Primary Stability: Mechanism, Measurement, Metric, and Remedy

Wei-Chung Cheng
Division of Imaging and Applied Mathematics
OSEL, CDRH, US Food and Drug Administration

Section V – Displays
Summit on Color in Medical Imaging
5-9-2013

Disclosures

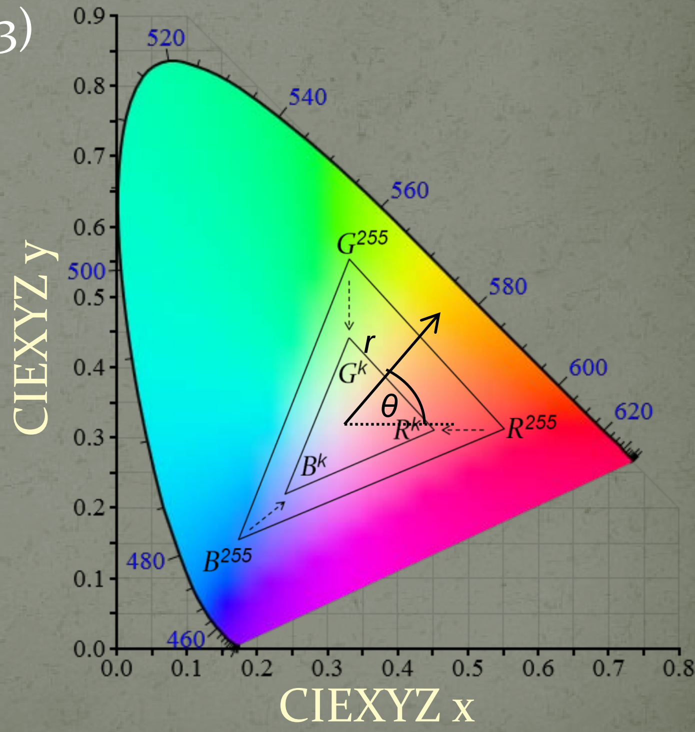
- Equipment loans: Eizo/Nanao, ChiMei-O

- The mention of commercial products herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services

- Acknowledgement
  - Chih-Lei Wu and Aldo Badano, DIAM
  - Colleagues in OIVD, ODE, and OSEL/DP
  - NIH
  - BSC
  - Critical Path Initiative grant

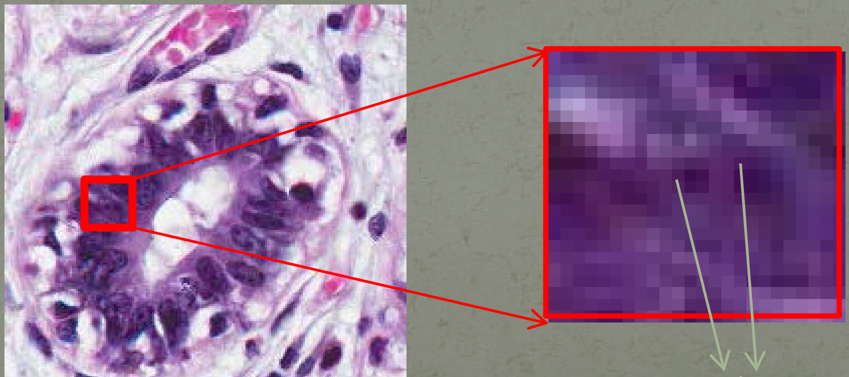
Introduction

- Color displays are based on *Trichromatic Generalization*
  - *"Color stimuli can be matched by additive mixtures of three **fixed** primary stimuli whose radiant powers have been suitably adjusted"*
- CIEXYZ *chromaticity diagram*
  - Any color has 3 components: *brightness*, *chroma*, and *hue*
  - Discard brightness and show chroma and hue on a 2D plane
    - x=cyan-red, y=purple-green, gray=(1/3,1/3)
  - Consider a polar system (r,θ) at (1/3,1/3)
    - r=chroma, θ=hue
- Display color gamut
  - Triangle representing RGB primaries
  - Larger triangle = More saturated primaries
    = Wider color gamut
- Stable primaries
  - Constant chroma and hue while adjusting brightness
  - Not realistic because for most displays chroma diminishes and hue shifts as digital driving level (DDL) decreases



