Viewing 1950s Color Over 50 Years Later

Was “Never Twice the Same Color” Ever Once the Right Color?

by Wayne E. Bretl

Outline

- Introduction
  - Motivation
  - Factors Affecting Color and Tone Reproduction
  - Methods of Presenting Results
- Studies
  - Receiver Effects
  - Camera Gamma Correction Effects and Noise
  - Camera Color Response Effects
  - Illumination Effects
- Conclusions

Introduction - Motivation

- Discussion of color quality of color TV images is always full of speculation about how good the color was when the system was new
- Many factors cannot be known, since they depend on the adjustments and performance of individual pieces of equipment at the time of use
- There is data, however for some factors, particularly the spectral response of some of the early cameras. This allows computation and accurate display of the colorimetric performance of early cameras using modern equipment

Many Factors Could Affect Color Quality

- In the camera chain and studio
- In the transmitter
- In the receiver

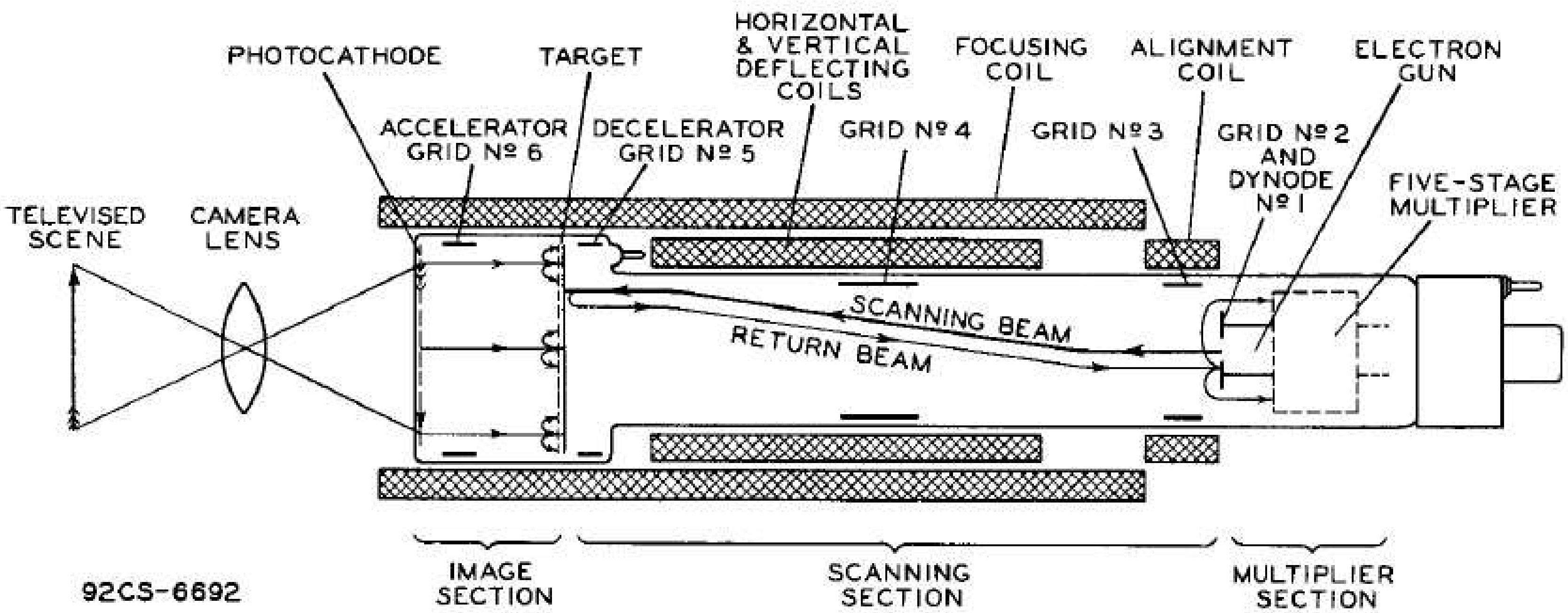
- In the following lists of factors, those that were simulated and studied are in **bold red** type

