Instrumentation for Control & Evaluation of Color Print Quality

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A Tutorial Presented at:

Toner & Photoreceptor Conference, The Tiara Group

Santa Barbara, Jun 4-7, 2006

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Outline

- Print quality in EP color printing - controlling factors
- Print quality requirements
- Instrumental analysis:
  - Tools
  - Methods
  - Standards
- Emphasis on the basics and the principles; application examples will be added during the presentation

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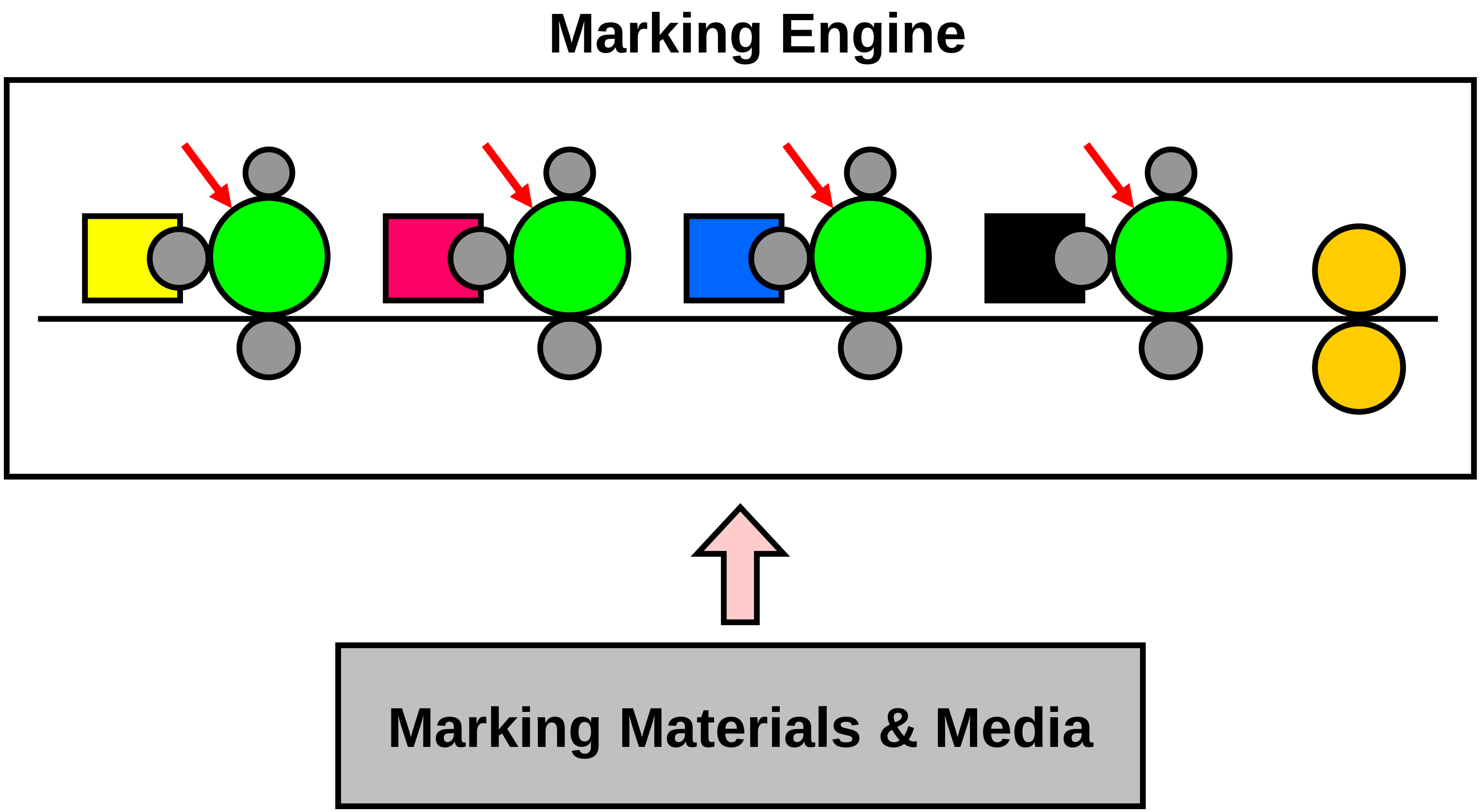
A Color Electrophotographic Printer

All components & subsystems affect print quality to varying extent



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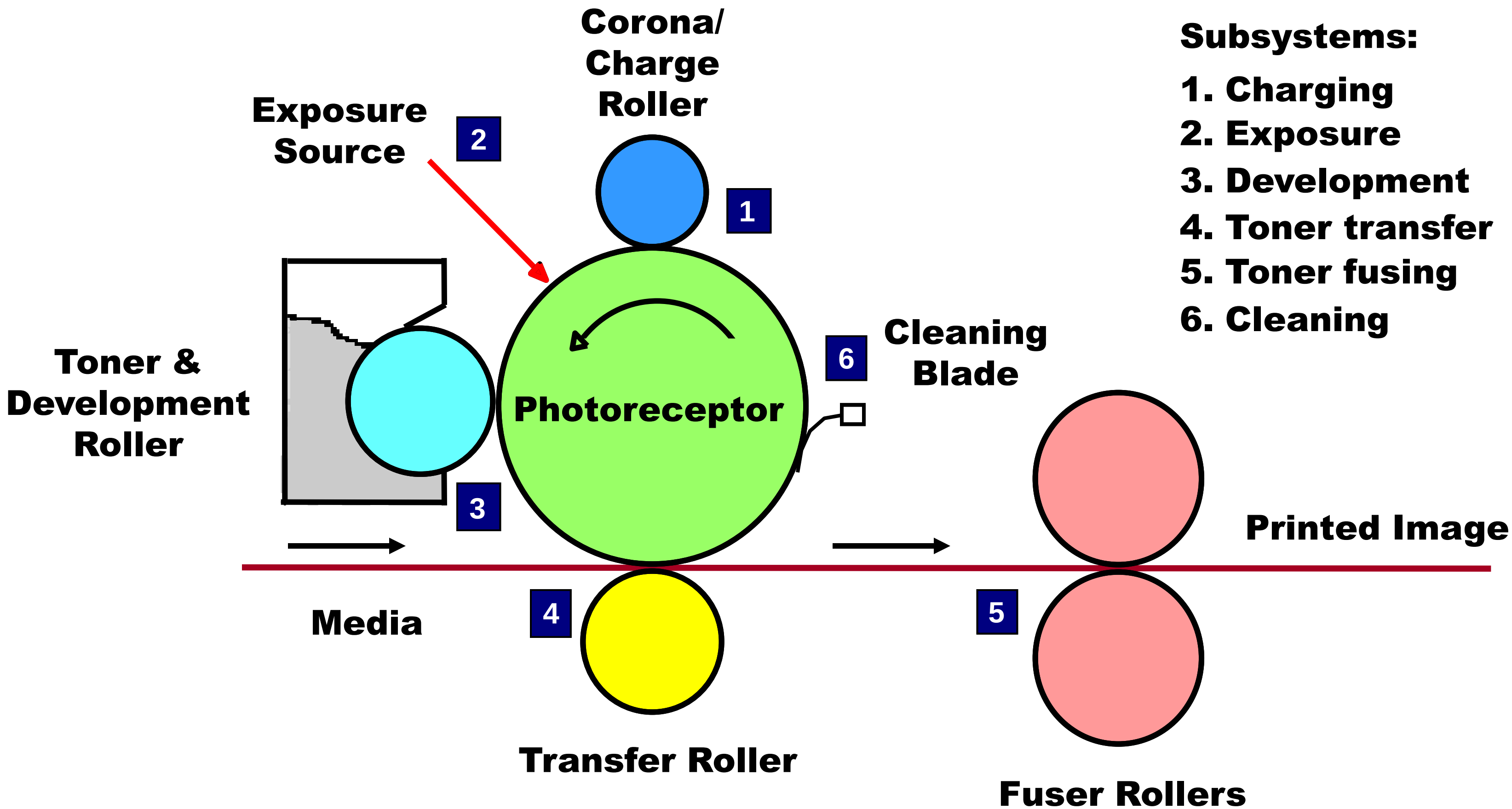
Electrophotography - Basic Processes

(2005 Toner & Photoreceptor Conference Tutorial)



Subsystems:

1. Charging
2. Exposure
3. Development
4. Toner transfer
5. Toner fusing
6. Cleaning

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Photoreceptors

(2005 Toner & Photoreceptor Conference Tutorial)

- **Charge acceptance (background)**
- **Dark decay (background)**
- **Photosensitivity/PIDC (print density)**
- **Residual (ghosting)**
- **Cyclic fatigue (process stability)**
- **Wear & abrasion resistance (life & stability)**
- **Uniformity & defects (image quality)**

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Semi-insulating Devices

(2005 Toner & Photoreceptor Conference Tutorial)

- Plenty of examples in the EP Process:
  - Charge roller
  - Development roller (donor roll)
  - Transfer media – belt and paper
- Dielectric relaxation is key to performance
  - Image quality and speed
- Uniformity and defects
  - Image quality

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Toner in Development, Transfer & Fusing

(2005 Toner & Photoreceptor Conference Tutorial)

- Size – average and distribution
  - Tone reproduction, uniformity & graininess, line & edge quality, offset appearance, …
- Charge – Q/M and q/d
  - Tone reproduction, uniformity & graininess, line & edge quality, …
- Fusing latitude
  - Fusing temperature & energy consumption
- Wax & oil
  - Offset appearance & gloss uniformity

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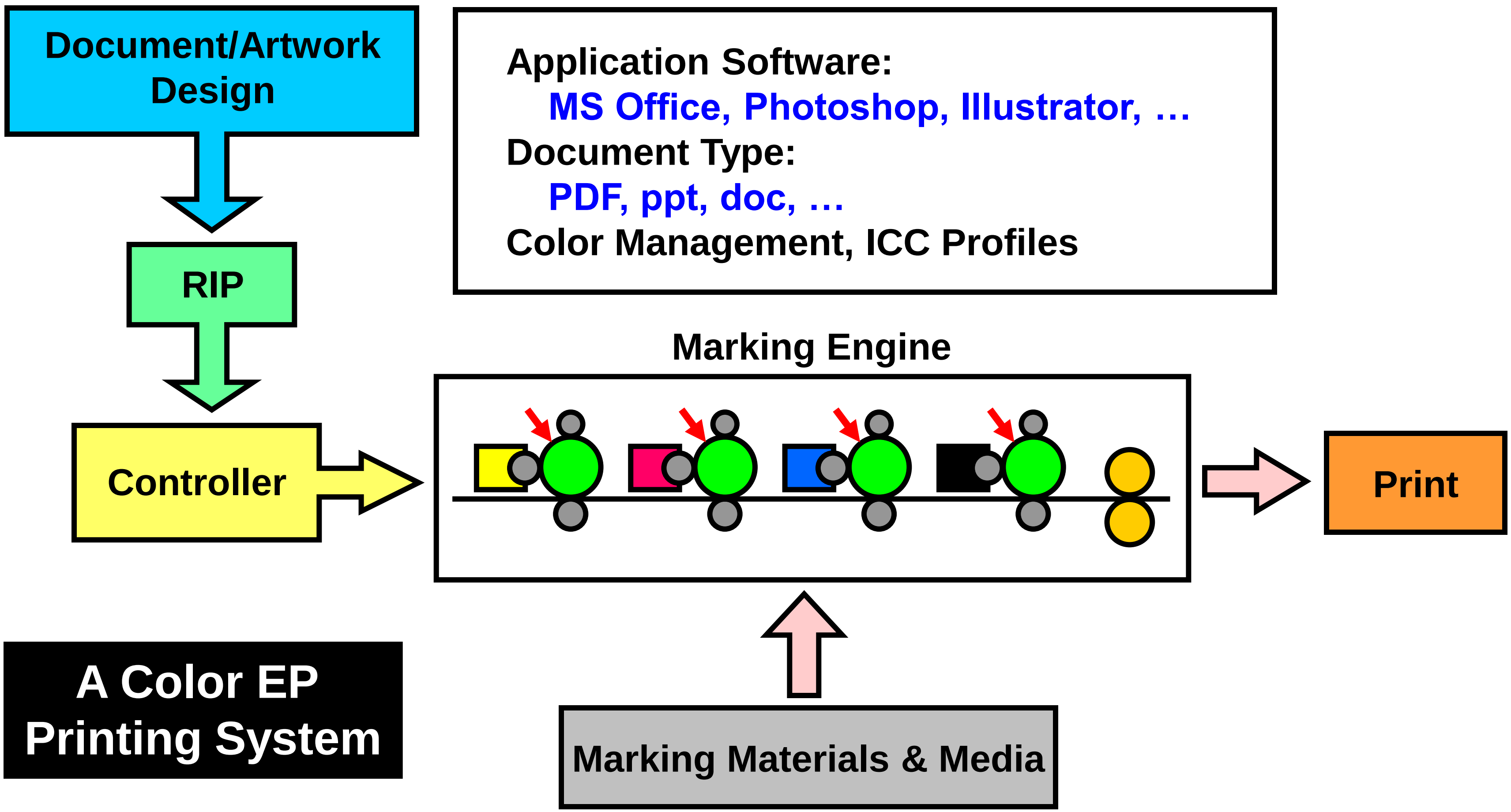
Color EP Print Quality is a System Issue

