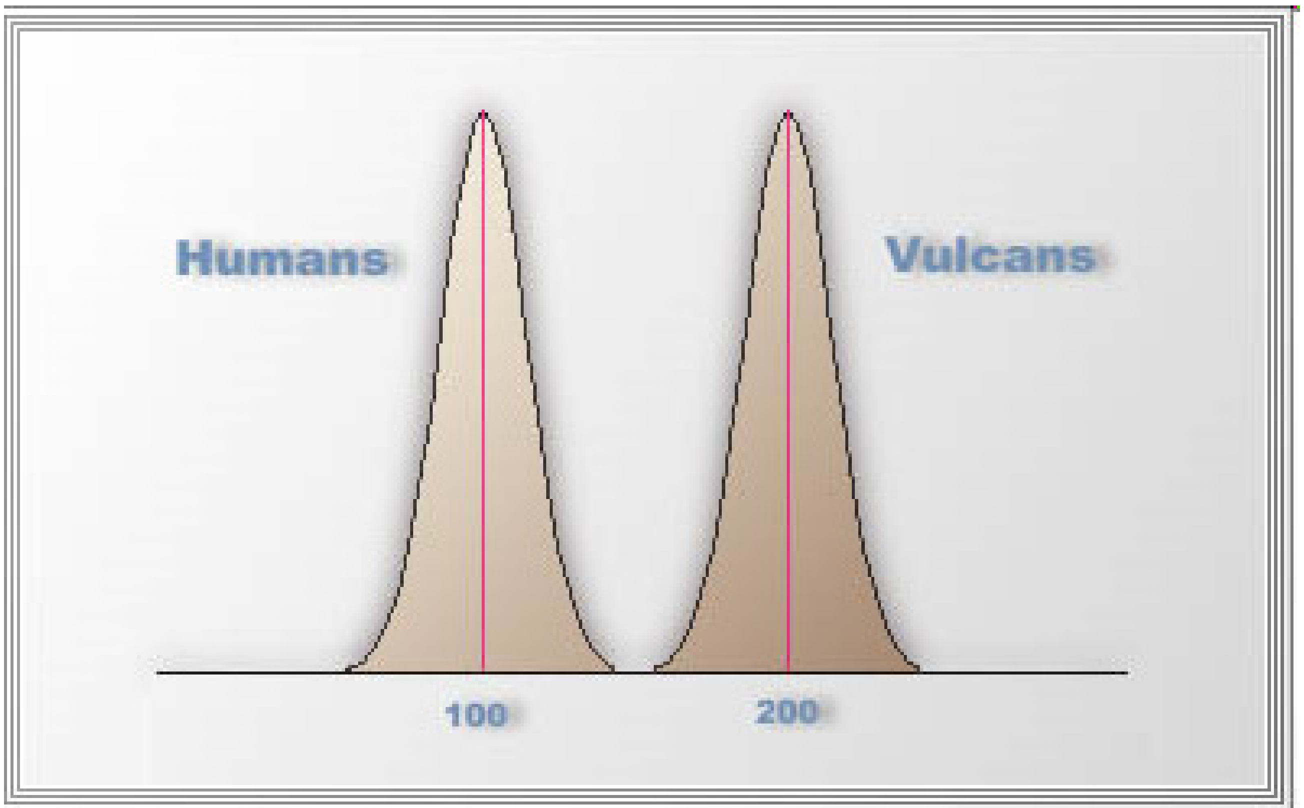
Shutter Lag Measurement

http://www.shooting-digital.com/columns/professorpixel/tools/lagtest/



Quicktime Movie

Measurement variability



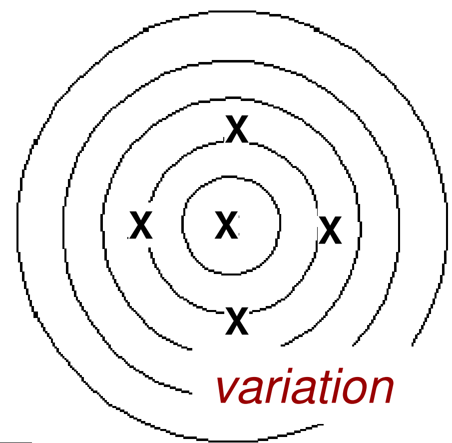
Measurement Requirements

Measurements usually require some level of both accuracy and precision.

– *Accuracy:* average error from a standard

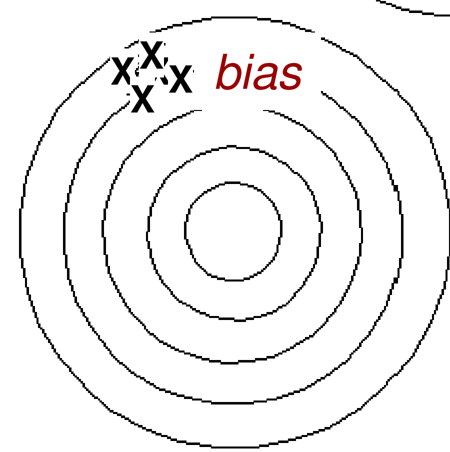
– *Precision:* variability about the average reading

Is your watch set to the correct time?



Factors that influence measurements

– Test target feature location estimation
– Signal processing
– Signal quantization
– Spatial sampling
– Image noise



Variation

Actual performance

e.g., Optical quality across the image field, or with lens zoom position

Measurement error

Estimation of sample statistics

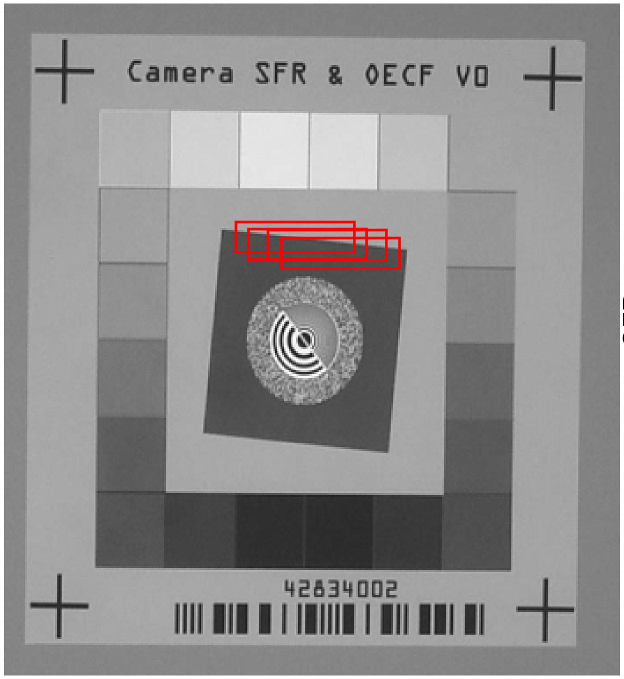
e.g. due to signal quantization, sampling

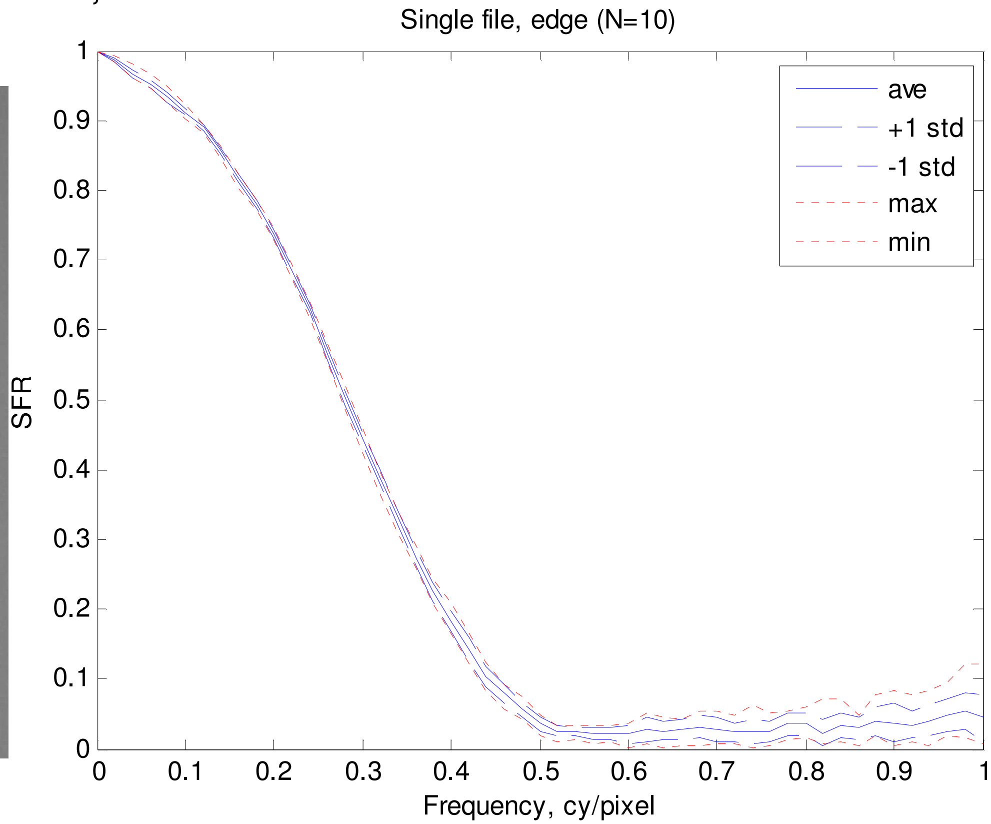
Sampling:

variation in estimating parameters (statistics) from test images

Measurement error example

- Simplest way to quantify measurement variation is by repeating the analysis
- This edge SFR example is for one test file and one edge, varying the location of the region of interest, N=10