Many Factors Affect Color Quality - In the Camera Chain and Studio

- Camera setup and operation

Many Factors Affect Color Quality - In the Camera Chain and Studio

- Image orthicon setup/operating conditions – a complex interaction of magnetic and electrostatic fields



Many Factors Affect Color Quality - In the Camera Chain and Studio

- Image orthicon setup/operating conditions - Image orthicon setup appears to have been as much art as science – the tube had a narrow optimum temperature range for operation, and many of the electrical and magnetic field adjustments affected each other.
- Excerpt from "Instructions for Care and Warranty Adjustment":

Prior to shipment from the factory, this camera tube was inspected and carefully tested on the basis of actual television pictures produced by it, and was found to equal or exceed specification quality. However, camera tubes contain certain chemical elements which are not very stable, such as cesium. Consequently, operating performance can vary substantially with time. RCA Image Orthicons are designed to reduce the possibility of such change to a minimum. If, for any reason, this camera tube does not give satisfactory service within the warranty-adjustment period stated in the RCA Adjustment Policy for this type, a claim for adjustment may be made through your RCA distributor or direct to RCA.

SAVE THE ENCLOSED RETURN AUTHORIZATION FORMS

Many Factors Affect Color Quality - In the Camera Chain and Studio

40 deg C for type 7037

The *operating temperature* of any part of the glass bulb should never exceed 50°C, and no part of the bulb at the large end of the tube (target section) should ever fall below 35°C during operation. The temperature of the target is essentially the same as that of the adjacent glass bulb and can, therefore, be determined by measuring the temperature of the glass bulb adjacent to the target. For best results, it is recommended that the temperature of the entire bulb be held between 35° and 45°C. Operation at

Many Factors Affect Color Quality - In the Camera Chain and Studio

too low a temperature will be characterized by the appearance of a rapidly disappearing "sticking picture" of opposite polarity from the original when the picture is moved. Operation at too high a temperature will cause loss of resolution and possibly permanent damage to the tube. Resolution is regained by waiting for the temperature to drop below 45°C. *No part of the bulb should run more than 5° hotter than the target section to prevent cesium migration to the target.* Such

Many Factors Affect Color Quality - In the Camera Chain and Studio

migration will result in loss of resolution and in probable permanent damage to the tube. Like other photosensitive devices employing cesium, the 5820 may show fluctuations in performance from time to time. Strict observance of the above recommendations with respect to operating temperature will not completely eliminate these variations but will greatly improve the stability of the characteristics during the life of the tube.

Many Factors Affect Color Quality - In the Camera Chain and Studio - Setup

- Make sure scan is OK (overscanned)
- Warm up 30 minutes to 1 hour with lens capped and beam off
- Make sure scan is OK (overscanned)
- Uncap momentarily and adjust grid 1 voltage for small beam current
- Recap and adjust beam current
- Adjust alignment coil current so that beam center does not move with focus
- Uncap lens and determine target cutoff voltage (image just visible)
- Raise target 2 volts higher
- Raise beam current to discharge highlights
- Adjust photocathode voltage and G4 voltage for sharpest picture
- Adjust G5 for highest voltage possible with minimum center-edge shading
- Adjust G3 for max signal
- Adjust G6 and photocathode voltage to remove any S-shape of a straight line
- Recap the lens and repeat the alignment current adjustment

Many Factors Affect Color Quality - In the Camera Chain and Studio - Setup (continued)

- Uncap the lens and set the iris so the highlights reach the knee
- Readjust the beam current to discharge the highlights
- Repeat the above two actions to be sure the knee has been reached rather than beam current limiting
- Recap lens and re-adjust G3 for minimum black shading
- Repeat all of the above for best results
- Raise the target voltage to 4 volts above cutoff to prevent gradual highlight compression

- DO ALL OF THE ABOVE for all 3 image orthicons, adjusting neutral density filters in two paths for equal performance of red, green, blue

- READY TO MAKE PICTURES? NO! - still have to do registration and shading adjustments

Many Factors Affect Color Quality - In the Camera Chain and Studio - Setup (continued)

•As you can see, setup of a 3- IO camera was like repeating a science experiment each time

•It’s no wonder that results varied and depended on the experience of the technicians

•Evidence in existing video tapes indicates that NBC Burbank got more consistent results than NBC New York, for example.