Controlling factors go beyond the print engine



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Color Print Quality Requirements

- Quality requirement depends on applications:
  - Office documents
  - Digital photographs – personal or commercial printing
  - Commercial printing – graphic arts, brochures, packaging materials, labels
- There are however a few important fundamentals

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Print Quality Requirements (1)

- Tone and color reproduction
  - Natural tone scale
  - Neutral gray balance
  - Rich details in highlight and shadow
  - Pleasing memory colors (flesh tone, blue sky, green grass, …)
  - Vibrant saturated colors (graphic arts, presentations, computer graphics, illustrations, …)
  - Light, bright pastels (ads, maps, …)
  - Smooth gradient (metallic, rendering, …)

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Print Quality Requirements (2)

- Sharpness and fine detail
  - Sharp and accurate lines
  - Crisp and legible texts
  - Clear reverse and color fonts
  - Sufficient line screen & good halftone quality

Note: Sharpness & detail is strongly affected by:

- Correct image processing & rendering in RIP
- Good color registration

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Print Quality Requirements (3)

- Noise and Image Defects
  - Low graininess or extraneous background ("micro-uniformity")
  - Uniform appearance with minimum banding, mottle or coalescence ("macro-uniformity")
  - Minimum inter-color bleed or color adjacency issues
  - No significant image defects (e.g. black or white spots, ghosting, …)

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Print Quality Requirements (4)

- Gloss Appearance
  - Gloss level matching customer preference (matte vs gloss)
  - Offset look and feel
  - No unacceptable differential gloss through highlight, midtone and shadow
  - Low haze
  - High distinctness of image (DOI)

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Print Quality Evaluation Methodologies

- Subjective Assessment by Human Observers
  - Customer preference
  - Focus group study
  - Psychometric scaling
- Instrumental Objective Measurements
  - Quantitative analysis
  - Proprietary algorithms vs industry and international standards

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Instrumental Analysis

- Two different types of instrumentation:
  - Dedicated instruments
    - Densitometer
    - Spectrophotometer
    - Gloss meter
    - DOI meter
  - General purpose instruments
    - Image analysis systems, camera or scanner based
- The two types are complementary

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Print Quality Analysis Instruments

	Dedicated Instruments				Image Analysis Systems	
Print Quality Requirements	**Densitometer**	**Spectrophotometer**	**Gloss Meter**	**DOI Meter**	**Camera**	**Scanner**
Tone Reproduction						
Density	√+	√+			√	√
Tone reproduction curve	√	√+			√	√
Gradients					√	√
Color Reproduction						
Gray balance		√+			√	√
Color gamut		√+			√	√
Color fidelity & difference		√+			√	√
Gloss Appearance						
Gloss level			√+	√		
Differential gloss			√			
Haze				√		
DOI (Distinctness of Image)				√+		
Sharpness & Detail						
Resolution & MTF					√+	√+
Line quality					√+	√+
Text quality					√+	√+
Color registration					√+	√
Halftone (dot) quality					√+	√
Noise and Image Defects						
Graniness					√+	√+
Mottle					√	√+
Banding					√	√+
Background					√+	√
Ghosting					√+	√+
Black or white spots					√+	√

Note: √+ = Optimized √ = Supported

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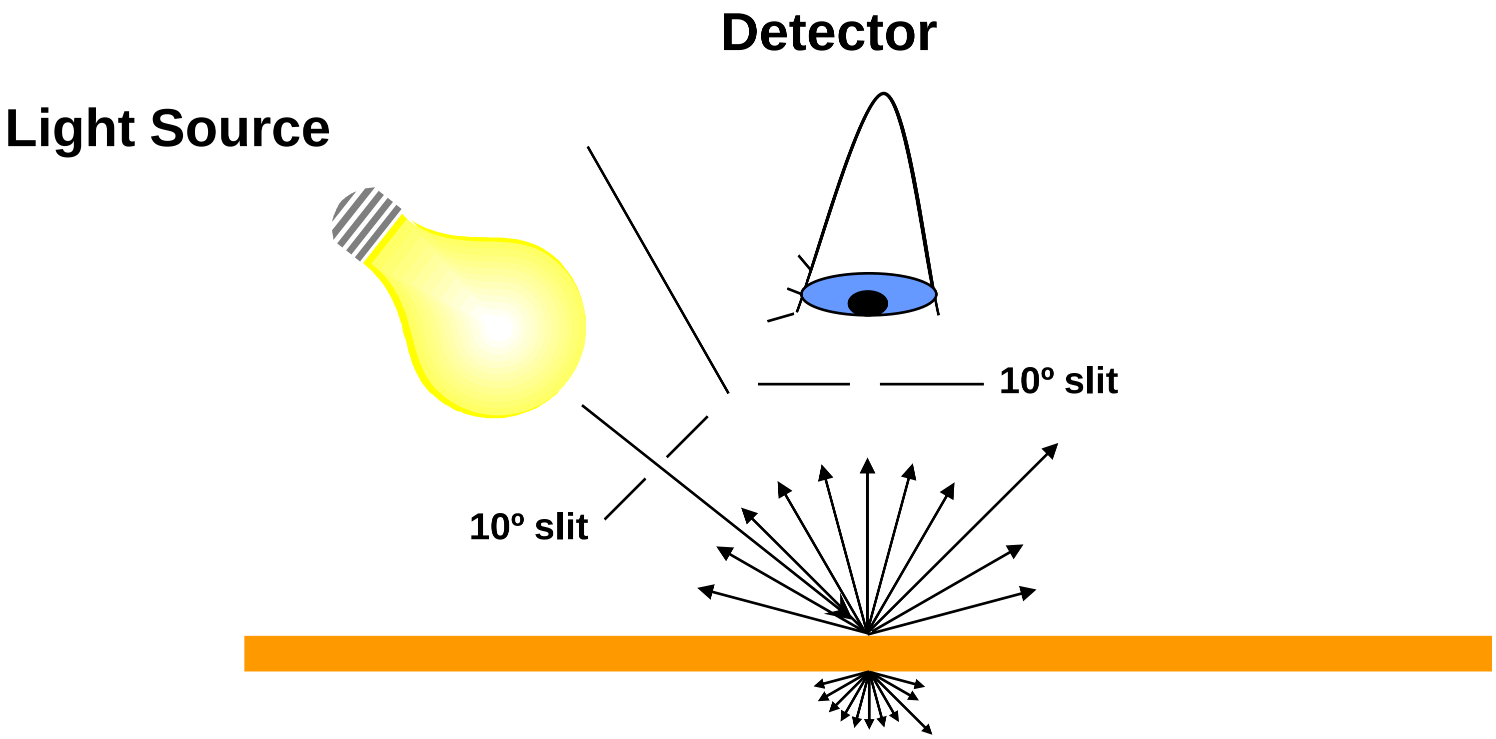
Density & Color Measurements - Standardized Reflectance

- Light source at 45º, sensor at 0º is the most common geometry in graphics art applications
- 10 degree wide source and detector slits



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Densitometer

- Measures amount of light transmitted through or reflected from a material
- Encodes the result logarithmically, or,
  - Density = -log10(R) or -log10(T)
  - Where R = reflectance & T = transmittance (both from 0 to 1 or 0 to 100%)

R (or T), %	Density
0.1	3
0.32	2.5
1	2
3.2	1.5
10	1
32	0.5
100	0

A Representative Densitometer (X-Rite)

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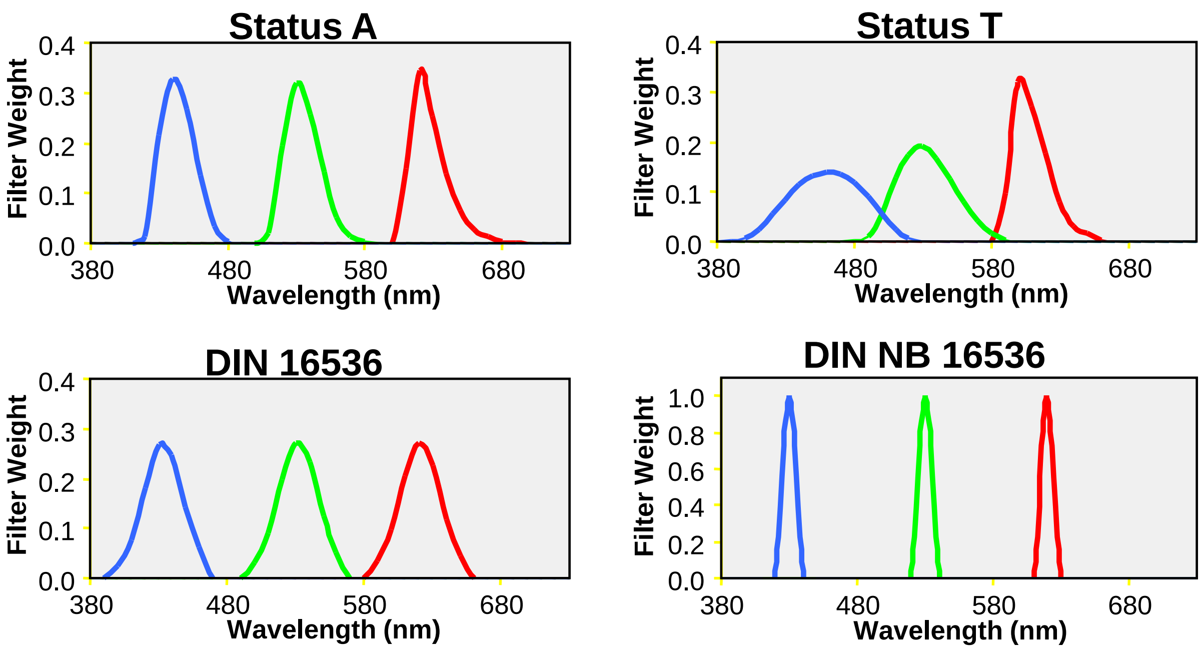
Color Densitometer

- Measures color density through narrow-band filters
- Measures colorants in photographic film or print media for quality control.
- Spectral response functions are not color-matching functions & cannot be used to compute tristimulus values.