Test plans – just a few words

- Don't collect too much data
  - Limit the experiment
- Control the variables
  - Operator, lighting, zoom position, image processing
- Distinguish benchmarking from monitoring
- Distinguish capability from performance
- Be reasonable with test targets designs
  - Any target can be designed to make a camera look bad
- Test under conditions that match expected usage.
- Prioritize the metrics exposure, SFR, noise/artifacts

Wrap Up of Part 1

1. Technology used influences imaging performance
2. Imaging performance measurement is standardized for
   - Large area image capture (OECF)
   - Image detail capture (SFR and MTF)
   - Image noise and artifacts (rms, dynamic range)
3. Visual inspection is often needed for artifacts
4. Understanding of technology modes helps interpretation of results. Area arrays, image formatting, software settings, etc.

Send questions to Peter at
pdburns@ieee.org

Part 2: Software Tools for Imaging Performance Evaluation

IS&T / SPIE Electronic Imaging SCIENCE AND TECHNOLOGY

In this part of our short course we discuss the needs for *imaging performance tools*.

Who needs them, and what do they need?

Should we develop our own or buy?

Are imaging standards important?

Are there common components or functions?

Imaging Performance Tools

Who needs imaging performance tools?

Those responsible for,

- selecting service providers or equipment
- specifying component performance or characteristics
- monitoring production
- comparing various systems

What do they need?

- Measurement system, e.g., test object, test plan, analysis software, etc.
- Standard testing, e.g., ISO
- Quality assurance system with tracking of results
- Metadata population
- System testing as product is actually used
- Scanner as instrument

Imaging Performance Tools

Should we buy or develop our own?

For common types of tasks, commercially available products can be adapted and adopted.

Are imaging standards important?

Often they are if you need to compare with published results, negotiate with vendors, or comply with regulations.

Is any free stuff available?

Common elements of system evaluation effort

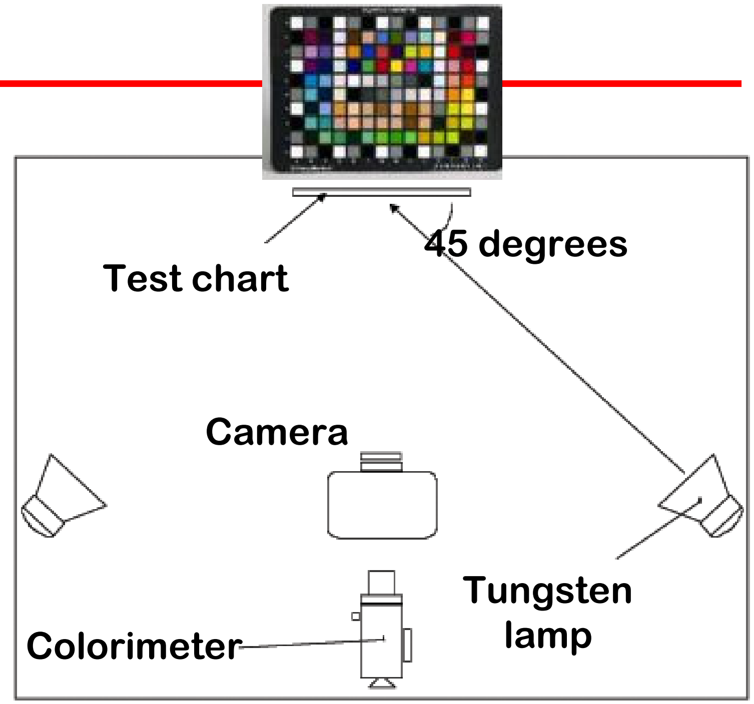
- Test plan
- Test target or object(s)
- Analysis software
- Report/result generation and organizing
- Test specification level(s)
- Corrective action plan
- …

Example: Color Accuracy

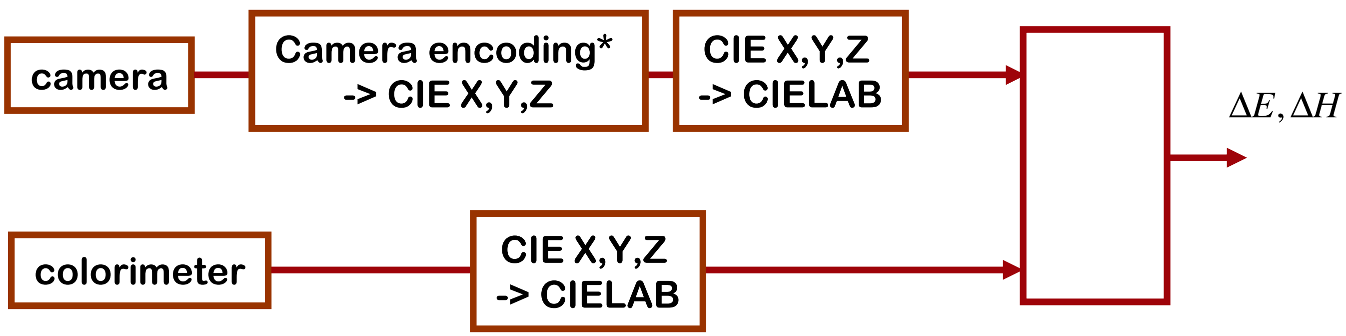
Colour difference in CIELAB colour-space

To do this, the camera signal values must to converted into CIELAB values (*of scene objects*)