Impacts of Unstable Primaries

- Primary instability raises difficulties in maintaining
  - *Gray balance* – constant chroma/hue for all gray shades (k,k,k)
  - *Color gamut* – constant chroma/hue for all primary shades $(k,0,0),(0,k,0),(0,0,k)$
- Hinder faithful color reproduction
  - In a color display as a medical device for diagnostic purposes
  - Digital pathology as an example
    - Hematoxylin and eosin (H&E) stained tissue sample of human breast
    - Texture inside the dark blue nuclei is difficult to discern on an LCD due to the reduced chroma



$12\Delta E_{ab}$

Slide from US Biomax, Inc.

Outline

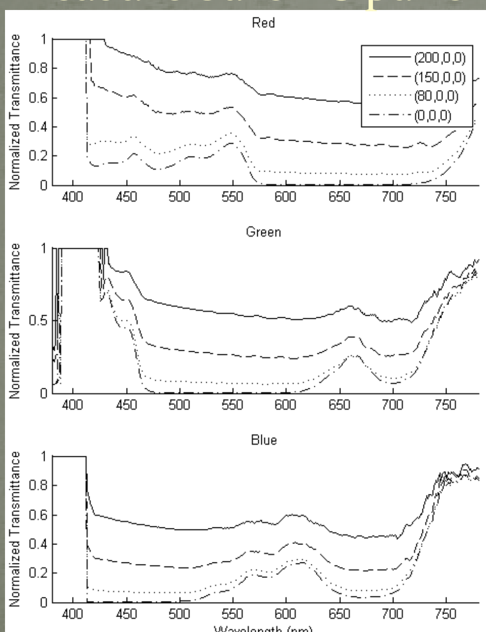
- Introduction
- Mechanism and measurement of LCD color shift
- Primary stability metric and applications
- Remedy
- Conclusions

Mechanism of LCD Color Shift

- Primary instability is caused by
  - Unstable LC spectral transmittance
    - Curves tilt CCW => hue shifts toward red
    - Non-zero black point => light leakage
  - Light leakage from inactive subpixels
    - No color shift when measuring subpixels
    - Dark primary color is a mixture of RGB