Color Density Standards

- Status A (ISO 5/3)
- Status T (ISO 5/3)
- DIN (16536)
- DIN NB (16536)



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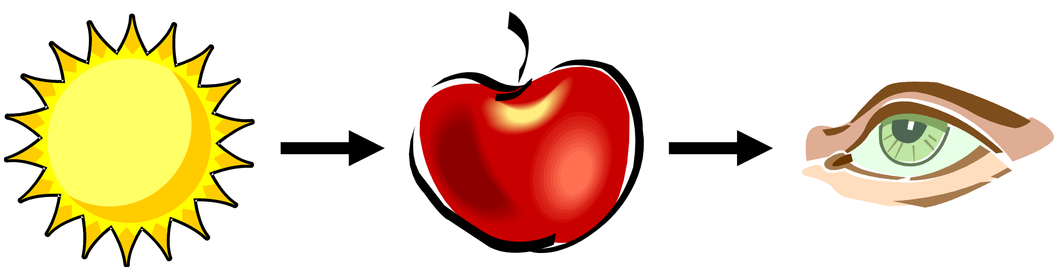
Perceptual Color

- Density is important for process monitoring & control, but it has no use in color communication because it does not account for:
  - the light source characteristics or
  - human color vision
- Perceived color depends on the combination of:
  1) light source
  2) object spectral reflectance curve
  3) eye's sensitivity & brain's interpretation

A RED apple?



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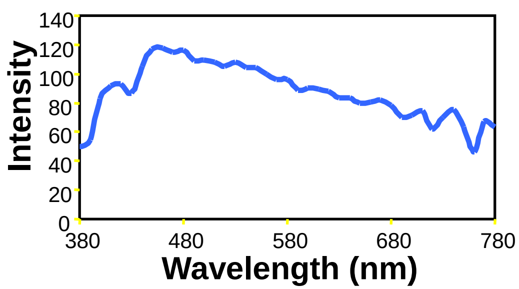
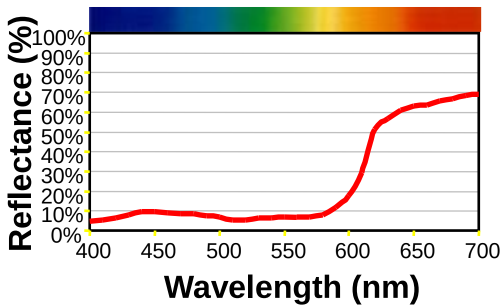
Perceptual Color Space

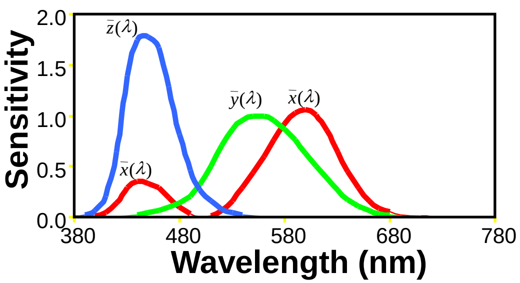
- In 1931 the CIE standards committee developed a technique to correct this problem
- They developed standardized:
  - Light sources (D50 and D65 most common in graphic arts)
  - Human color vision (2º or 10º)
  - Computation method (color matching functions, color space transformation, uniform spaces …)



Illuminant
Spectral Characteristics



Spectral Reflectance Curve



Color-matching Functions

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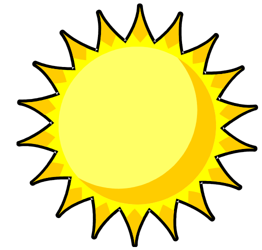
Tri-Stimulus Values

$$X = K\int_{380}^{780} S(\lambda)\,\bar{x}(\lambda)\,R(\lambda)\,d\lambda$$

Illuminant Spectral Power

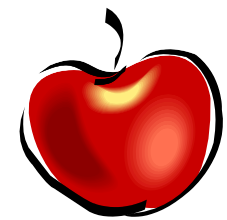
$S(\lambda)$



$$Y = K\int_{380}^{780} S(\lambda)\,\bar{y}(\lambda)\,R(\lambda)\,d\lambda$$

Spectral Reflectance

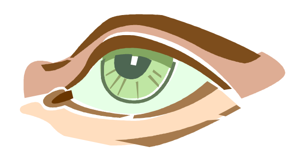
$R(\lambda)$



$$Z = K\int_{380}^{780} S(\lambda)\,\bar{z}(\lambda)\,R(\lambda)\,d\lambda$$

Color Matching Functions

$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$



$$K = 100/(\int_{380}^{780} S(\lambda)\,\bar{y}\lambda)\,d\lambda)$$

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CIELAB Color Space

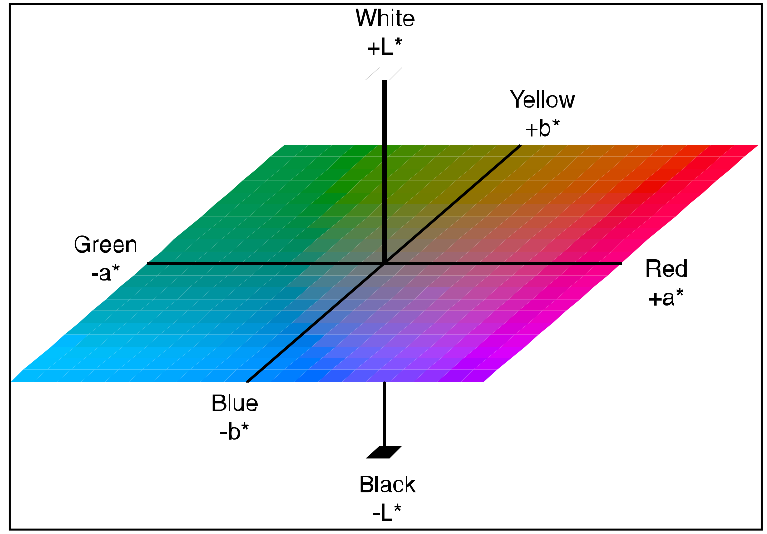
- CIELAB color space is derived from the tristimulus values X, Y, Z of the sample and the tristimulus values X_n, Y_n, Z_n of the reference illuminant:
  - The lightness variable L* is

    $L^* = 116(Y/Yn)^{1/3} - 16$

  - The chromaticity coordinates a* and b* are

    $a^* = 500[(X/Xn)^{1/3} - (Y/Yn)^{1/3}]$

    $b^* = 200[(Y/Yn)^{1/3} - (Z/Zn)^{1/3}]$



Same object, two illuminants

	Illuminant	
	A	D65
L*	57.04	51.72
a*	52.04	55.12
b*	-10.60	-22.13

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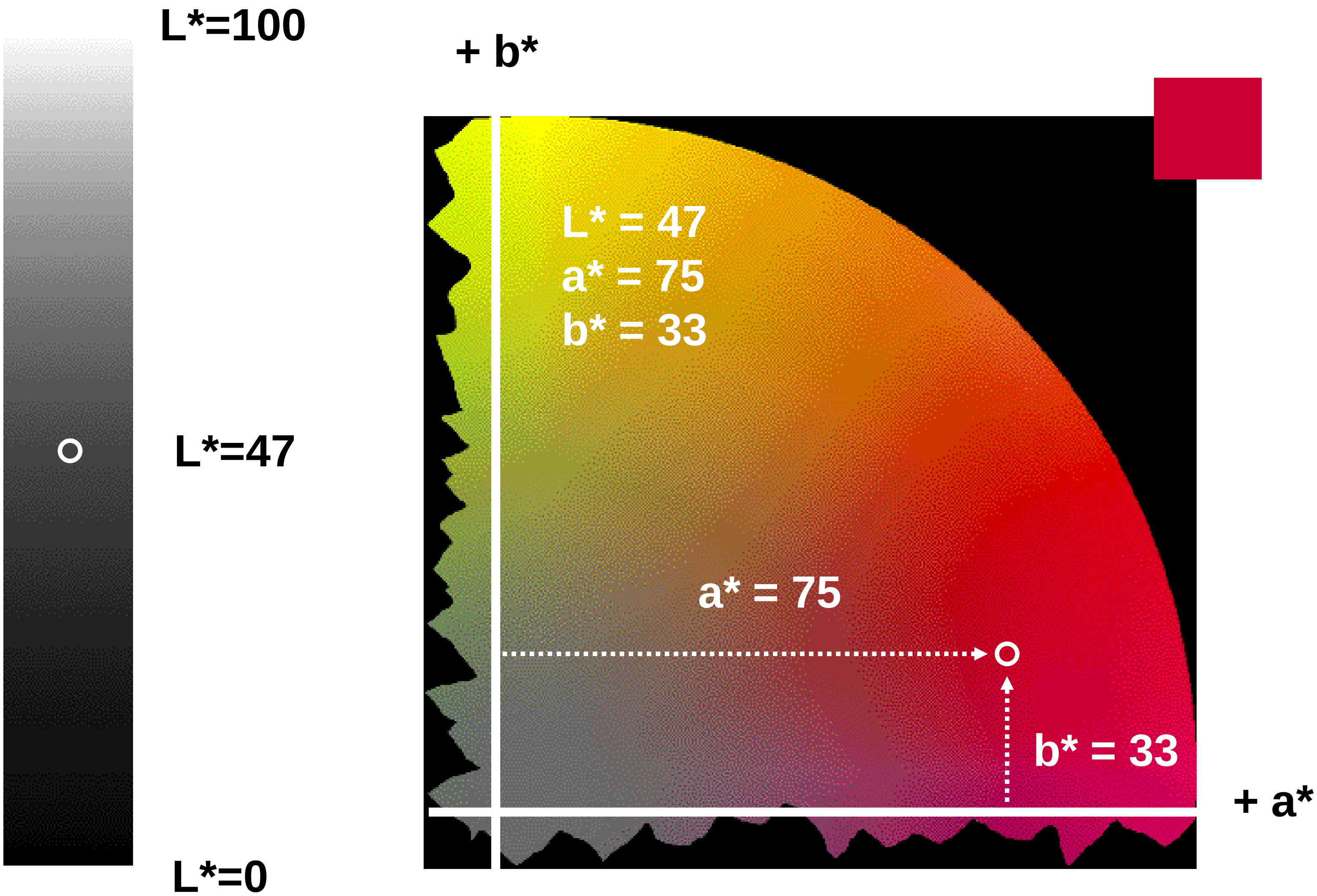
CIELAB Space – An Example



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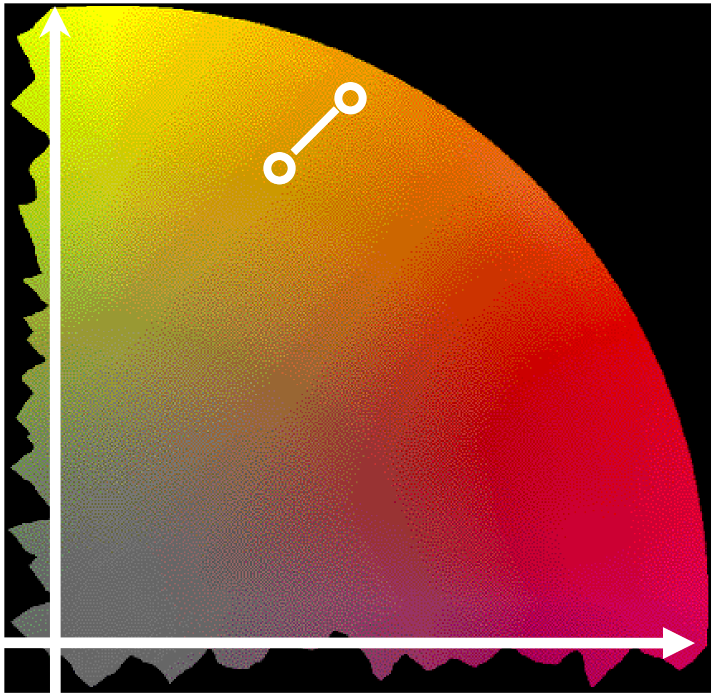
Color Difference

- $\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)}$
- The distance between two points in a 3 dimensional space.
- One ΔE is in theory the minimum just noticeable color difference. In practice, the JND depends on many factors such as the image content.
- Alternative ΔE (for improved correlation with visual assessment and color tolerancing), e.g. ΔE_{CMC}, ΔE_{94}, and ΔE_{2000}



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Colorimeter & Spectrophotometer

- Colorimeter
  - Uses filters to approximate the color-matching functions
- Spectrophotometer
  - Measures (samples) the reflection spectrum of a sample
  - Computes the tristimulus values. Typically output in L*a*b* or other color spaces
  - Computes color difference against a reference sample

(a)

(b)

A representative spectrophotometer: (a) In stand-alone use, and (b) in a scanner (Gretagmacbeth).