•Round-CRT receivers were actually a blessing, as corner shading and misregistration weren’t visible at home

Many Factors Affect Color Quality - In the Camera Chain and Studio

Image orthicon
- **target voltage**
- affected
- gray scale
- response

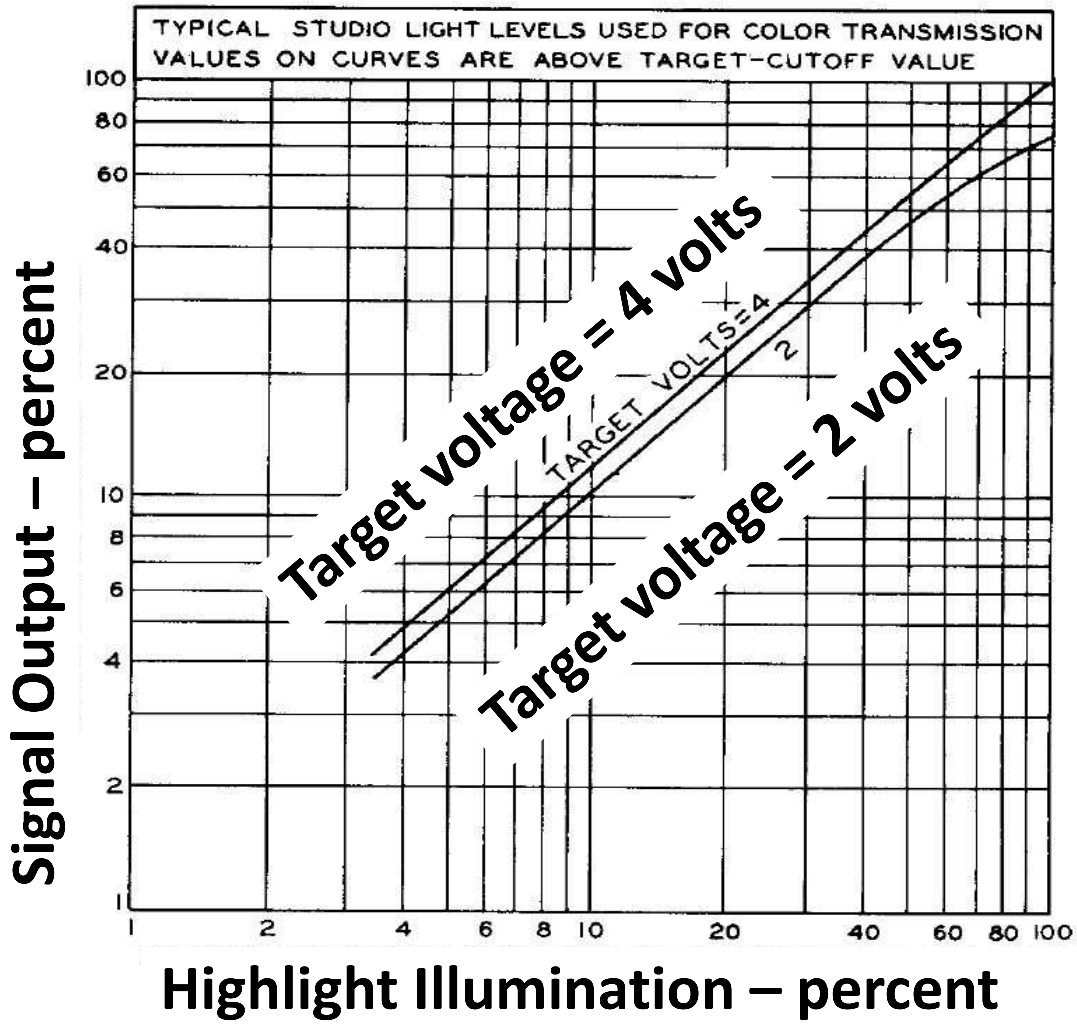


Fig. 7 – Light Transfer Characteristics of Type 6474.