Often a GretagMacBeth Colour Checker chart is used

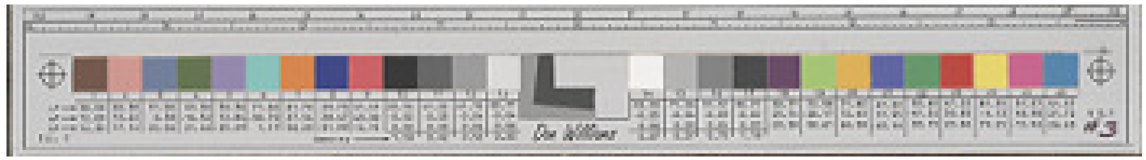


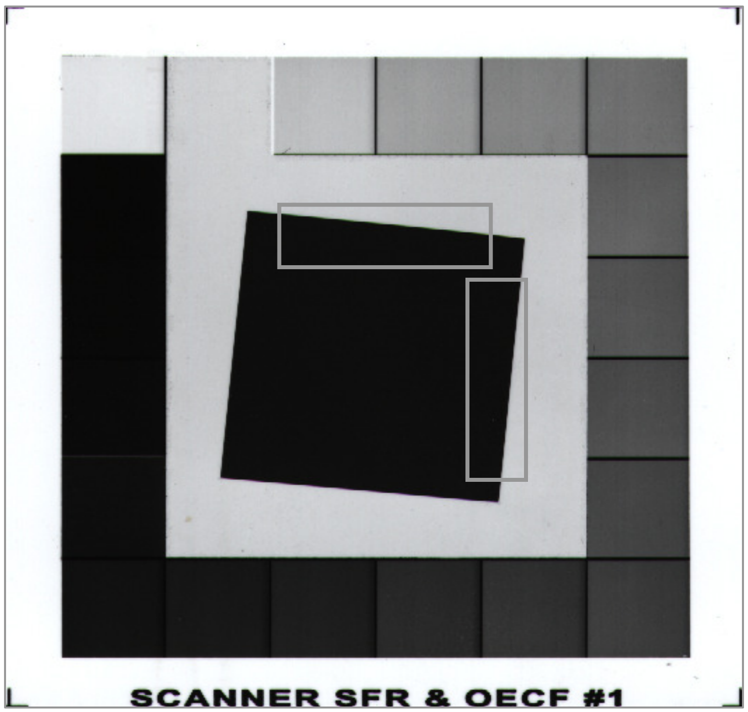
Example

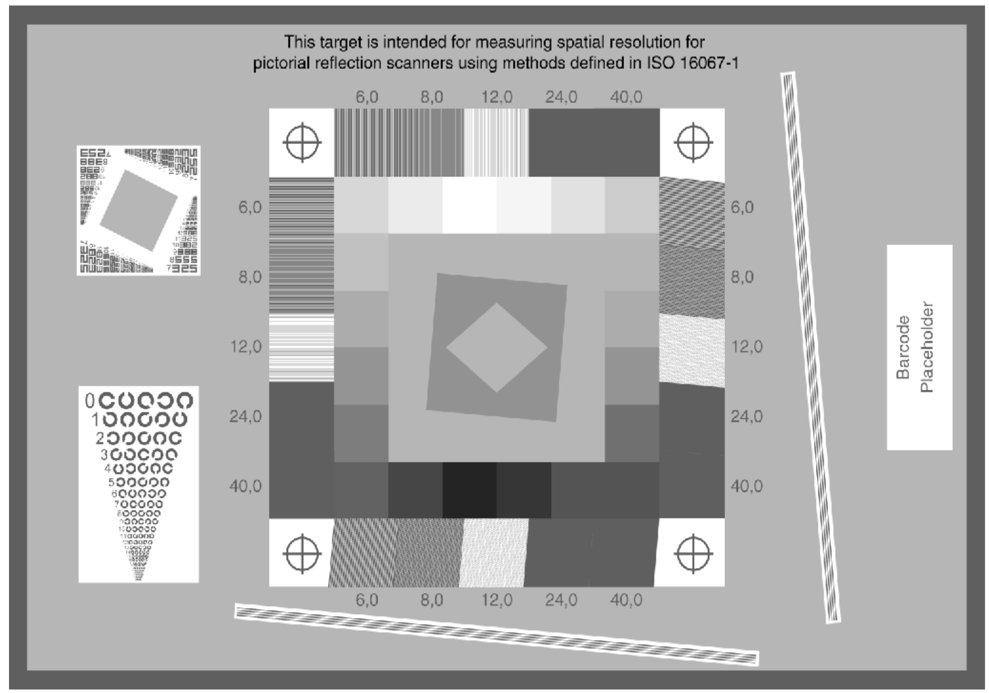


*e.g., ***sRGB***

Resolution/OECF charts: camera, scanner

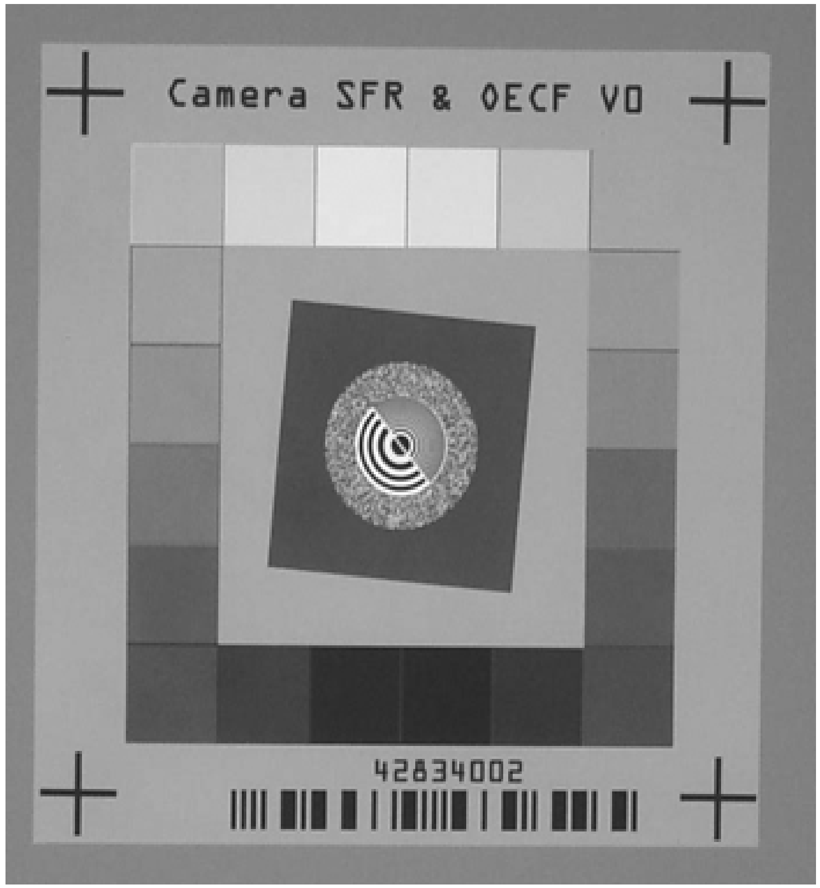




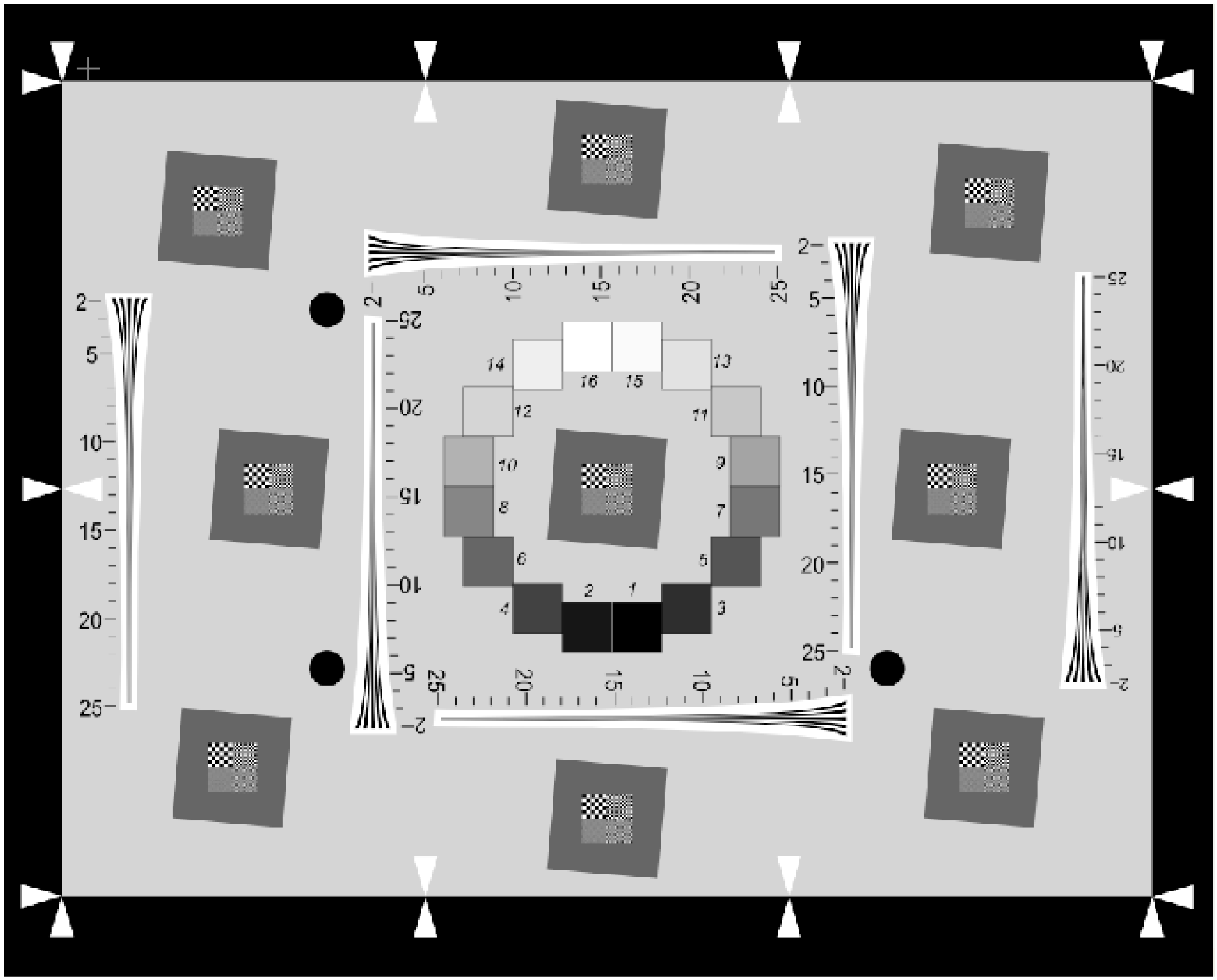


Imaging Performance Tools

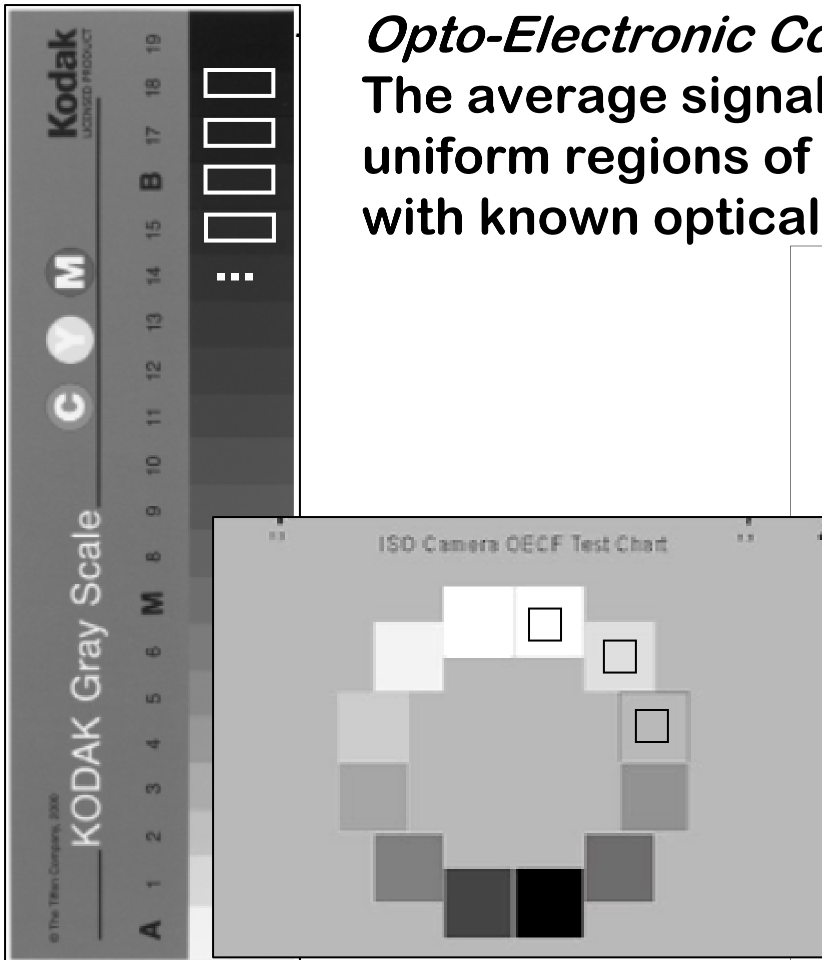
Example of test target that can be used to evaluate OECF and SFR



Proposed Cell Phone Resolution Target

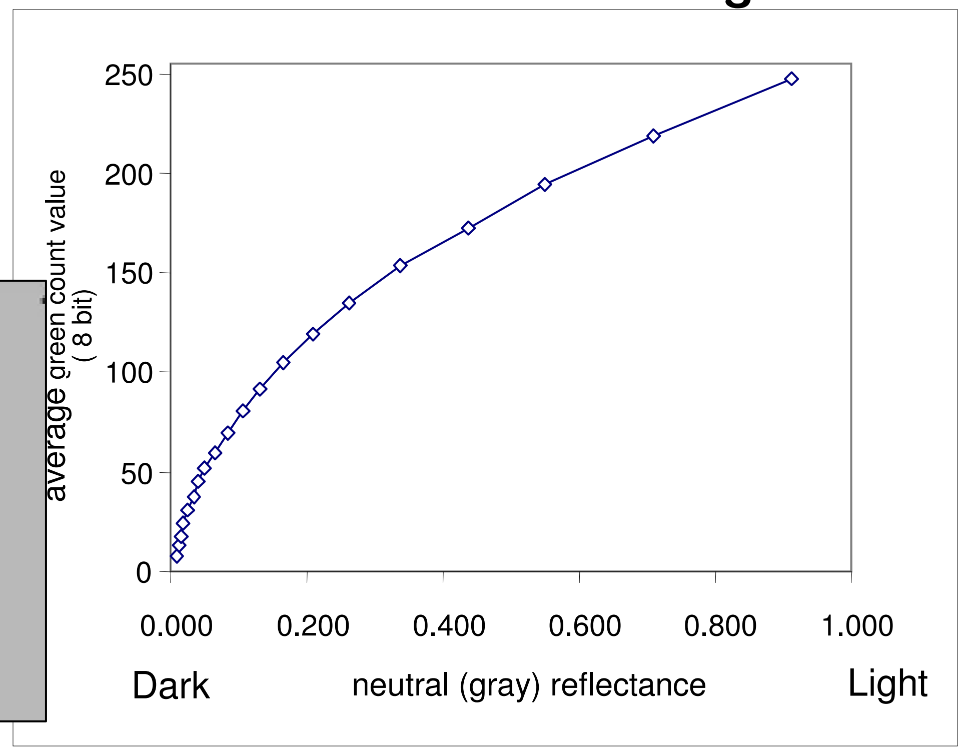


Measurement and control of tone-reproduction



Opto-Electronic Conversion Function OECF:

The average signal value of selected large area and uniform regions of interest (ROI) are associated with known optical reflectances values of a target.

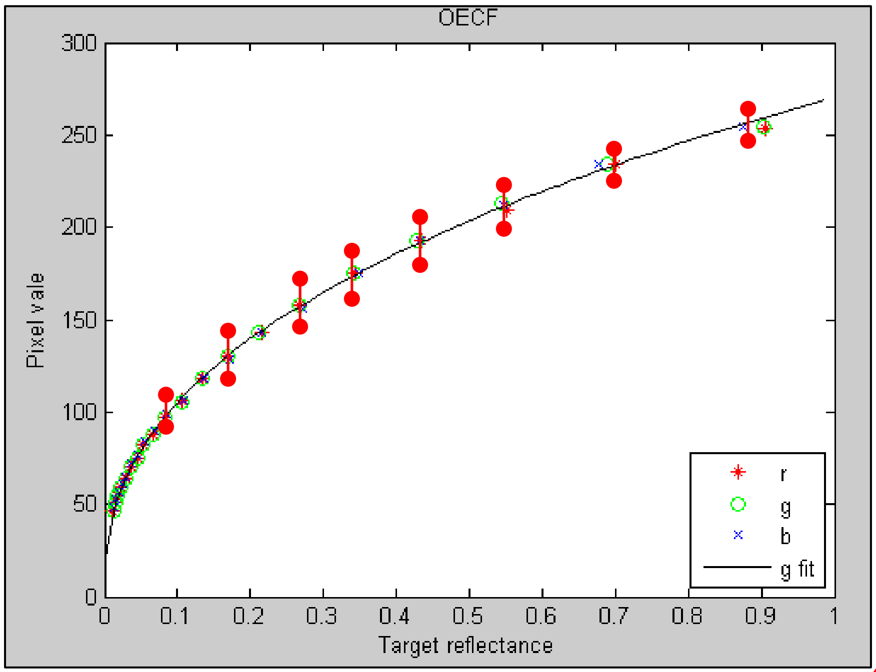


ISO-14524, Photography - Electronic Still Picture Cameras - Methods for Measuring Opto-Electronic Conversion ...

Common functions of performance analysis software

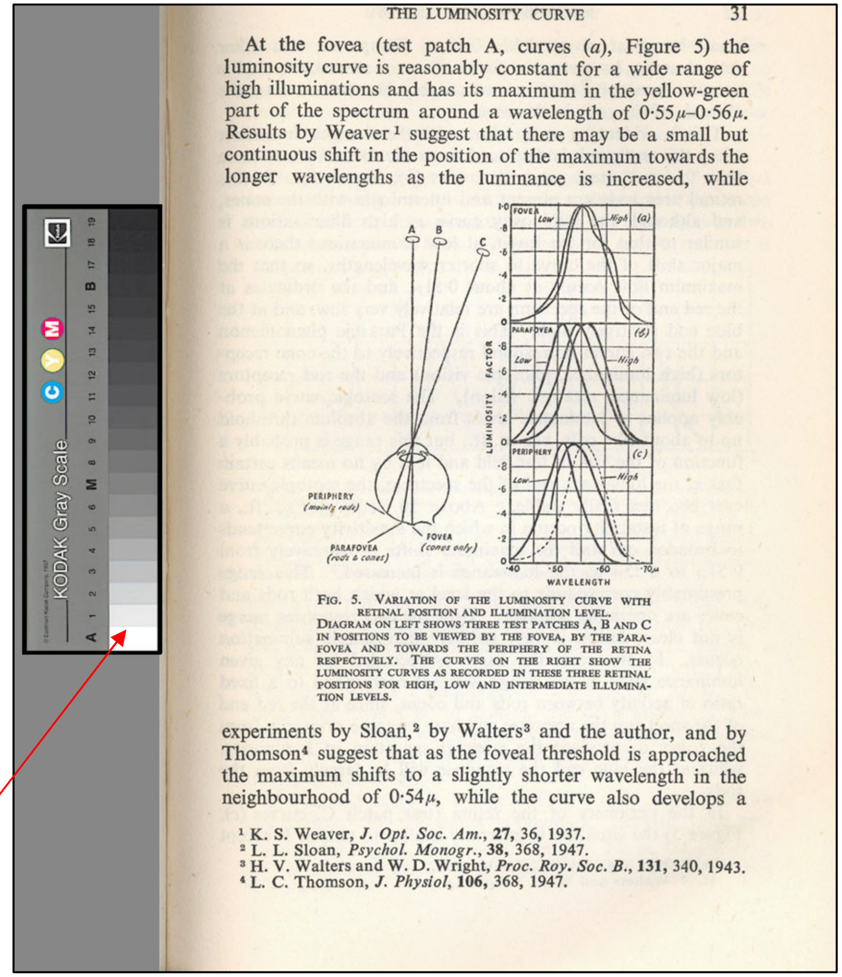
- File selection (input image/data and output results)
- Region-of-interest (ROI) selection
- Reading of digital image files
- Analysis of image data (pixel values)
- Testing of results (against specifications)
- Displaying of results (plots, listings)