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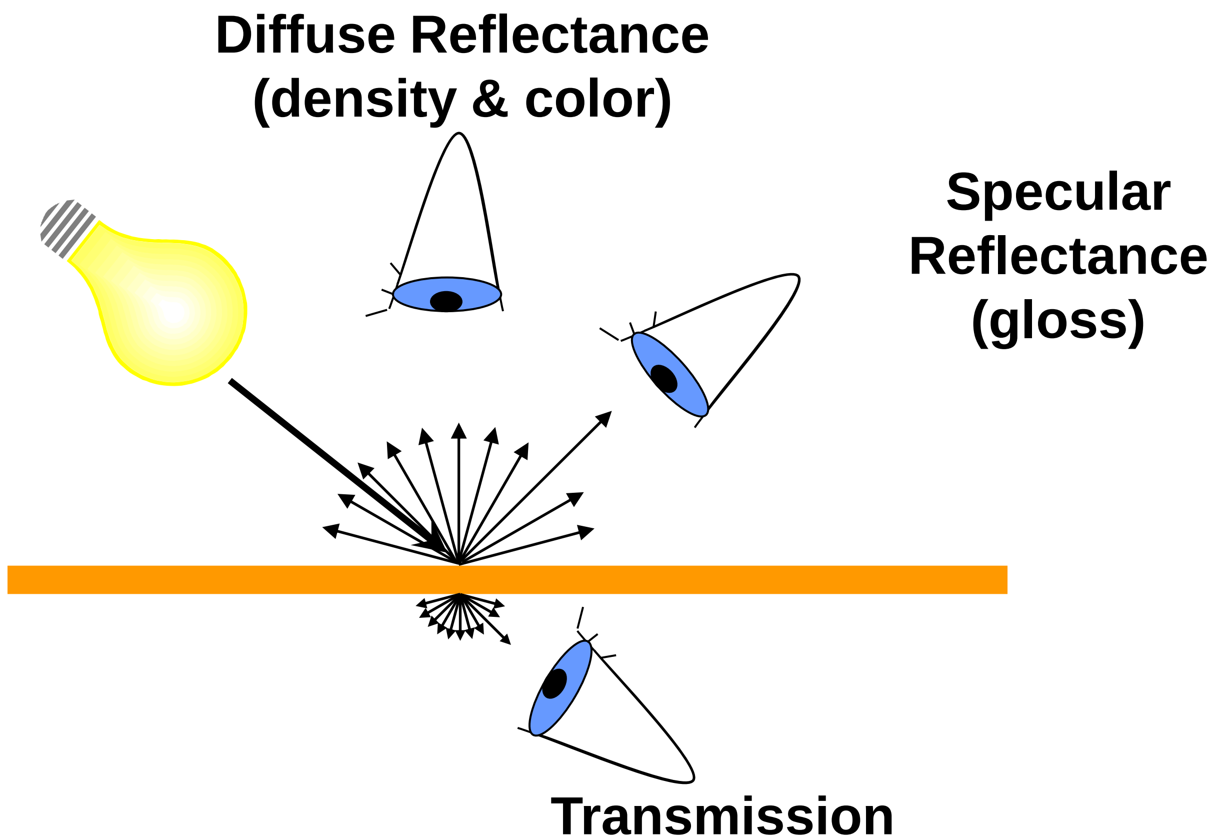
Specular Gloss Measurement

- What you see depends on where you look.



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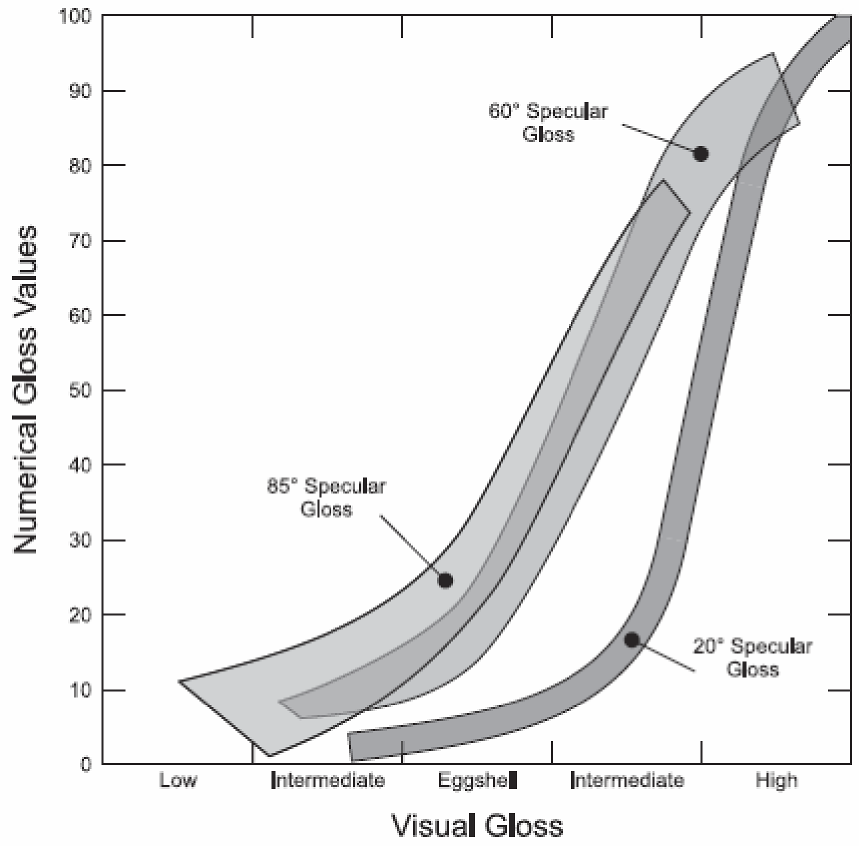
Choice of Incident Angles

- Standard incident angles (from normal to the sample under test) are 20°, 60° and 75° (or 85°).
- Typically, 20° is for high gloss surface and 75° (85º) for low gloss surface.



Numerical gloss values vs visual gloss rating for ASTM Specular gloss standards (after Hunter and Harold)

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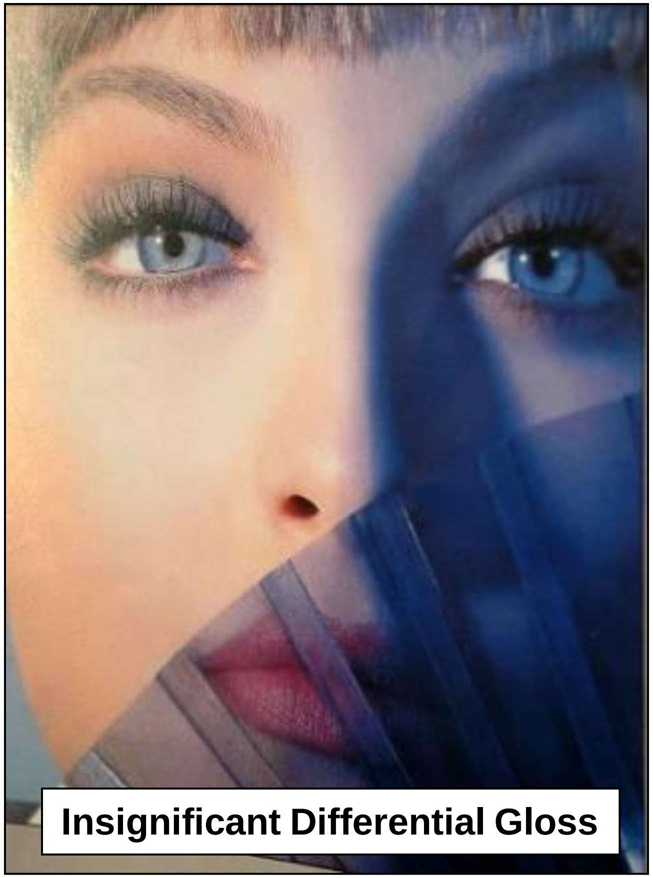
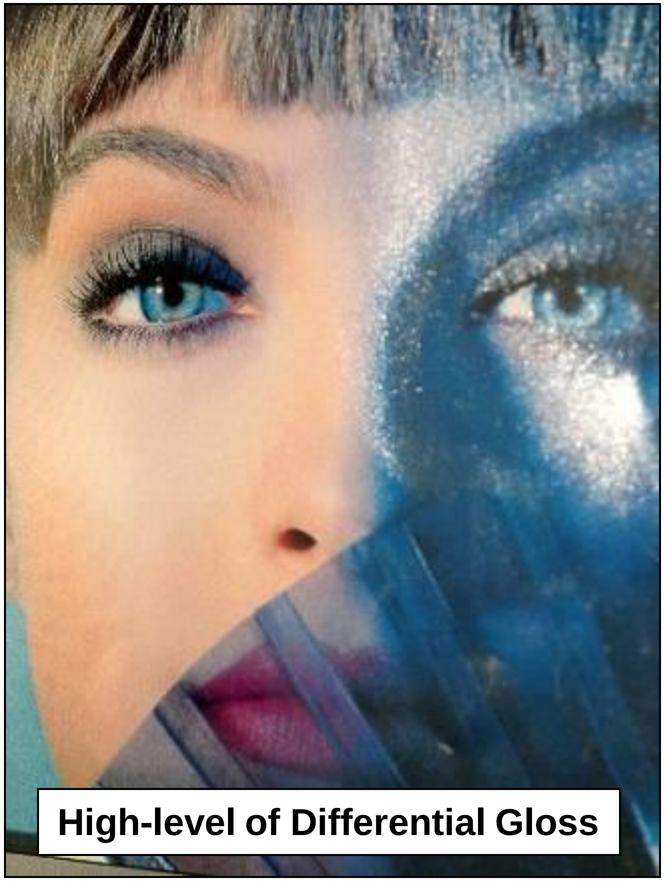
An Appearance Issue - Differential Gloss

(Prints photographed at a 45-45 geometry)





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Differential Gloss Measurement

- ISO 19799 in preparation
- A 40 patch test chart
- Mean Gloss:

  $G_m = (\Sigma G_{60})/40$

  If $G_m > 70$, use G_{20}
  if $G_m < 15$, use G_{75}
- Differential Gloss:

  $\Delta G = G_{max} - G_{min}$
- Just Noticeable Difference (JND) for G_{60}

  $JND_{60} \sim 0.14 G_{60}^{0.96} \sim 0.14 G_{60}$

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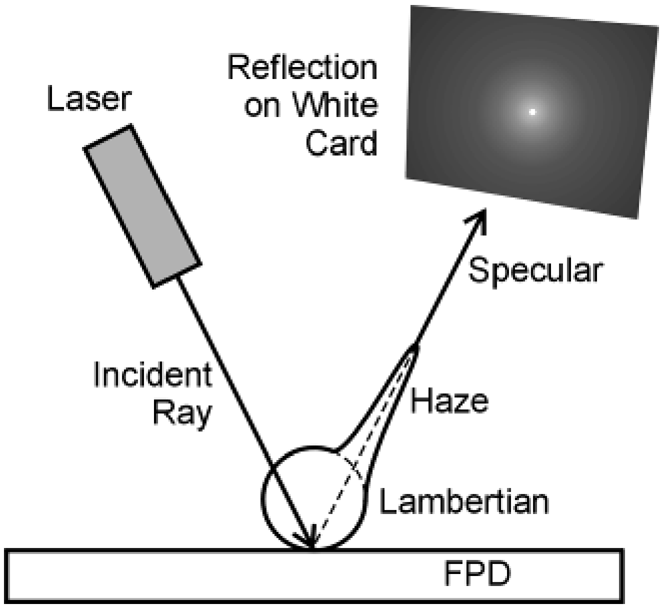
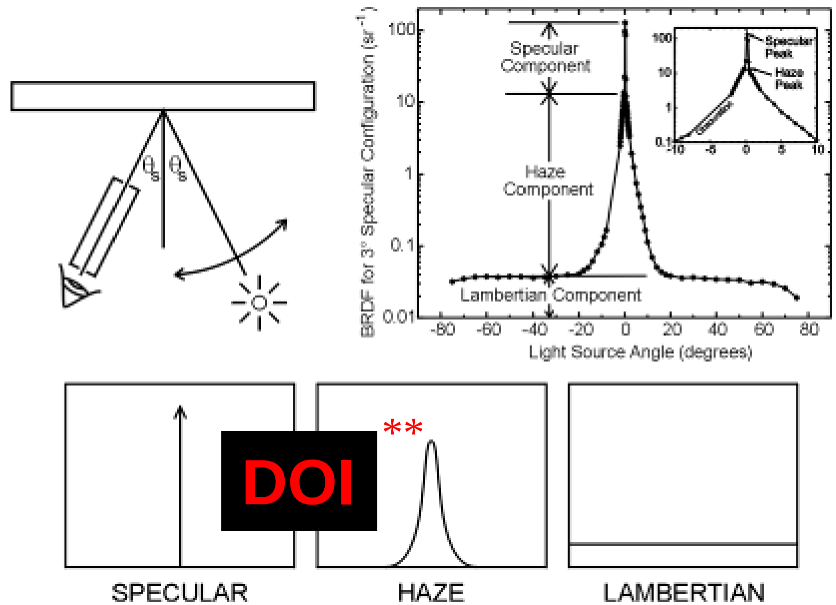
Different Components of Gloss*





* Ed. Kelly, Display Metrology, NIST, 2001
** Added by M. Tse, QEA

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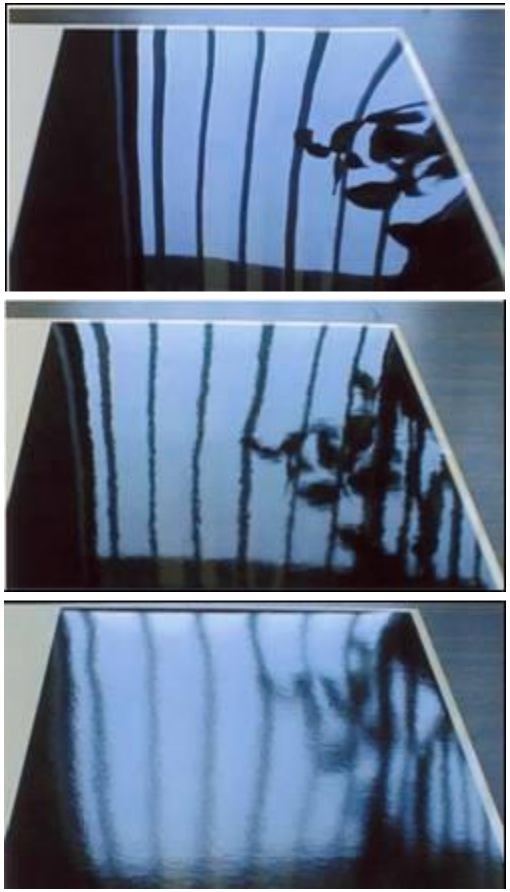
Distinctness of Image (DOI)

- There is growing recognition that gloss measurements alone often do not correlate well with customer preference.
- Following the lead of the automotive industry, who has been concerned with DOI and orange peel on paint and coating for a long time, DOI is a new addition to gloss appearance consideration in color print quality.



High DOI

Low DOI

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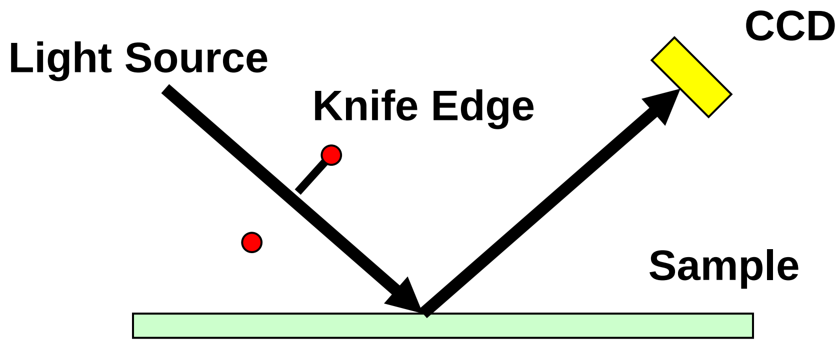
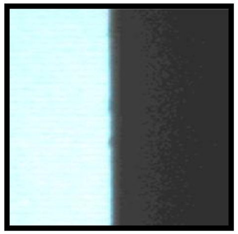
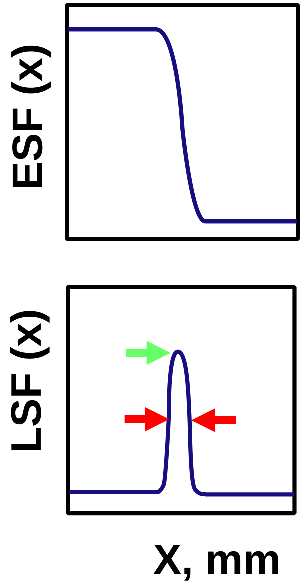
The QEA DOI Measurement Method







- A sharp edge is projected onto the sample surface and its reflected edge profile is captured using a CCD camera.
- This profile is the edge spread function (ESF) and its derivative is the line spread function (LSF).
- If a surface is perfectly smooth (i.e., very high DOI), the ESF would be a step function and the LSF would be a delta function.
- Two convenient parameters to characterize the LSF are peak height and half width.

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Gloss Meter and DOI Meter

A representative gloss meter
(BYK Gardner)

A representative DOI meter
(QEA)

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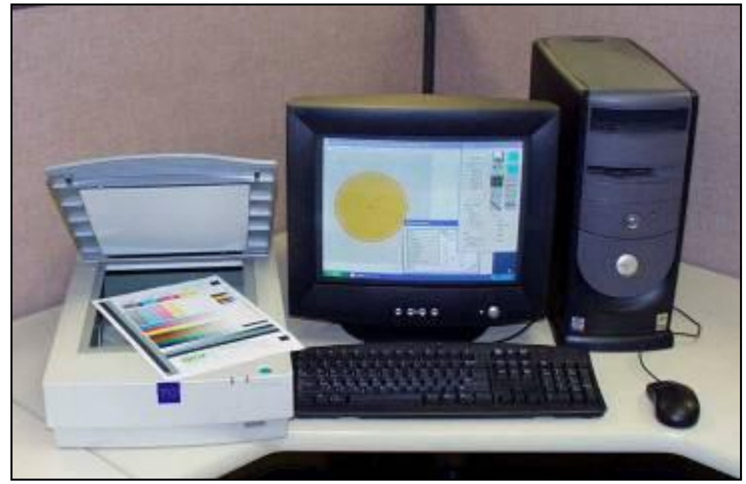
Image Analysis Systems
(Camera or Scanner –based)

Representative camera-based systems (QEA)



Representative scanner-based systems (QEA)

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Sharpness & Detail

- **Characterized by MTF (Modulation Transfer Function), CTF (Contrast Transfer Function), and SFR (Spatial Frequency Response).**
- **An example on contrast:**

$$Contrast = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

Left Side

$L_{max} = 0.58$
$L_{min} = 0.32$

***Contrast* = 0.28**

Right Side

$L_{max} = 1.0$
$L_{min} = 0.0$

***Contrast* = 1.0**

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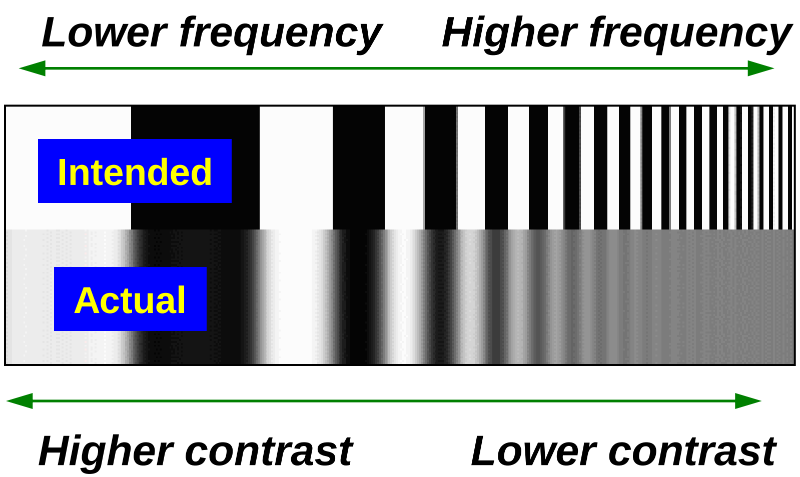
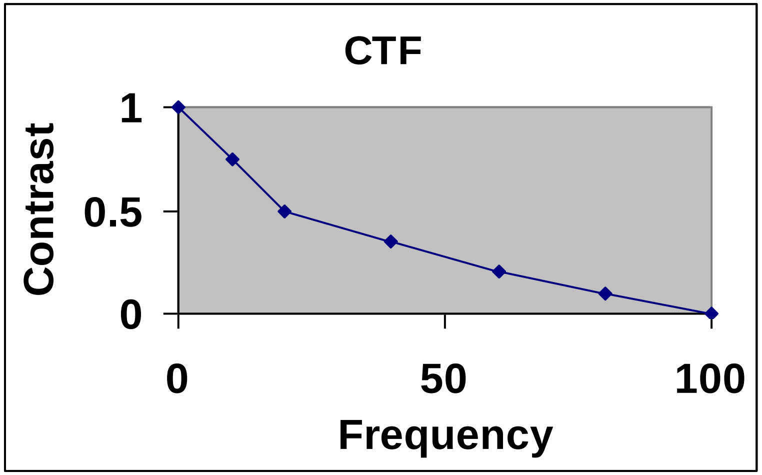
Frequency Dependence

- In most systems, contrast decreases at higher spatial frequencies.
- Objective measurement of contrast at several known frequencies is the Contrast Transfer Function (CTF) curve.