Many Factors Affect Color Quality - In the Camera Chain and Studio

- Camera video processing adjustments (**black level and gamma correction**)

  Note that early cameras with all-tube circuits were typically warmed up for hours before critical adjustment was attempted; the last version of the TK-41 boasted improved stability to reduce the necessary stabilization time.

Many Factors Affect Color Quality - In the Camera Chain and Studio

- **Signal-to noise ratio (SNR) of the cameras**
  - Despite the relatively low SNR of the image orthicon output compared to modern cameras, the video processing added even more noise.
  - RCA made improvements over the years.

Many Factors Affect Color Quality - In the Camera Chain and Studio

- **Signal-to noise ratio (SNR) of the cameras**
  - Xavier University, Cincinnati, received hand-me-down cameras and gutted them and substituted transistorized circuits throughout the processing chain.
  - This resulted in an 8 dB SNR increase [Jay Adrick, private communication, 2007].

Many Factors Affect Color Quality - In the Camera Chain and Studio

- **Signal-to noise ratio (SNR) of the cameras**
  - Noise limits the amount of **gamma correction** gain that is practical in the lowlights and thus limits the contrast range of the over-all system

Many Factors Affect Color Quality - In the Camera Chain and Studio

- Stability of the chroma encoding and maintenance of the color subcarrier integrity through the distribution chain (a reason commonly cited for color variations)
- Polarization sensitivity of the color-splitting dichroic optics (the effect typically was noticed as green highlights on back-lit hair)

Many Factors Affect Color Quality - In the Camera Chain and Studio

- Camera "taking characteristics" (spectral response)
  - Actual measurements of complete early cameras are available
  - Specifications of some parts of early camera optics are also available

Many Factors Affect Color Quality - In the Camera Chain and Studio

- **Illumination Color Temperature**
  - Camera optics not easily adapted to light-quality change
  - The TK-41s had neutral density filters in the R,G and B paths to adjust for rough white balance, but did not have a filter wheel for color-compensating filters.
  - It was the practice in some studios to run all (incandescent) lighting at 70% on the dimmers, and then adjust up and down from there.

Many Factors Affect Color Quality – In the Transmitter

- Transmitter differential gain and phase
- Transmitter group delay response

- (Neither is addressed in this presentation)

Many Factors Affect Color Quality - In Receivers

- Stability of receivers
- Lack of coordinated chroma and contrast controls (as a "Picture" control) in early receivers
- Lack of full DC restoration in all but the earliest generation receivers
- Low contrast capability in early receivers except in darkened rooms due to relatively high-reflectance screens. (The earlier picture tubes could have some internal contrast and purity reduction due to scattered electrons as well)
- Receiver phase/group delay distortions
- Other distortions peculiar to individual circuit designs

Many Factors Affect Color Quality - In Receivers

- **Changes in receiver phosphors over the years to increase brightness at the expense of colorimetry**
- **Early adoption of high color temperature white points in receivers**
- **Adoption of approximate corrective matrices in receivers, which reduced hue errors due to phosphor changes, but introduced saturation and brightness errors in colors other than skin tones; particularly visible as over-bright reds**