Measure bare LC panel

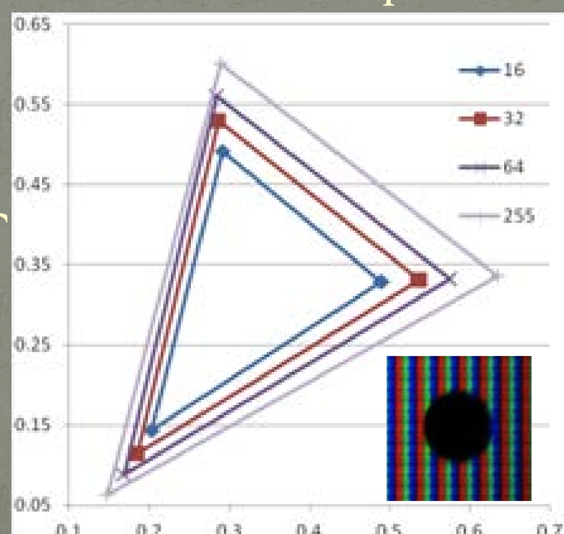
Normalized Transmittance



Wavelength

Measure 10 subpixels

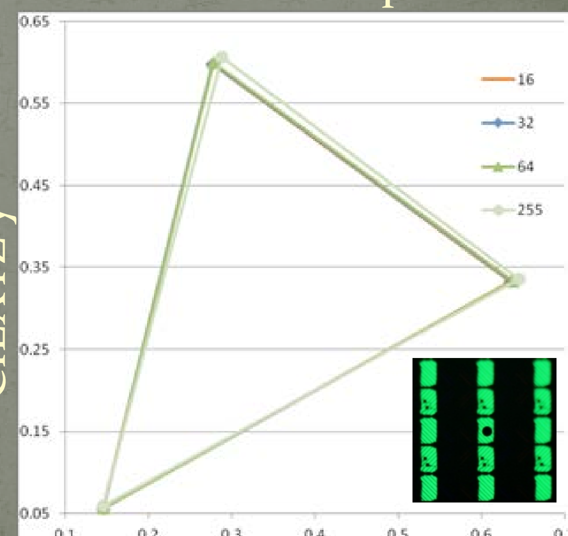
CIEXYZ y



CIEXYZ x

Measure 1 subpixel

CIEXYZ y



CIEXYZ x

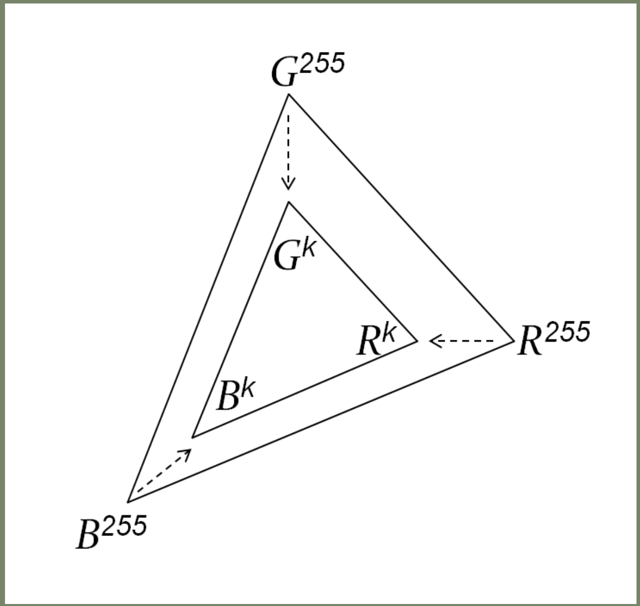
Primary Stability

$$R^k \equiv Tristimulus(k,0,0) \equiv [R_X^k \; R_Y^k \; R_Z^k]$$
$$G^k \equiv Tristimulus(0,k,0) = [G_X^k \; G_Y^k \; G_Z^k]$$
$$B^k \equiv Tristimulus(0,0,k) = [B_X^k \; B_Y^k \; B_Z^k]$$

- On CIEXYZ chromaticity diagram
  - R^{255}, G^{255}, and B^{255}: original primaries at DDL=255
  - R^k, G^k and B^k: desaturated primaries at a lower DDL=k
- By Trichromatic Generalization, R^k can be mixed by
  - $R^k = 0.7R^{255} + 0.1G^{255} + 0.1B^{255}$
- Define *Primary Stability* of *Red* at k as
  - $s(R^k) = 0.7/(0.7+0.1+0.1)$

$$\begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix} * \begin{bmatrix} w_R(Q) \\ w_G(Q) \\ w_B(Q) \end{bmatrix} = \begin{bmatrix} Q_X \\ Q_Y \\ Q_Z \end{bmatrix}$$

$$\begin{bmatrix} w_R(R^k) \\ w_G(R^k) \\ w_B(R^k) \end{bmatrix} = \begin{bmatrix} R_X^{255} & G_X^{255} & B_X^{255} \\ R_Y^{255} & G_Y^{255} & B_Y^{255} \\ R_Z^{255} & G_Z^{255} & B_Z^{255} \end{bmatrix}^{-1} * \begin{bmatrix} R_X^k \\ R_Y^k \\ R_Z^k \end{bmatrix}$$