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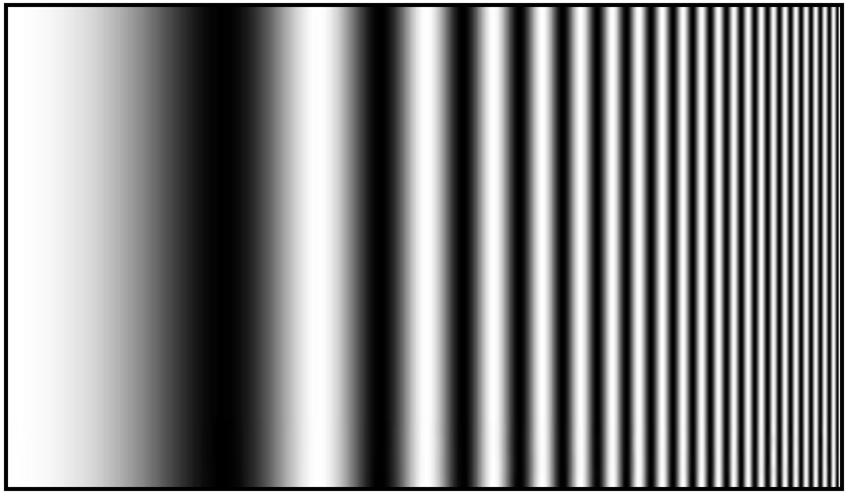
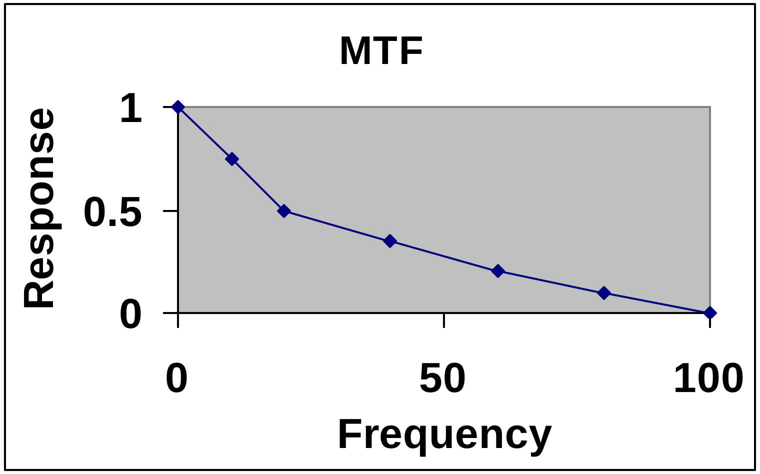
MTF - Sine Wave Test Patterns

- To measure the modulation transfer function (MTF), a sine wave pattern is used instead of a square wave.
- Measurement and interpretation of MTF is similar to CTF.





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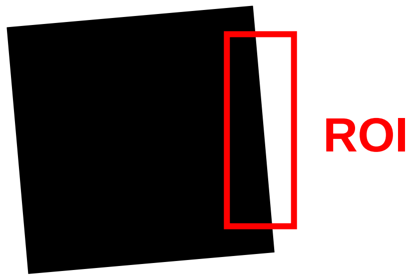
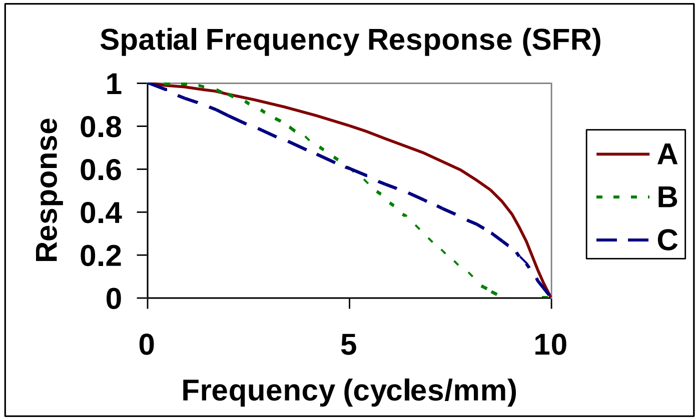
SFR Method - Slanted Edge Analysis

- An efficient and repeatable method using Fourier techniques to measure the spatial frequency response (SFR) to a slanted edge, based on the ISO 12233:2000 standard
- The slanted edge causes the edge gradient to be measured at many phases relative to the sensor.
- Interpretation and analysis of SFR curve is the same as MTF



- Sample A: good response at all frequencies
- Sample B: high contrast at low frequencies, but poor contrast at high frequencies
- Sample C: lower contrast than B, but better response at higher frequencies



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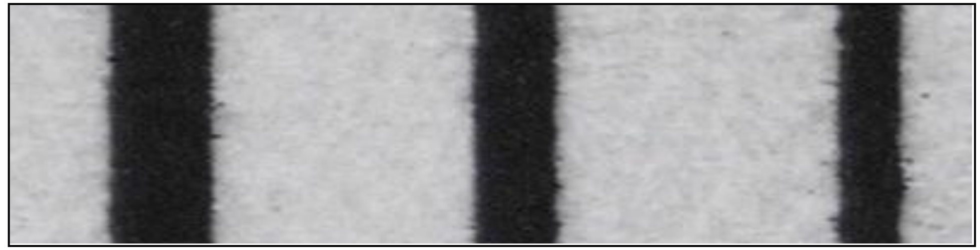
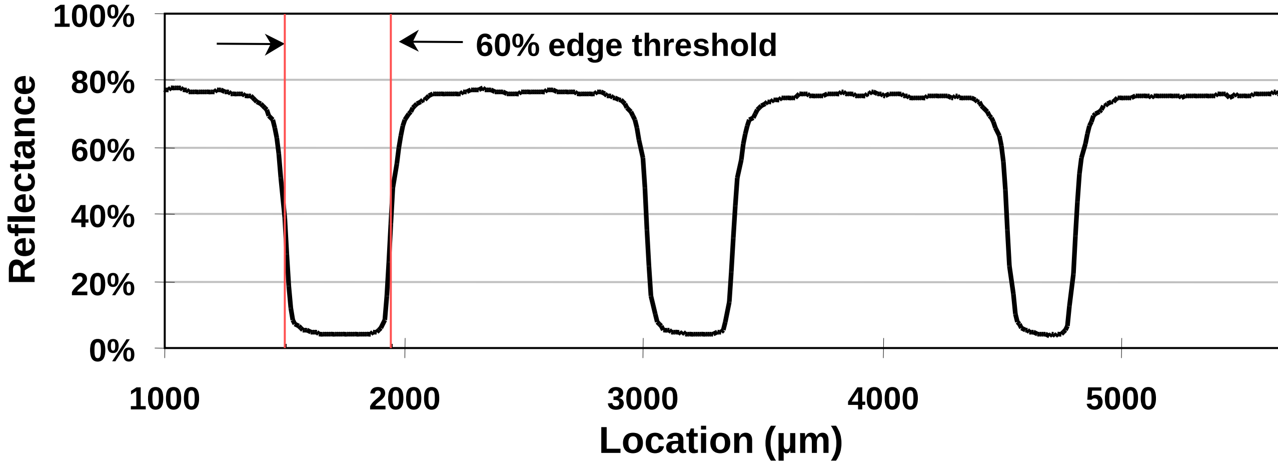
Line Quality

ISO 13660 Line Quality Attributes

- Width
- Density
- Blurriness
- Raggedness
- Contrast
- Fill





Edge Analysis	μm
Lead Blurriness	134.8
Trail Blurriness	133.8
Lead Raggedness	4.64
Trail Raggedness	4.75
Line Width	441.0

Darkness	
Reflectance	6%
Density	1.22
Contrast	0.934
Fill	0.980

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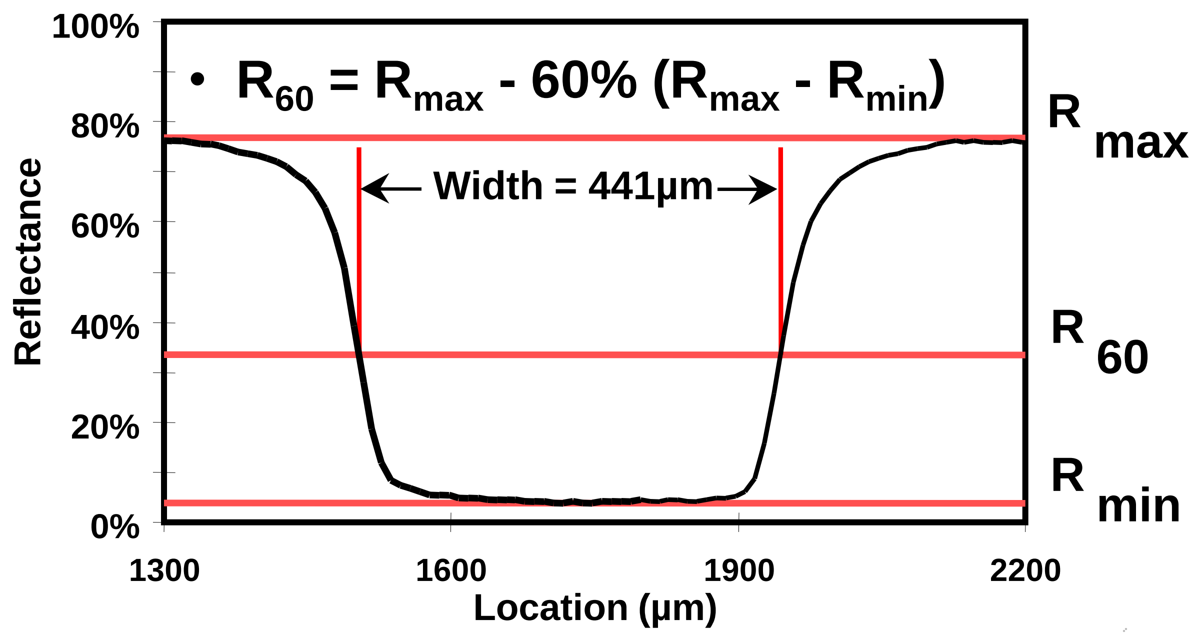
Example of ISO-13660 Application - Line Width Determination

ISO 13660 Line Quality Attributes

- Width
- Density
- Blurriness
- Raggedness
- Contrast
- Fill



- Line width is the distance between the R_{60} edge thresholds
- A robust technique against variations in ink & media reflectance

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Text Quality

- Most important is ***Stroke Weight***, e.g.
  - Stroke width
  - Stroke density
- Also important is line edge quality, e.g.
  - Raggedness
  - Blurriness
- ISO 19751 (in preparation)
  - Character Fidelity
  - Text Contrast
  - Text Uniformity

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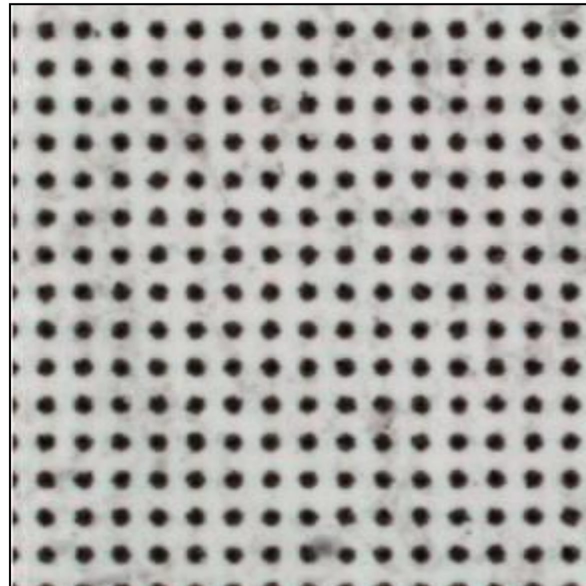
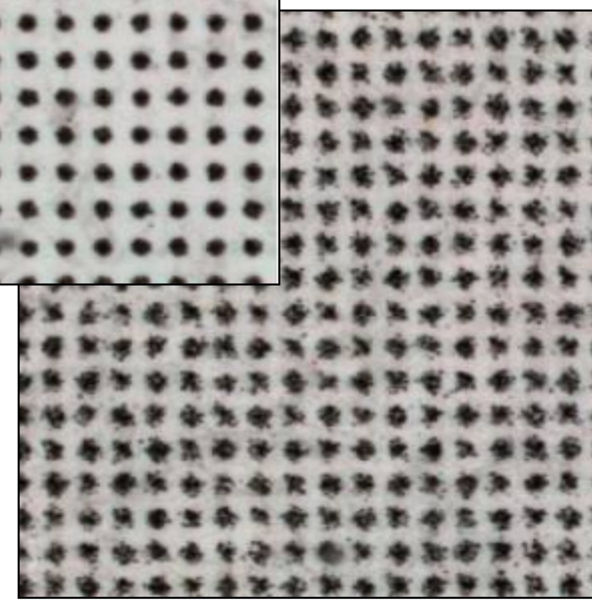
Halftone (Dot Quality) Analysis