Order of Presentation for Factors Studied in this Presentation

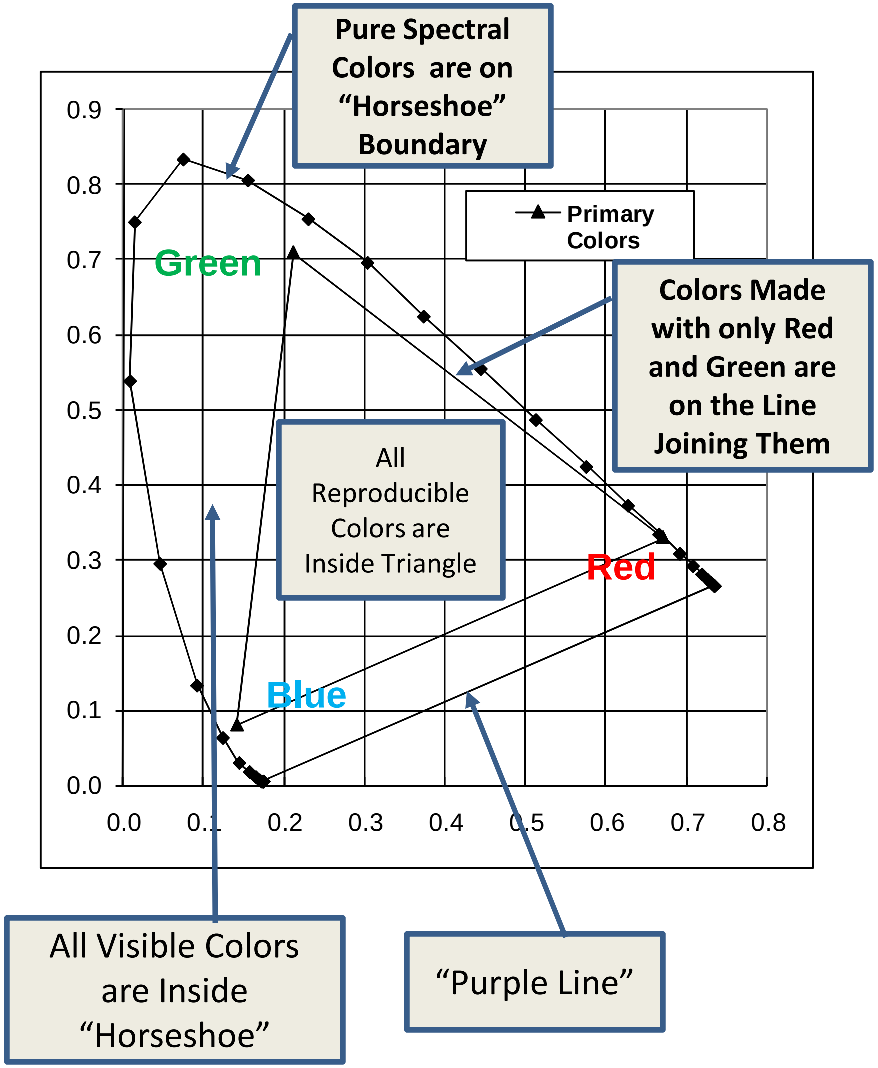
- Receiver primaries, white point, corrective matrices
  - Affect all colors
  - Based on 3x3 matrix calculations
- Camera gamma correction and noise
- Camera color response
  - Can affect some colored objects more than others depending on interaction of light source, object reflectance spectrum, and camera spectral response
  - Calculated by *integration* of *product* of illumination spectrum, object spectrum and camera response, plus 3x3 matrix calculations
- Illumination
  - Same calculations as camera color response