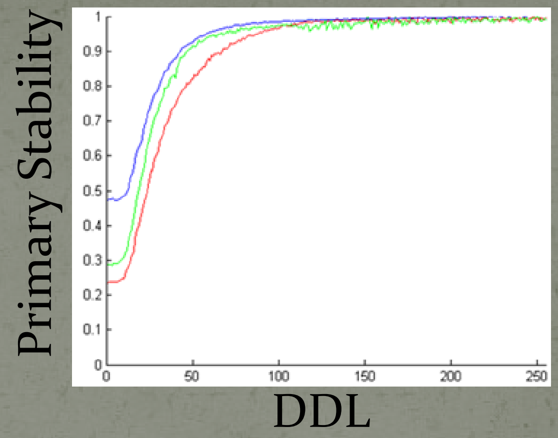
$$s(R^k) \equiv \frac{w_R(R^k)}{w_R(R^k) + w_G(R^k) + w_B(R^k)}$$

$$s(G^k) \equiv \frac{w_G(G^k)}{w_R(G^k) + w_G(G^k) + w_B(G^k)}$$

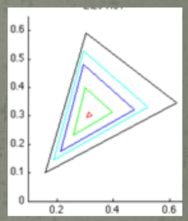
$$s(B^k) \equiv \frac{w_B(B^k)}{w_R(B^k) + w_G(B^k) + w_B(B^k)}$$

Primary Stability Examples

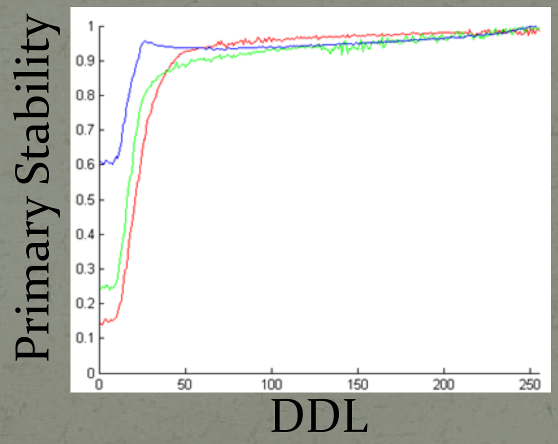
- A medical LCD
  - Curves overlap 150<DDL<255
  - Curves drop when DDL<120
    - Primaries desaturated
    - Gamut reduced
  - Curves separate when DDL<150
    - Gray shifts toward blue

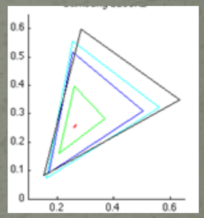


Color gamut at DDL=255, 40, 30, 20, and 10



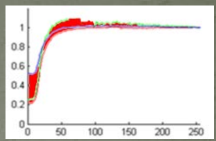
- A gaming-oriented LCD
  - Curves drop when DDL<50
    - Less gamut reduction
  - Curves separate when DDL<240
    - Blue -> Green -> Red -> Blue
    - Poor gray balance