- Line screen (lpi)
- Screen angle
- Dot% (dot gain)
- Dot size & shape
- Mean and standard deviation


Offset


Electrophotographic

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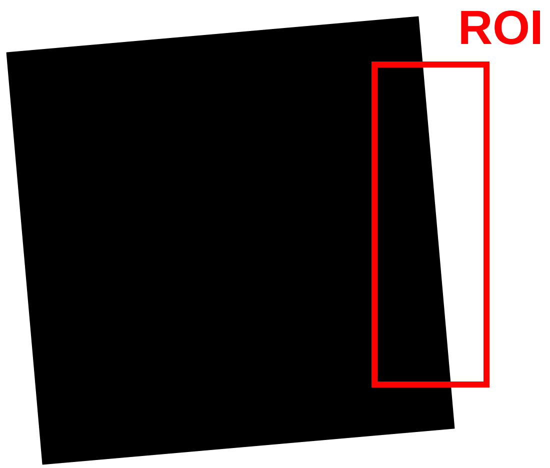
Registration Using Slanted Edge Analysis

- The same tool in SFR analysis can be used for registration analysis
- Target is a black/white transition
- In an ideal system, the transition would occur at the same spatial coordinate in all color planes
- In this analysis, the relative location of the transition in each of the color planes is reported



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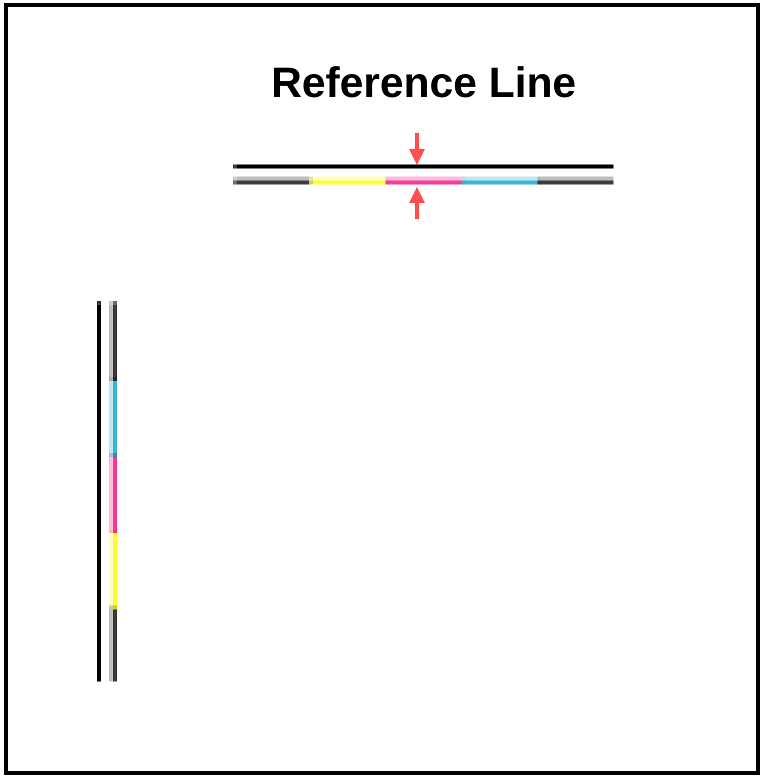
Registration Using CMYK Lines

- One of the process colors is used as a reference.
- The variation in distance between the reference line and the other process colors is a measure of color registration errors.



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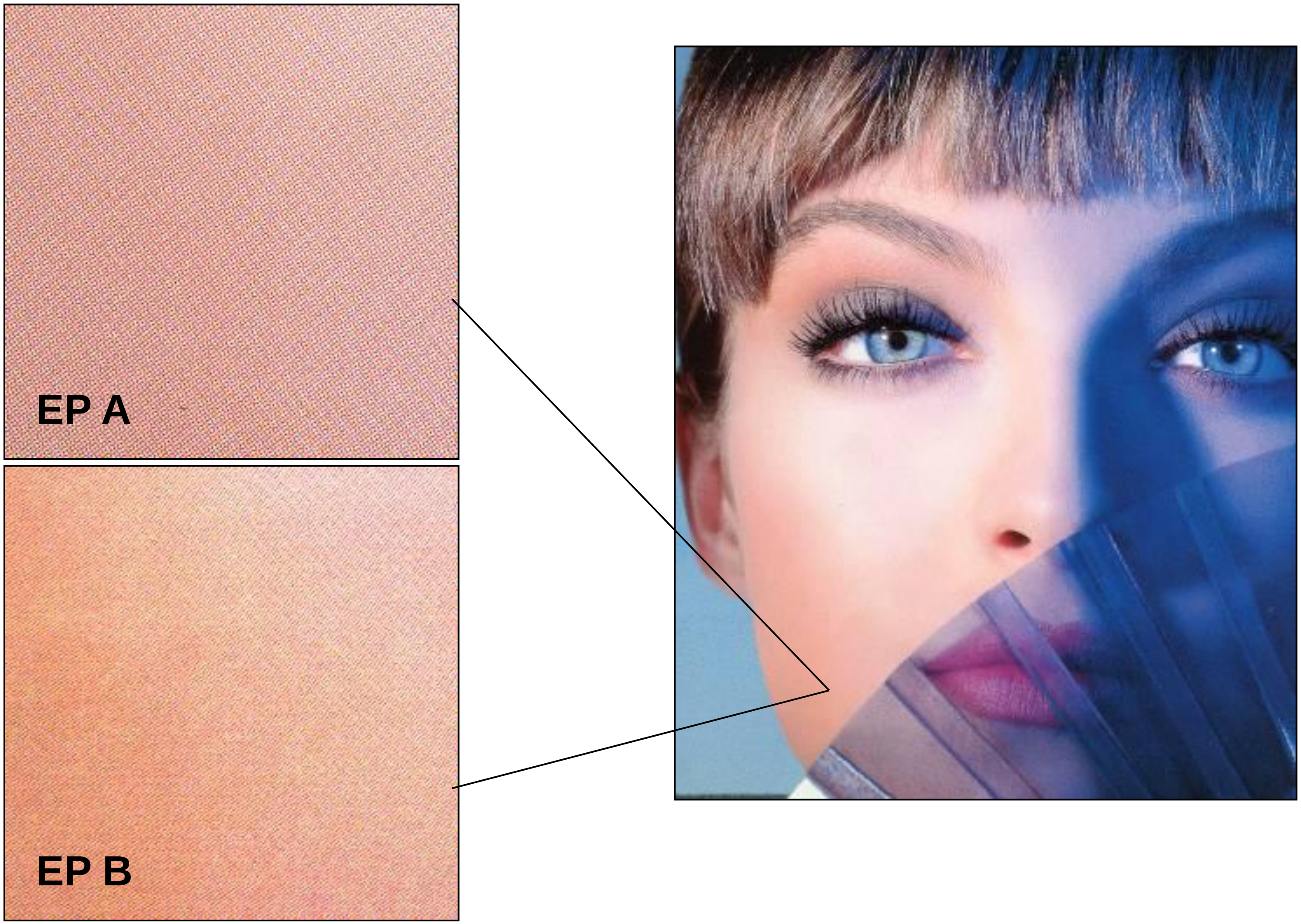
Graininess & Mottle



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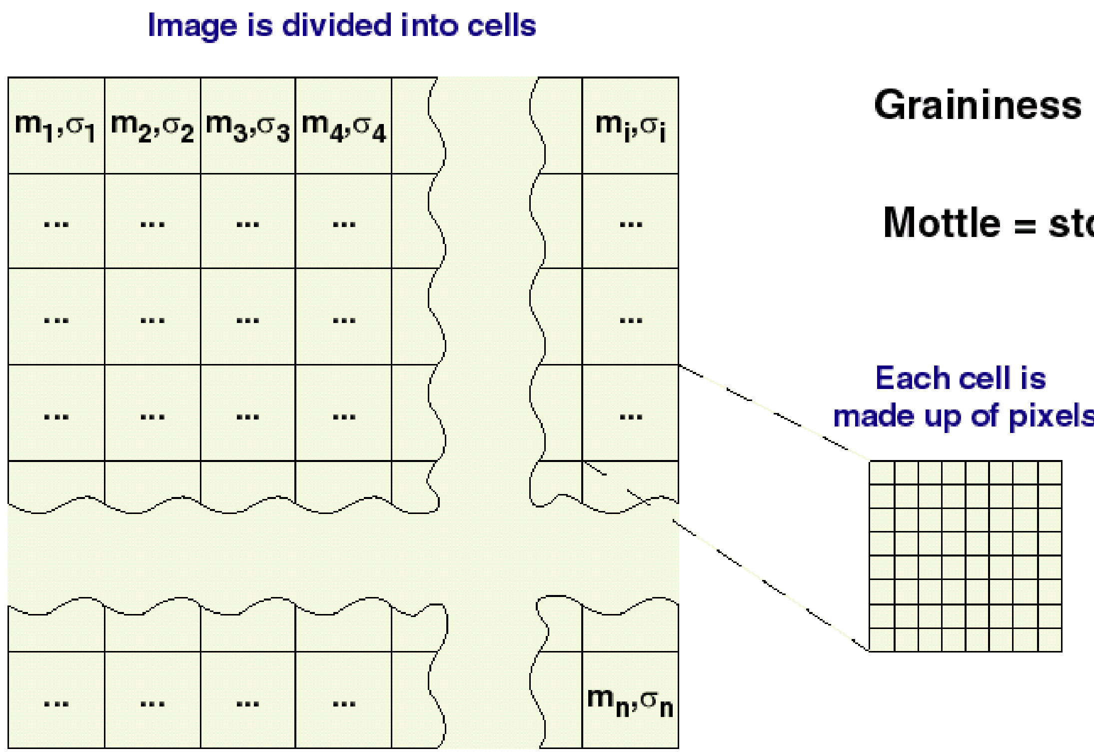
Graininess & Mottle Analysis Using the ISO-13660:2001 Method



$$\text{Graininess} = \sqrt{\frac{\sum_i \sigma_i^2}{n}}$$

$$\text{Mottle} = \text{stdev}(m_i)$$

*** Extension in ISO 13660 revision and additional considerations in ISO 19751 are in preparation.**

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Image Noise Analysis Using the Noise Power Spectrum (NPS) Method (1)