Example of image-level target



- **Simple interpretation**
- **Single attribute**

OECF
Color
balance



THE LUMINOSITY CURVE 31

At the fovea (test patch A, curves (*a*), Figure 5) the luminosity curve is reasonably constant for a wide range of high illuminations and has its maximum in the yellow-green part of the spectrum around a wavelength of 0·55μ–0·56μ. Results by Weaver[1] suggest that there may be a small but continuous shift in the position of the maximum towards the longer wavelengths as the luminance is increased, while

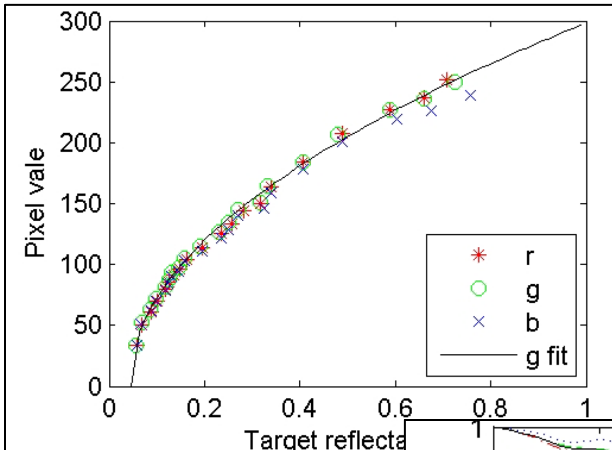
FIG. 5. VARIATION OF THE LUMINOSITY CURVE WITH RETINAL POSITION AND ILLUMINATION LEVEL. DIAGRAM ON LEFT SHOWS THREE TEST PATCHES A, B AND C IN POSITIONS TO BE VIEWED BY THE FOVEA, BY THE PARAFOVEA AND TOWARDS THE PERIPHERY OF THE RETINA RESPECTIVELY. THE CURVES ON THE RIGHT SHOW THE LUMINOSITY CURVES AS RECORDED IN THESE THREE RETINAL POSITIONS FOR HIGH, LOW AND INTERMEDIATE ILLUMINATION LEVELS.

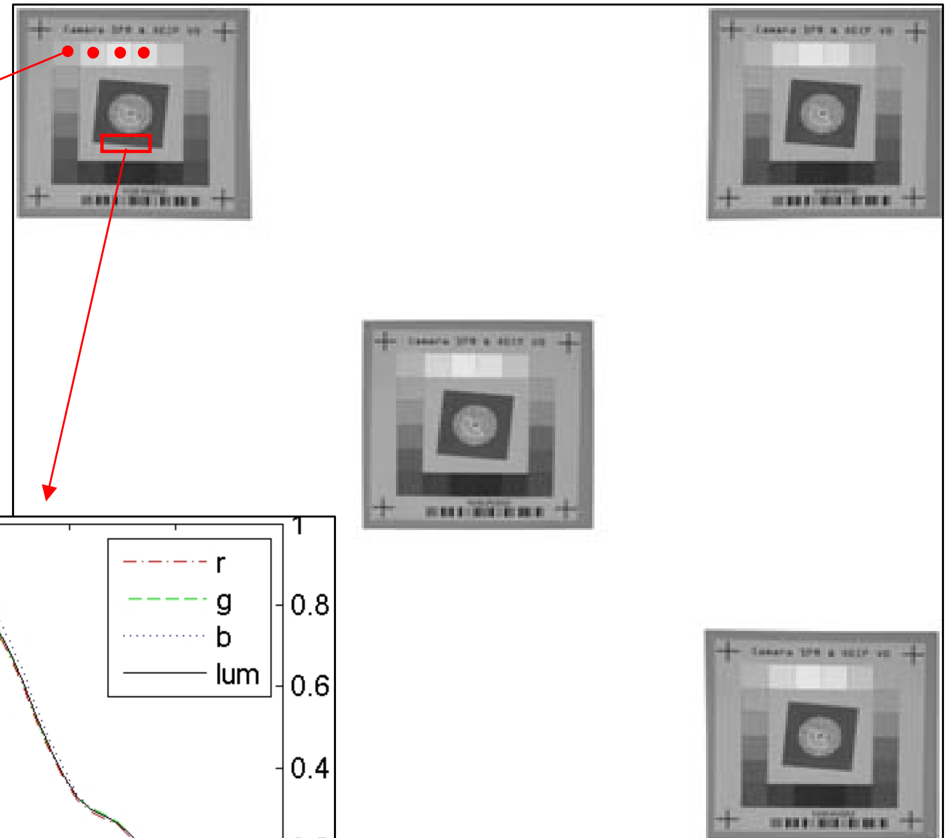
experiments by Sloan,[2] by Walters[3] and the author, and by Thomson[4] suggest that as the foveal threshold is approached the maximum shifts to a slightly shorter wavelength in the neighbourhood of 0·54μ, while the curve also develops a

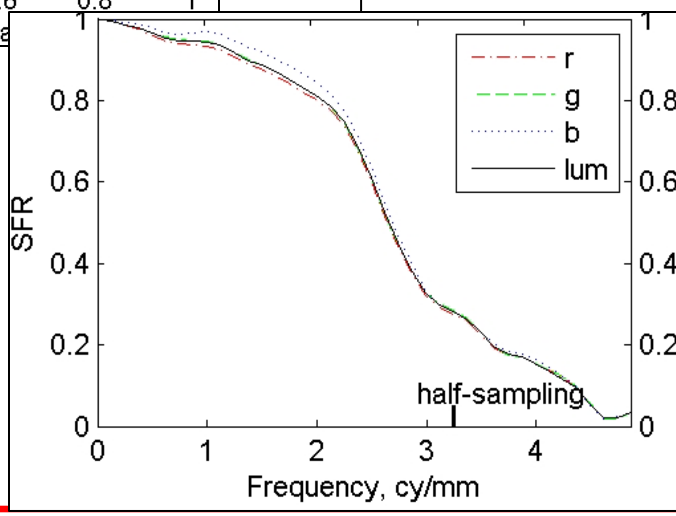
[1] K. S. Weaver, *J. Opt. Soc. Am.*, **27**, 36, 1937.
[2] L. L. Sloan, *Psychol. Monogr.*, **38**, 368, 1947.
[3] H. V. Walters and W. D. Wright, *Proc. Roy. Soc. B.*, **131**, 340, 1943.
[4] L. C. Thomson, *J. Physiol*, **106**, 368, 1947.

W.D.Wright, Photometry and the Eye, Hatton Press, 1949

Device-level testing







Variation in

- **OECF**
  optical falloff
- **SFR**
  MTF falloff
- **colour misregistration**

OECF
Spatial frequency response

Notes

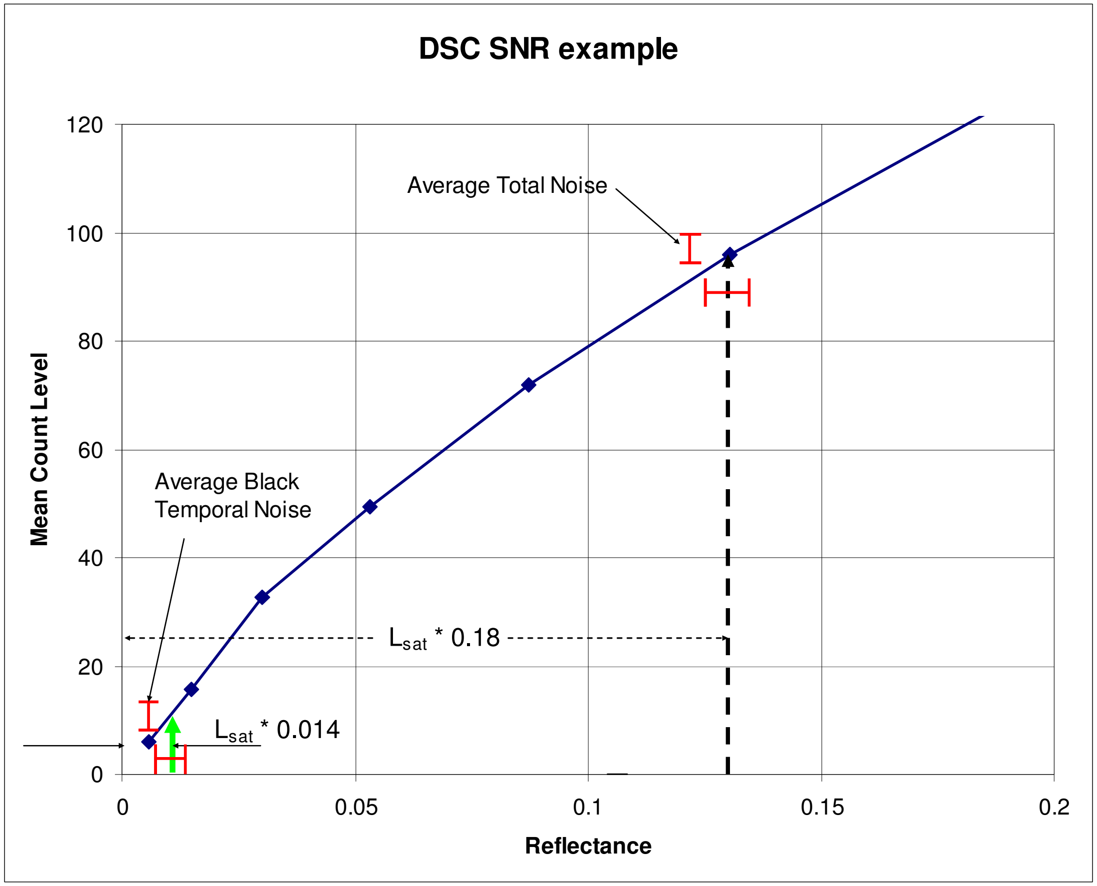
Digital Camera Evaluation Sites Using ISO Targets