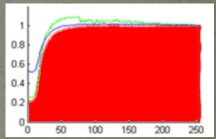
- Primary stability reveals more info

Applications



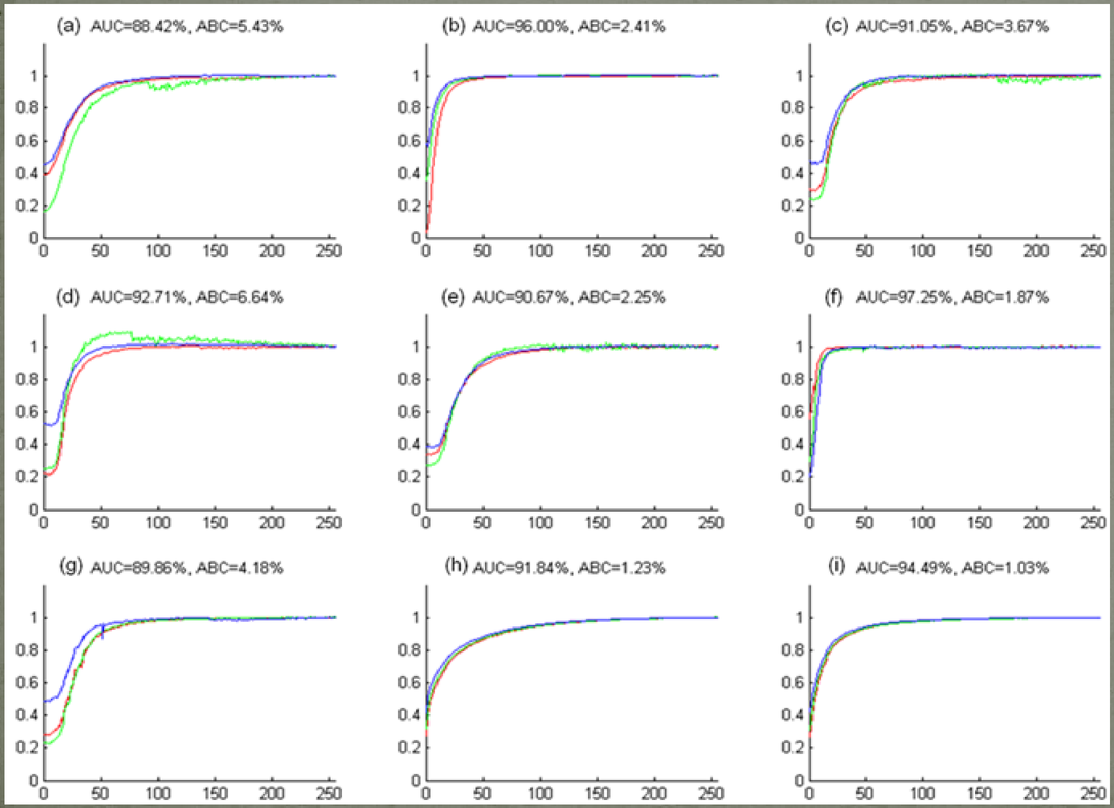
- Measure *Gray Imbalance* with *Area-between-Curves* (ABC)
  - ABC=0 for ideal display

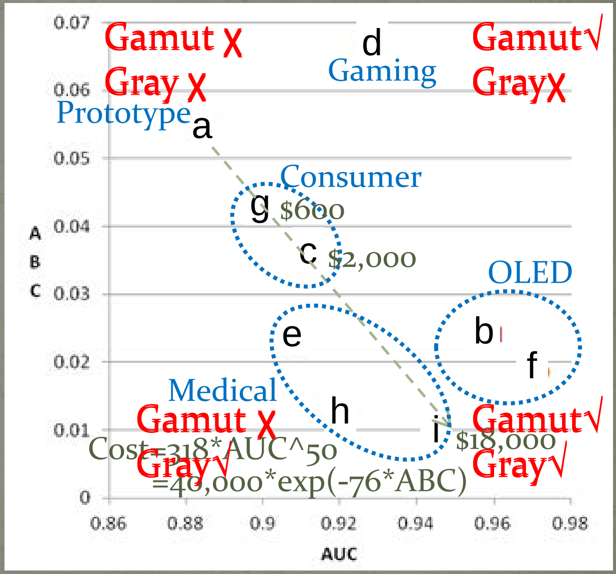
$$ABC \equiv \frac{1}{256}\sum_{k=0}^{255} MAX\left(s(R^k), s(G^k), s(B^k)\right) - MIN\left(s(R^k), s(G^k), s(B^k)\right)$$



- Measure *Color Gamut Reduction* with *Area-under-Curve* (AUC)
  - AUC= 100% for ideal display
  - (1-AUC) = color gamut reduction