- **A powerful technique to analyze image noise (graininess) is to compute the Fourier transform of the auto-correlation function C(λ) of an image.**
- **When applied to a spatial image, this is often called the Wiener Spectrum W(ω):**

$$W(\omega) = F\{C(\lambda)\} = \int_{\infty} C(\lambda) \cdot e^{-i2\pi\lambda\,\omega} d\lambda$$

$$C(\lambda) = \int_{\infty} W(\omega) \cdot e^{-i2\pi\lambda\,\omega} d\omega$$

- **In practical terms, the Wiener Spectrum measures the noise variance at each spatial frequency.**
- **The area under the NPS curve equals the total variance of the image (σ^2):**

$$C(0) = \sigma^2 = \int_{\infty} W(\omega) d\omega$$

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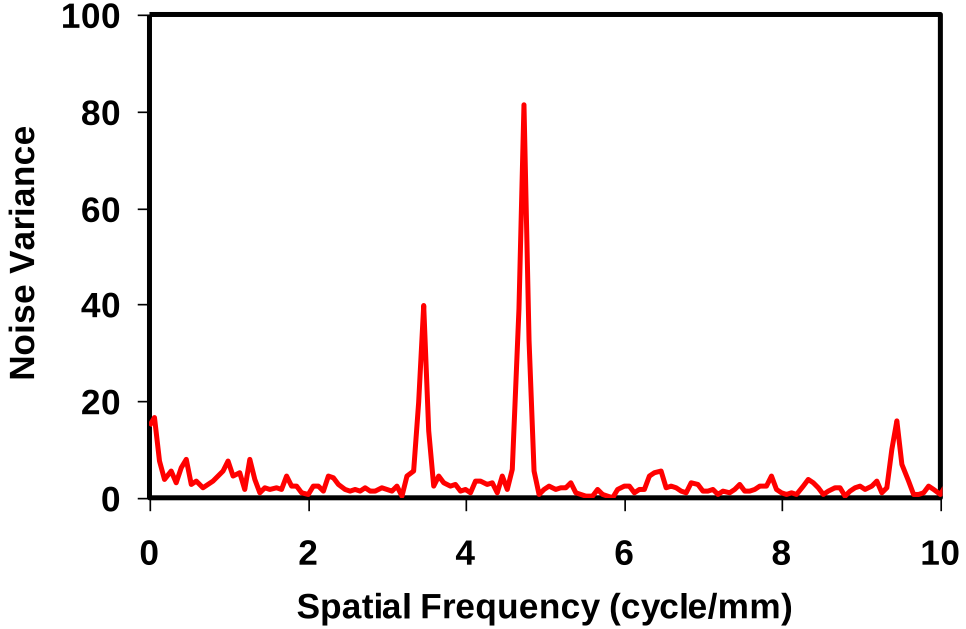
Noise Power Spectrum (NPS) (2)

- Nyquist frequency, hence the range of frequencies analyzed, is determined by the spatial resolution of the image
- Frequency resolution is determined by the dimension of the ROI
- For A/B comparisons, the same spatial resolution (DPI) and ROI dimensions should be used



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Banding Analysis

- A method for analyzing banding is a direct extension of the noise power spectrum (NPS) method:

  Perform a Fourier transform of the auto-correlation function of the image under analysis, and convolve with a model of the Human Visual Transform Function (VTF) to measure the noise variance at each spatial frequency on a scale corresponding to human sensitivity. For example, variations at very high frequencies (imperceptible to humans) are ignored.

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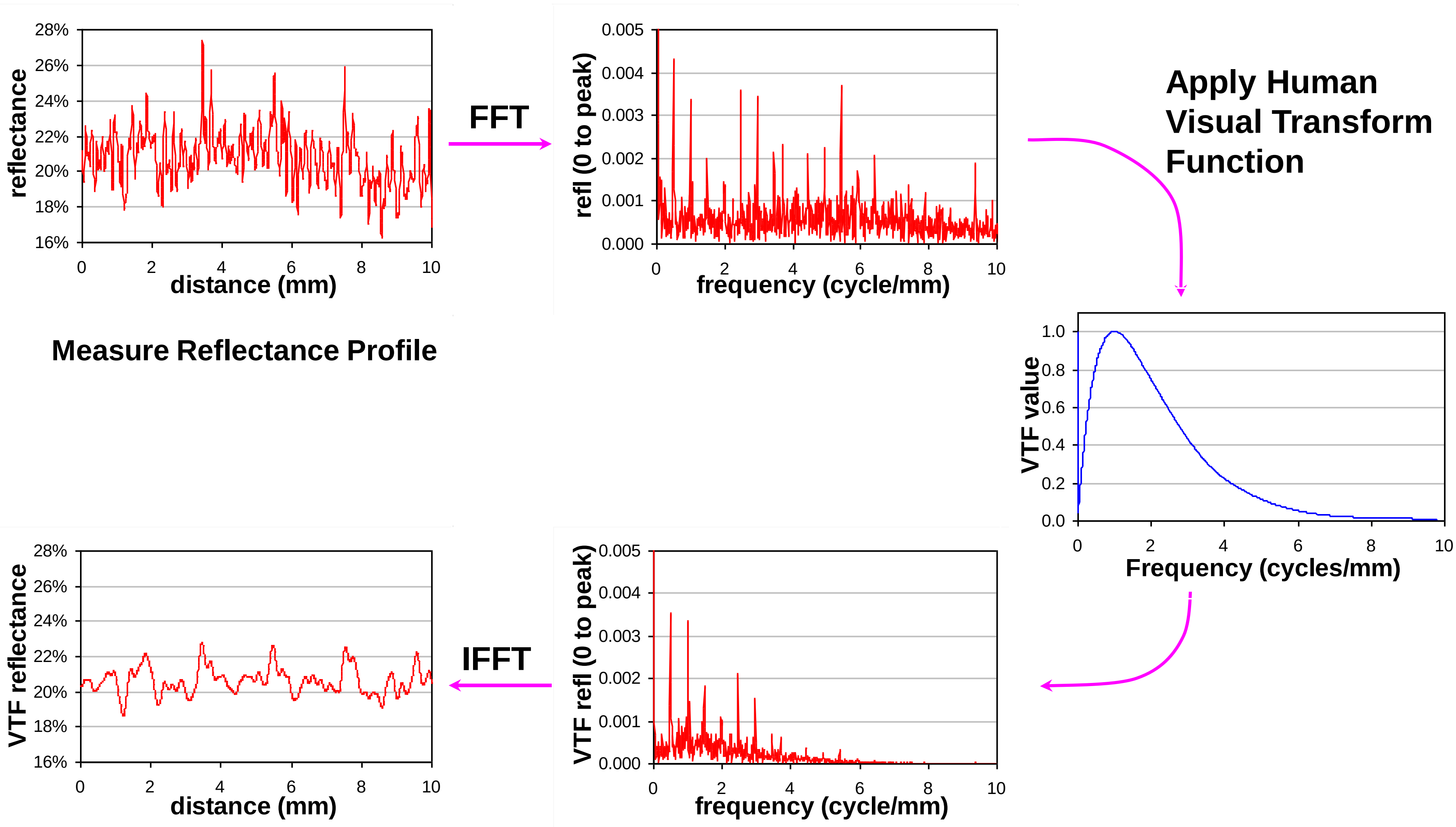
Banding analysis



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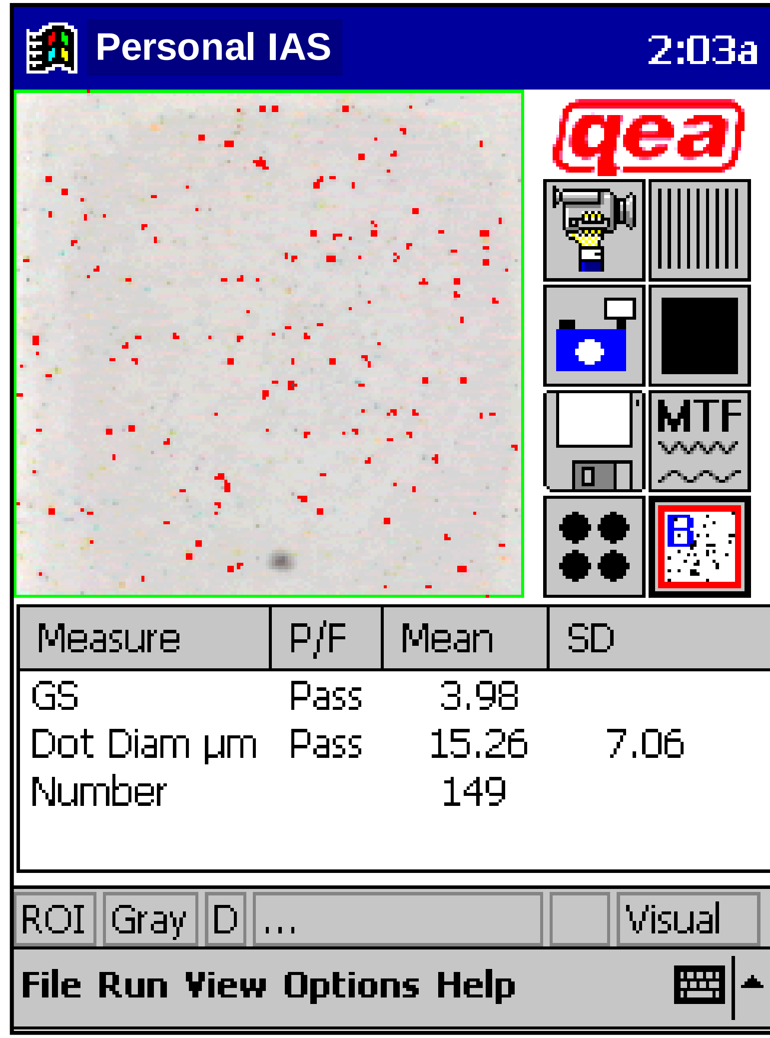
Background Measurement By RMSGS

$$GS = \sqrt{\frac{4.74 \times 10^{-6} \sum_{i} (d_i)^4}{a}}$$

where i = 1 to N



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Calibration Issues in Image Analysis System

- There are two key areas of calibration
  - Spatial (distance)
  - Reflectance (lightness and darkness)
- Spatial can be done using something like a chrome-on glass Ronchi ruling.
- Reflectance calibration requires conversion from raw camera/scanner RGB to
  - Density/reflectance (e.g. ISO 5/3)
  - L*a*b* (CIE)
- Different quality metrics require analysis in density space or L*a*b* space. There are limitations in accuracy.

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Practical Considerations in Image Analysis Systems

- Input devices & file formats
- User interface
- Interactive vs batch mode of operation
- Analysis and algorithms - flexibility & extension capabilities
- Process control tools
- Reporting
- Database management
- Throughput vs resolution/accuracy

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Correlating Objective Measurements & Subjective Assessments

- **Importance of appearance based print quality measurements - putting the results of objective measurements in context:**

  “Beauty is in the eye of the beholder”

  “Fit-for-use”

- **Quantifying subjective evaluation - psychometric scaling**
- **An IQ framework - Image Quality Circle (Engeldrum)**

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Published & In-Preparation ISO Standards *

- ISO-10561:1999 – Method for measuring throughput of printing devices.
- ISO-13660:2001 – Measurement of image quality attributes for hardcopy output – binary monochrome text and graphic images
- ISO-14545:1998 – Method for measuring copying machine productivity.
- ISO-15775:1999 (amended 2005) – Method of specifying image.
- ISO-19752:2004 Toner cartridge yield for monochromatic EP & MFP printers.
- ISO/IEC 18050 – PQ attributes for machine readable digital postage marks.
- ISO/IEC 19751 – Appearance-based image quality standards for printers
- ISO/IEC 19798 – Toner cartridge yield on color EP devices
- ISO/IEC 19799 – Method of measuring gloss uniformity on printed pages
- ISO/IEC 24712 – Color test targets for measurement of office equipment consumable yield
- ISO/IEC 24734 – Method for measuring digital printer productivity
- ISO/IEC 24735 – Method for measuring digital copier productivity
- ??? Method to determine resolution of EP printers

* Partial list of relevant standards

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