http://www.cameralabs.com/reviews
edited by Gordon Laing

http://www.dpreview.com/reviews

http://www.imaging-resource.com/
Dave Etchells
(downloadable full-res ISO 12233 images)

Appendix 1:Camera SNR and Dynamic Range – Example



SNR: Large Area

$$\frac{L_{sat} * 0.18 * \text{Incremental Gain}}{\text{Average Total Noise}}$$

$$\frac{1 * 0.18 * 507}{4.87} = 18.72$$

DSC Dynamic Range

$$\frac{L_{sat} * 0.014 * \text{Incremental Gain}}{\text{Average Black Temporal Noise}}$$

$$\frac{1 * 0.014 * 1091}{5.0} \times 100 = 264.25$$

Appendix 2: Frequency Unit Conversion Table

LW/PH = Line width per picture height
LP/mm = Line pairs per millimetre
L/mm = Lines per millimetre
To convert from left column units to top row units, use operation at their row/column intersection.
(e.g., 5 LP/mm × 2.0 = 10.0 L/mm)

	LW/PH	LP/mm	L/mm	Cycles/mm	Cycles/pixel
LW/PH	×1	∕[2 × picture height (mm)]	∕picture height (mm)	∕[2 × picture height (mm)]	∕[2 × # vert. pixels]
LP/mm	× [2 × picture height (mm)]	× 1	× 2.0	× 1	× pixel pitch (mm)
L/mm	× picture height (mm)	× 0.5	× 1	× 0.5	× [pixel pitch (mm) ∕2]
Cycles/mm	× [2 × picture height (mm)]	× 1	× 2.0	× 1	× pixel pitch (mm)
Cycles/pixel	× [2 × # vert. pixels]	∕pixel pitch (mm)	× [2∕pixel pitch (mm)]	∕pixel pitch (mm)	× 1

Appendix 3: Sampling Frequency

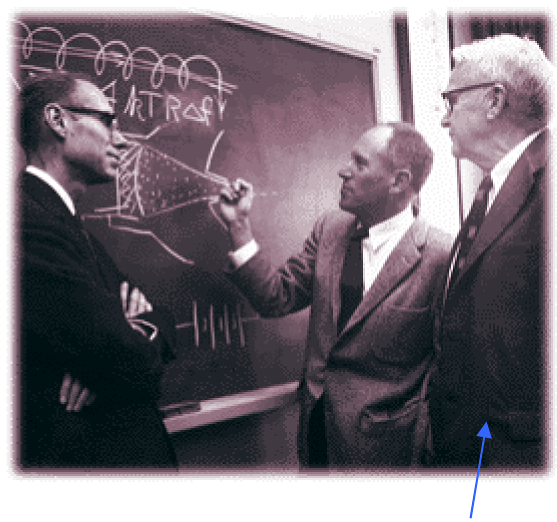
To capture all information in a continuous (analog) signal, the signal should be sampled at a rate (or *sampling frequency* in samples/mm, samples/sec) that is equal to or higher than twice its highest frequency. This highest frequency, f_{max} is sometimes referred to as the *Nyquist Frequency. Nyquist Frequency* is defined differently in different disciplines.

If the *highest frequency* of interest *is* f_{max}, then the *sampling interval* should be

$$dx \le \frac{1}{2 f_{\max}}$$

The *sampling frequency* is then

$$\begin{aligned} f_{sampling} &= 1/dx \\ &= 2 f_{max} \end{aligned}$$



Harry Nyquist

Appendix 4: ISO 12233, SFR and MTF

- The ISO standard for measuring digital still camera resolutions specified a particular method, based on a modified form of edge gradient analysis (EGA)
- The ISO standard, however, refers to the camera resolution metric as Spatial Frequency Response (SFR), rather than an MTF
- There are three basic reasons for this
  - Established photographic standards measure MTFs using other methods (sine waves), and the results often differ from EGA results
  - The term MTF has been associated with the measurement of systems or subsystems* for which it (approximately) uniquely describes the signal transfer from input to output). For many electronic imaging systems, however, the results will vary with system and image conditions.
  - EGA measurement of a system MTF requires compensation for the input target edge characteristics. While this is possible, the original ISO standard did not require it.

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* Linear systems, or those with combinations of linear and point-wise nonlinear subsystems

Appendix 5: Limiting Resolution and Sampling Efficiency

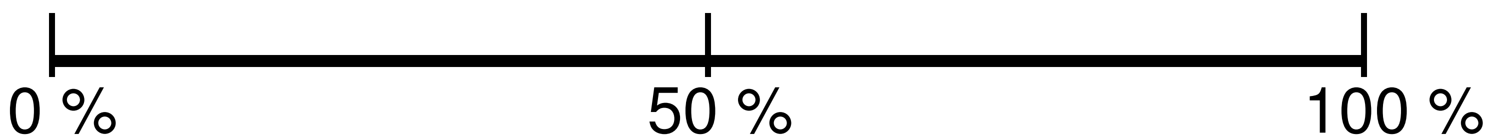
Optical

Adopt an accepted optical criteria for resolution.

Digital

Determine where this criteria falls relative to the sampling limit for digital capture

$$\text{Resolution Efficiency} = \frac{\text{Optical Limit}}{\text{Sampling Limit}}$$



Resolution and sampling efficiency

Quantity: The number of (mega)pixels (MP) or sampling rate
Quality: Optical effects; factors such as focus, F-number, optical glass quality and assembly, camera motion

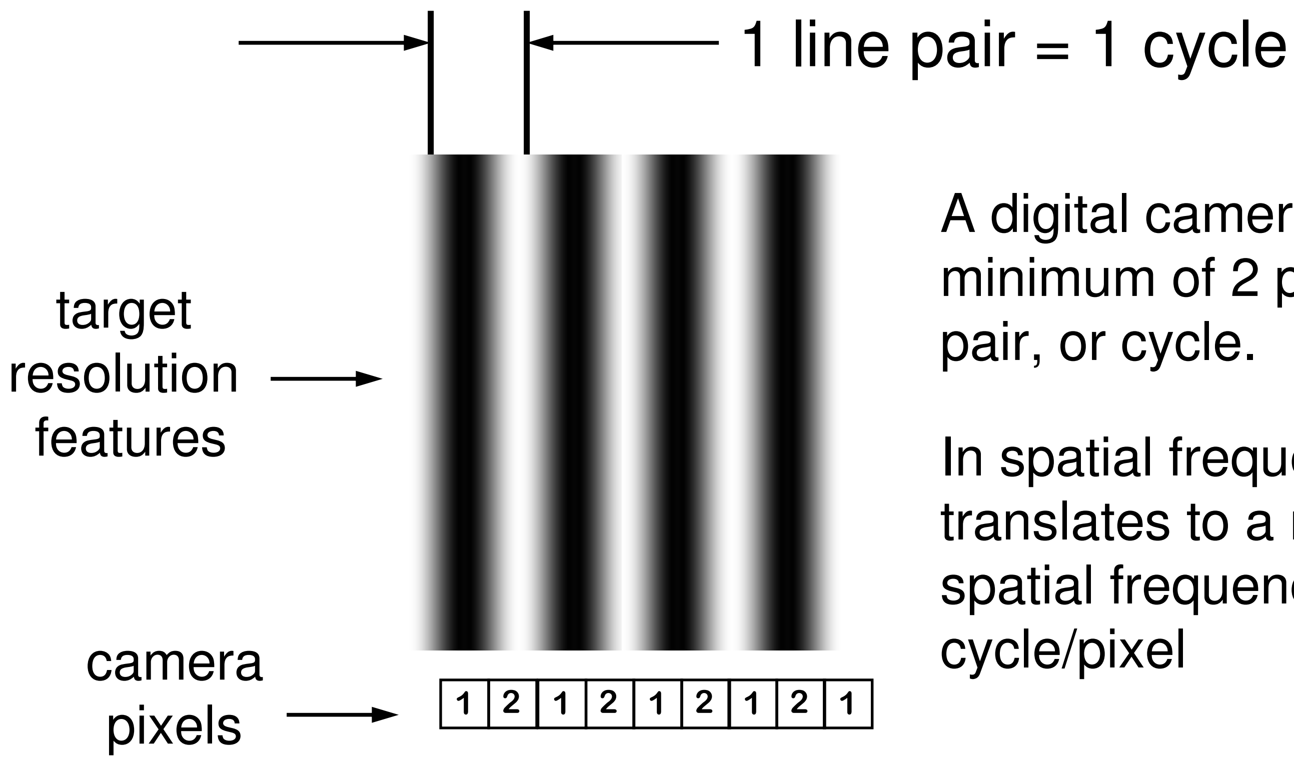
These can be combined:

Quantity × Quality = Effective Utility

Sensor Resolution × Optical Quality = Effective Resolution

Advertised Pixels × Efficiency = Resolved Pixels

Sampling Resolution

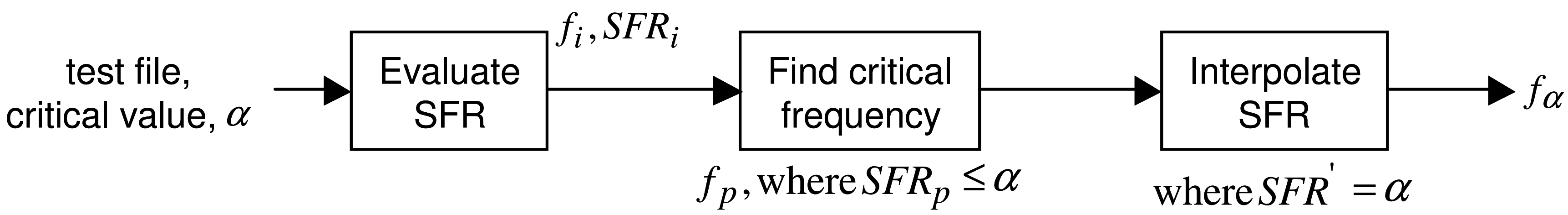


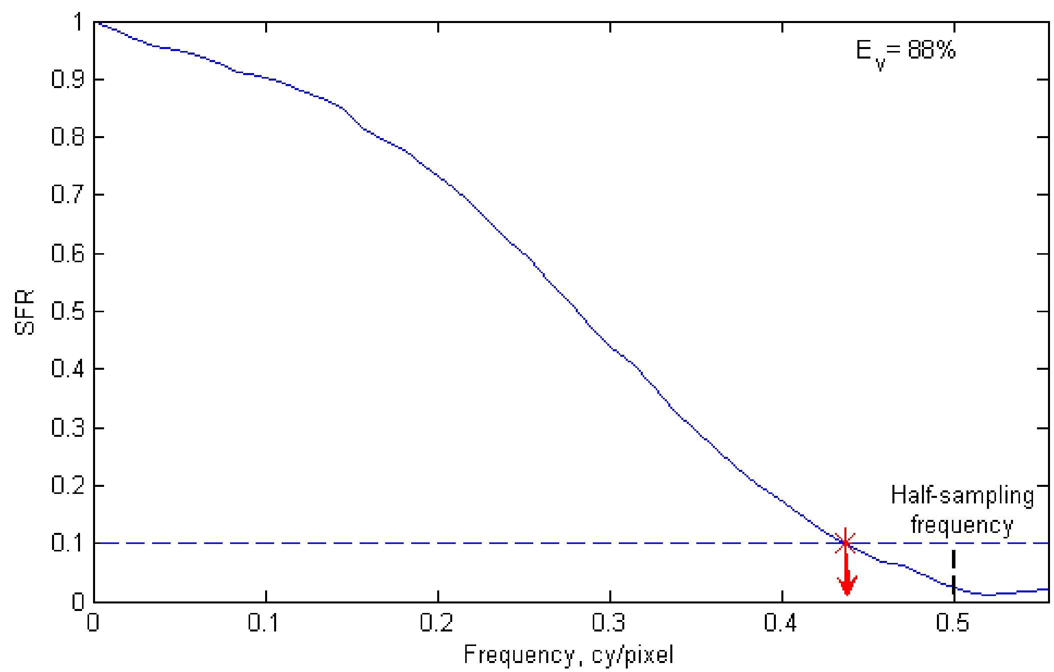
A digital camera requires a minimum of 2 pixels per line pair, or cycle.

In spatial frequency terms, this translates to a maximum spatial frequency of ½ cycle/pixel

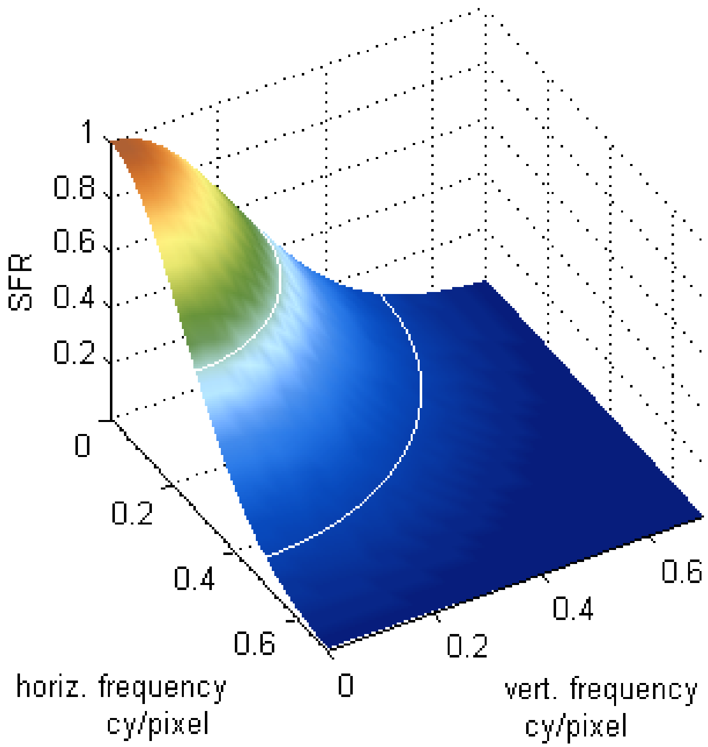
Theoretical maximum resolution for a digital camera is 0.5 cycles/pixel

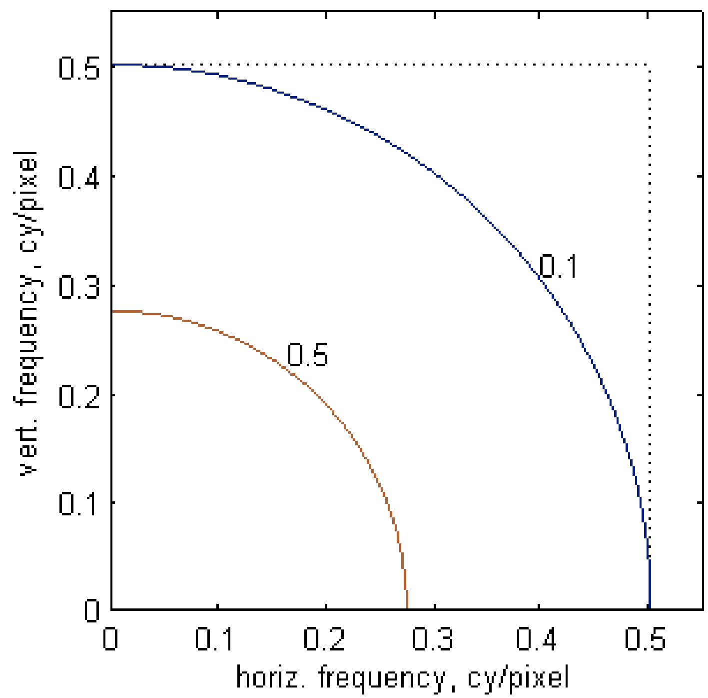
Limiting Resolution Estimation from SFR





Two dimensional example





Example of two-dimensional symmetric SFR and corresponding 50% and 10% response contours