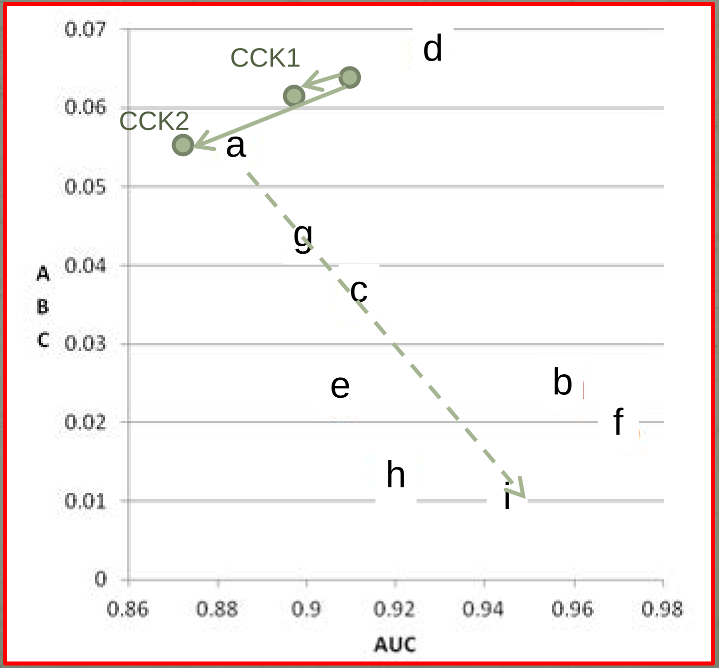
$$AUC \equiv \frac{1}{256}\sum_{k=0}^{255} MIN\left(s(R^k), s(G^k), s(B^k)\right)$$

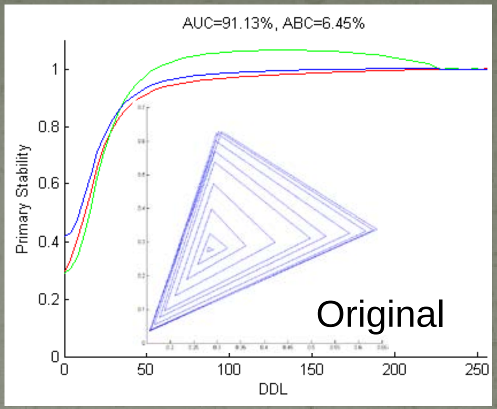


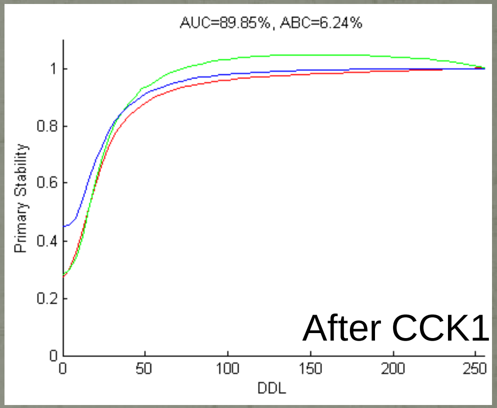


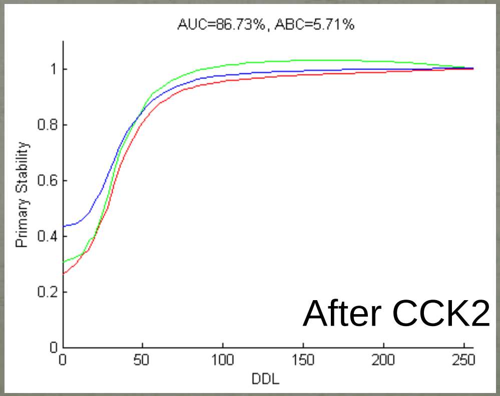
Applications (Cont.)