Presentation of Results

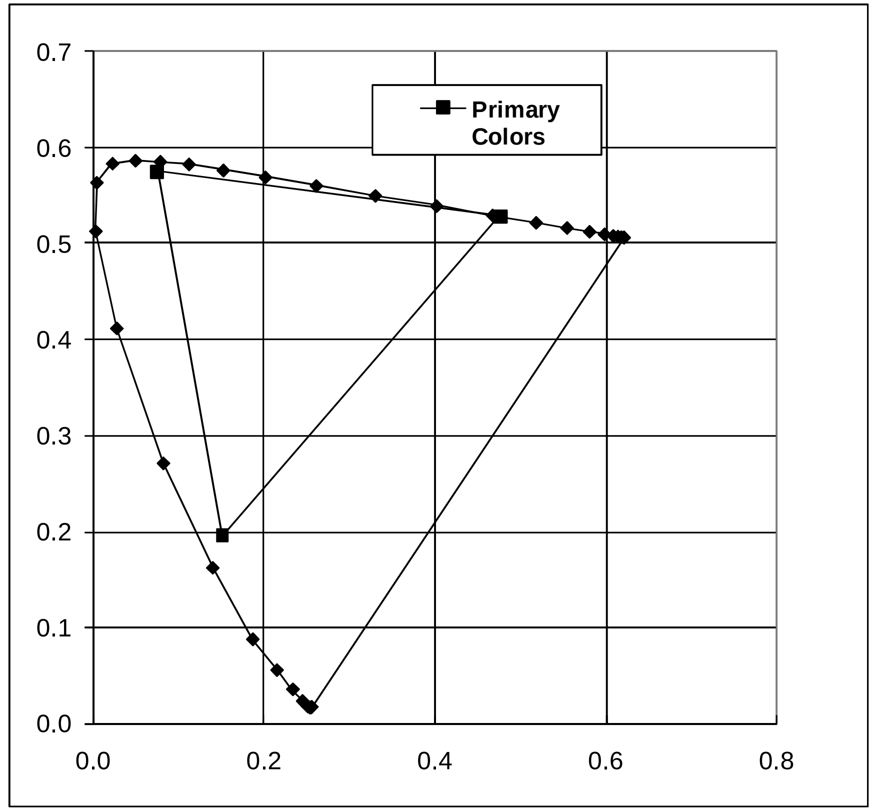
- Spectral Graphs / Chromaticity Charts
- Reproductions of Color Test Chart
- Reproductions of Natural Images

Display of Results on Chromaticity Charts

1931 CIE x,y chart



1976 UCS* chart
(Projection of 1931 Chart)



- Better Match to Eye's Sensitivity to Color Differences
- Triangles Remain Triangles

***Uniform Chromaticity Scale**

Visual Display of Effects

- Gretag-Macbeth ColorChecker chart
  - SMPTE Standard 0303M-2002, Television – Color Reference Pattern
  - Color coordinates and spectra are both available
  - http://www.babelcolor.com/main_level/ColorChecker.htm#How_about_data