Effective resolution for digital cameras

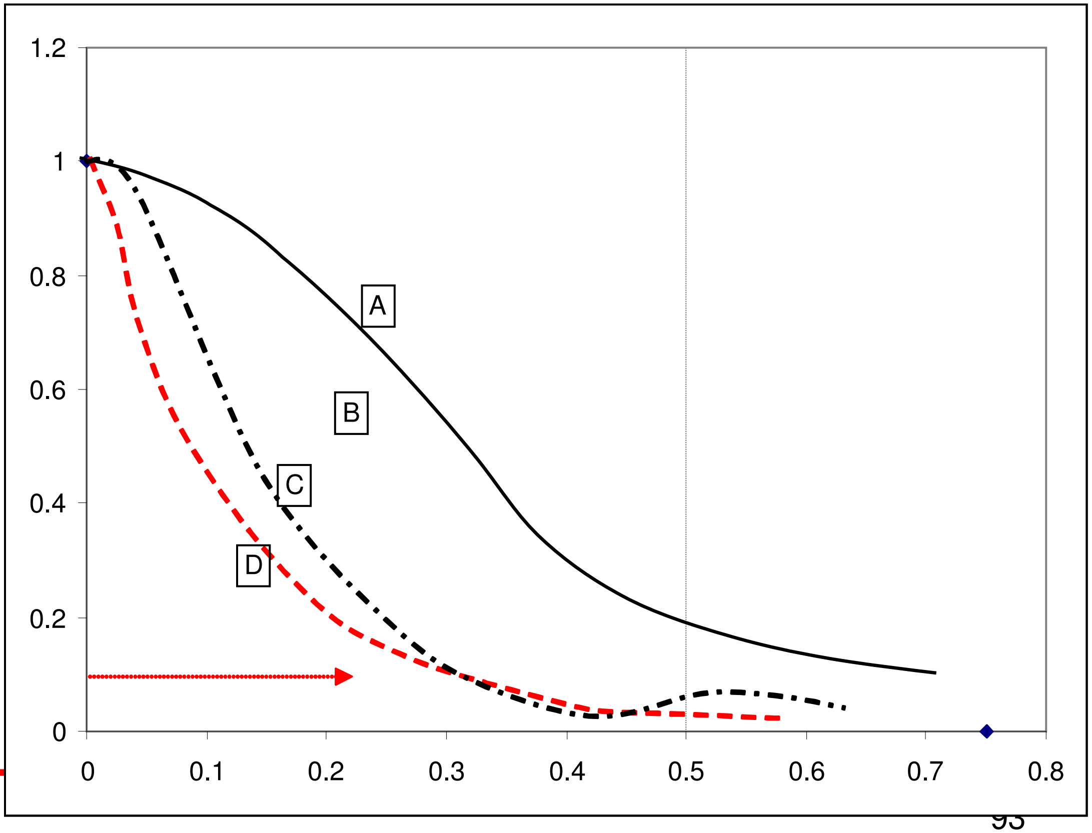
1. *Efficiency*- Normalize limiting resolution frequency by digital sampling limit of 0.5 cycles/pixel
2. Take product of vertical and horizontal components
3. Multiply by camera's finished file size

6.0 MPixel camera SFRs

Cameras A and B
E=100%

Cameras C&D:

E = 36%



ISO Camera Resolution Efficiency Rating Proposal

Electronic still picture cameras are normally marketed using a “megapixel” value, which normally provides the number of effective pixels of the image sensor. This can be confusing or misleading, since it is a value related to the number of addressable photoelements on the image sensor, and is not a based on any type of resolution measurement.

There is interest in developing a single-value resolution numeric for reporting the measured resolution of electronic still picture cameras. One proposed metric is the “resolution efficiency rating.”

1. Determine the maximum resolution in LW/PH for the horizontal (R_H), vertical (R_V), and +/- 45° (R_{+45} , R_{-45})directions.
2. Calculate individual directional efficiencies (E_H , E_V , E_{+45} , E_{+45}) by normalizing the maximum resolutions of item #1 by the captured image’s picture height. If any normalized value is greater than 1.0, assign that value to 1.0.
3. Combine E_{+45} and E_{-45} efficiencies into an equally weighted average diagonal value E_D.
4. Calculate the resolution efficiency rating (E_R) as the product of 100, E_D and the average of E_H and E_V.

Resolution Efficiency Rating $E_R = 100 \times (E_D \times (E_H + E_V) /2)$

Example using the CIPA tool: 2048 pixel high x 3072 pixel wide, 6.0 MPixel camera file

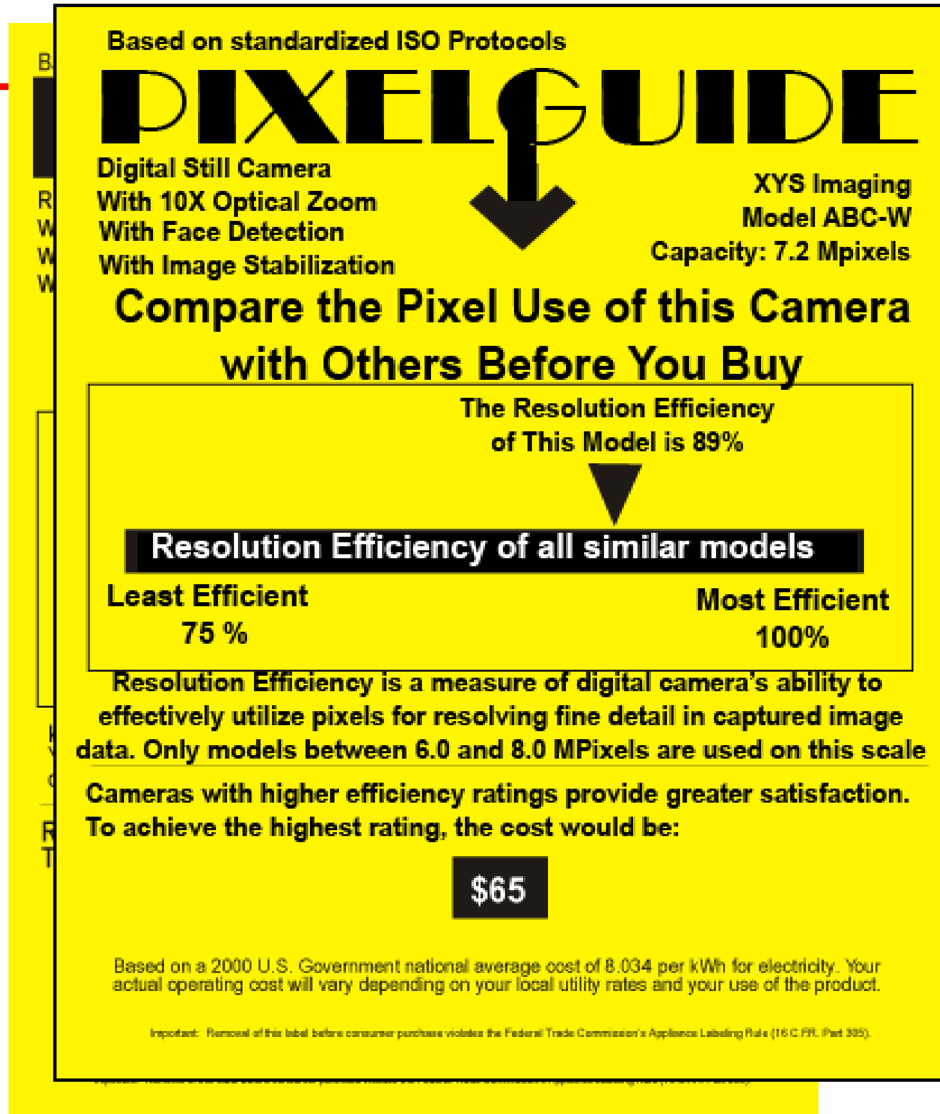
Maximum horizontal resolution : R_H = 1970 LW/PH
Maximum vertical resolution : R_V = 1980 LW/PH
Maximum +45° resolution : R_{+45} = 1500 LW/PH
Maximum -45° resolution : R_{-45} = 1500 LW/PH

Horizontal Resolution Efficiency: E_H= 1970/2048 = 0.96
Vertical Resolution Efficiency: E_V = 1980/2048 = 0.97
Diagonal Resolution Efficiency: E_D = (1500 + 1500)/2 = 0.73

Resolution Efficiency Rating = 100 × [(0.73 × (0.96 + 0.97)) /2] = 70.6

Sampling efficiency Summary

- Sampling efficiency measure is considered as an extension of the current ISO 12233 standard revision effort.
- Based on the ratio of a 10% SFR-spatial frequency bandwidth to the bandwidth implied by the image sampling alone
- Not intended to include the influence of sampling artifacts and image noise
- Provides guidance when considering the level of image signal detail likely to be delivered by a camera
- Sampling efficiency provides a convenient factor to adjust advertised values to yield an *effective megapixel* value.


Based on standardized ISO Protocols
PIXELGUIDE
Digital Still Camera
With 10X Optical Zoom
With Face Detection
With Image Stabilization
XYS Imaging
Model ABC-W
Capacity: 7.2 Mpixels
Compare the Pixel Use of this Camera with Others Before You Buy
The Resolution Efficiency of This Model is 89%
Resolution Efficiency of all similar models
Least Efficient
75 %
Most Efficient
100%
Resolution Efficiency is a measure of digital camera's ability to effectively utilize pixels for resolving fine detail in captured image data. Only models between 6.0 and 8.0 MPixels are used on this scale
Cameras with higher efficiency ratings provide greater satisfaction.
To achieve the highest rating, the cost would be:
$65
Based on a 2000 U.S. Government national average cost of 8.034 per kWh for electricity. Your actual operating cost will vary depending on your local utility rates and your use of the product.