- Evaluate color calibration kits (CCK)
- Experiment
  - Consumer-grade LED-backlit LCD
    - Excessive color shift and gamut reduction
  - After ICC profile-based calibration
    - Gray balance improved
    - Color gamut worsened



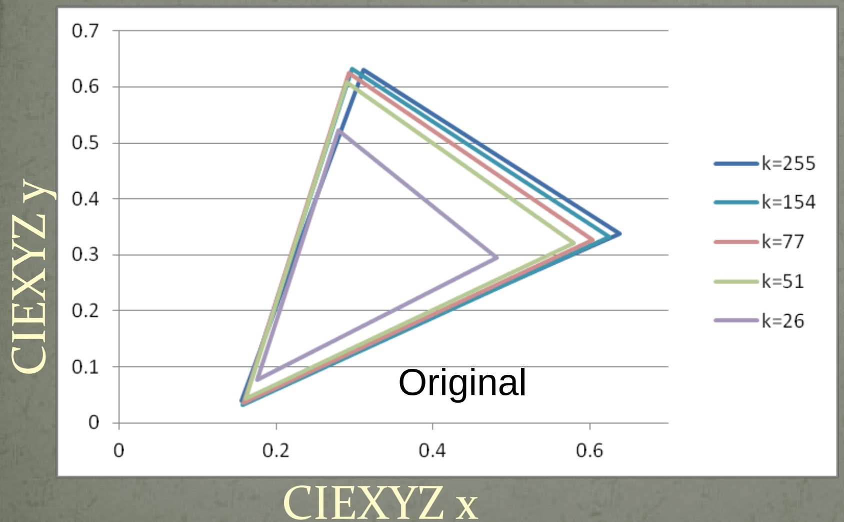


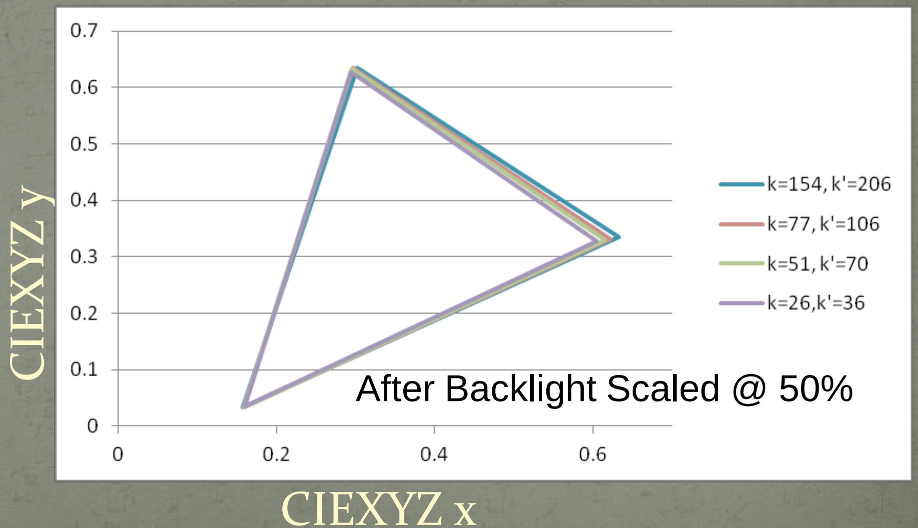




Remedy

- Use *Backlight Scaling* to increase primary stability for dark shades
- LCD luminance = [backlight intensity]*[LC panel transmittance]
  - To preserve the same luminance
    - Increase [LC panel transmittance] to increase primary stability
    - Decrease [backlight intensity] to preserve the original luminance
- Improve color gamut and gray balance for dark shades
- Cannot show bright shades – performance is image-dependent





Conclusions

- Primary stability function measures desaturation of each primary
- Primary stability ABC measures gray imbalance
- Primary stability AUC measures color gamut reduction
- Displays and color calibration kits can be evaluated by ABC and AUC
- Backlight scaling recovers color gamut for dark shades

Thank You

Wei-Chung.Cheng@fda.hhs.gov