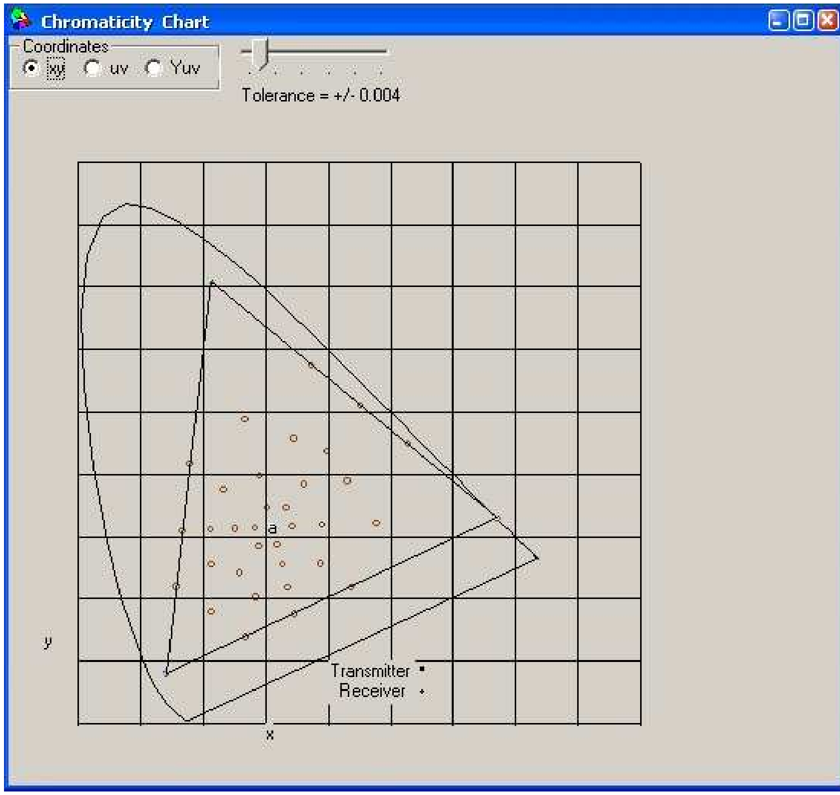
Visual Display of Effects

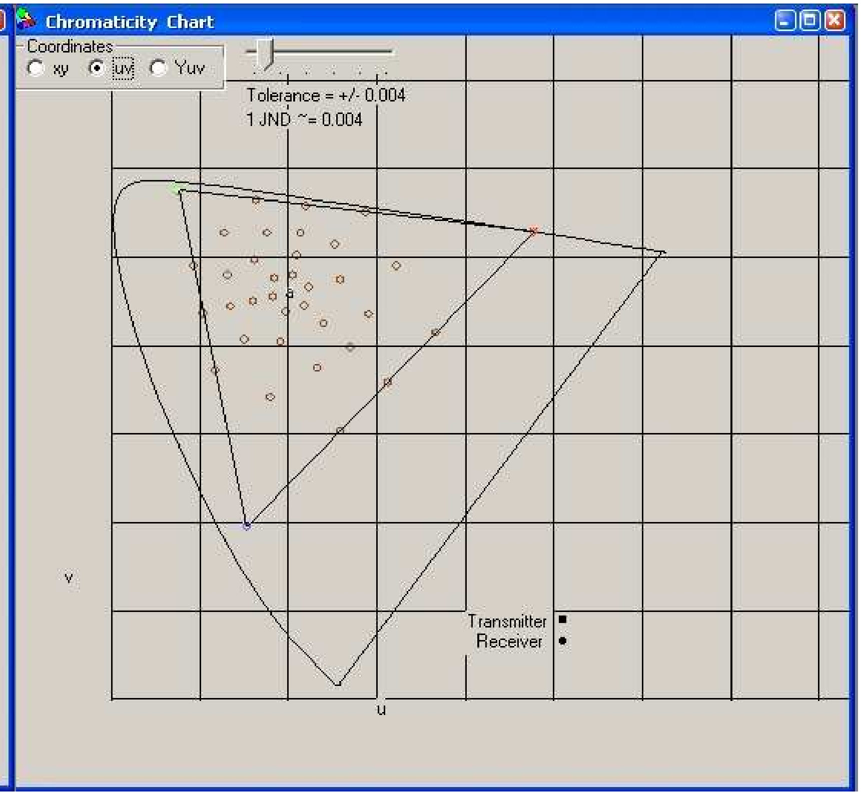
- Images
  - Exact results for receiver effects (3x3 matrix)
  - Approximate results for camera and illumination (assumes natural object spectra are similar to test objects)

Test Colors

- For Receiver, need only color coordinates – can easily make up hypothetical colors
- For Camera, need to know reflectance spectrum of test objects

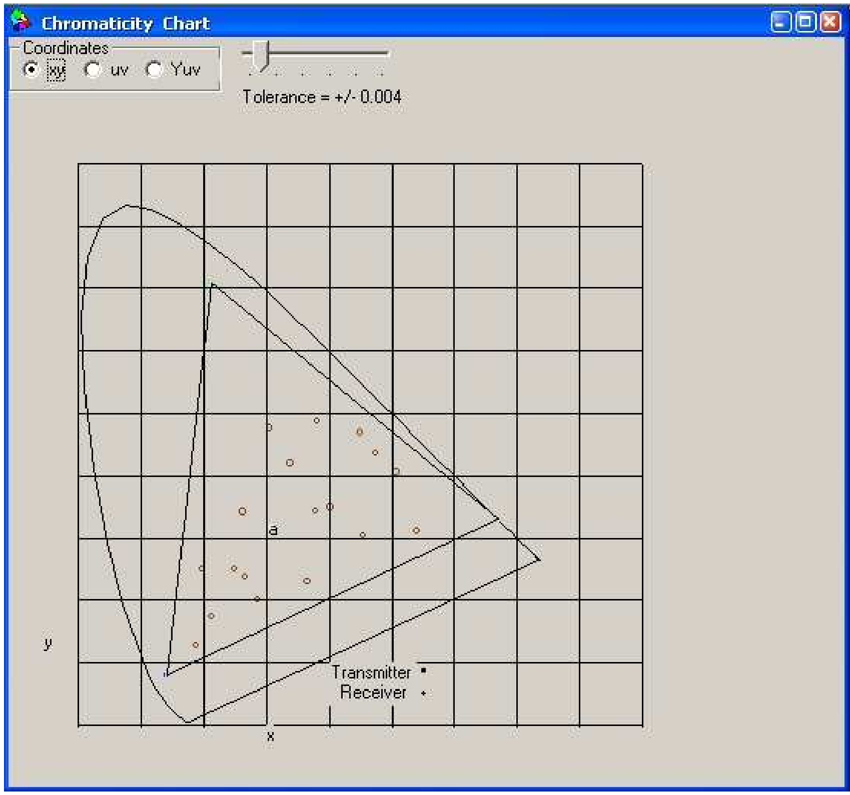
Test Colors – Assorted
(Spectrum is Unspecified – Use for Receiver Studies Only)

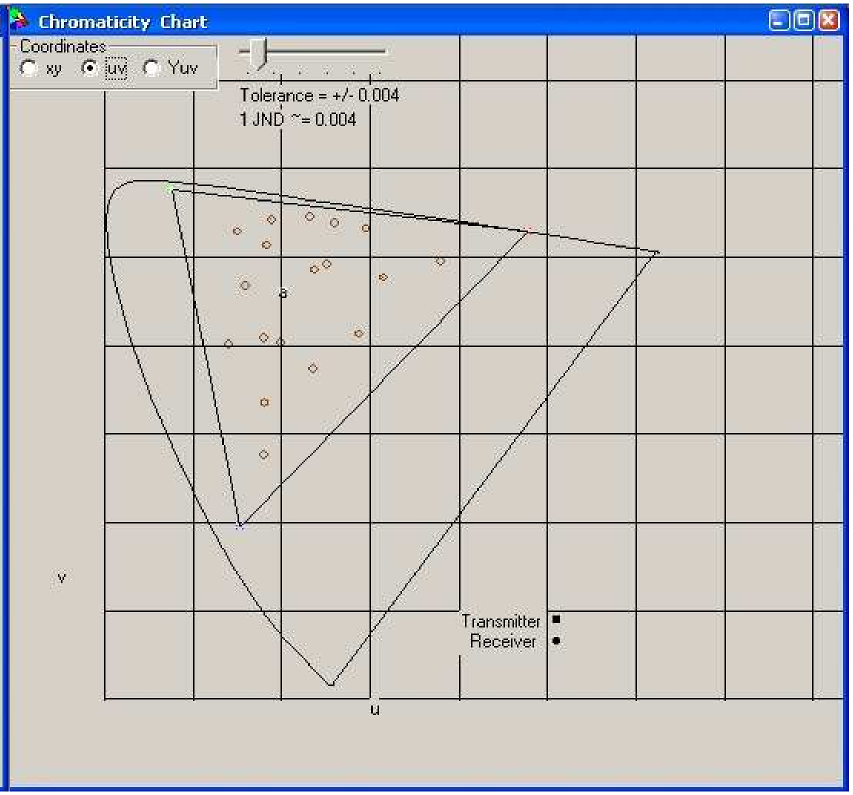




Test Colors – Gretag-Macbeth ColorChecker Chart
(Known Reflectance Spectra –Use for Camera and Receiver Studies)

SMPTE Standard 0303M-2002, Television – Color Reference Pattern





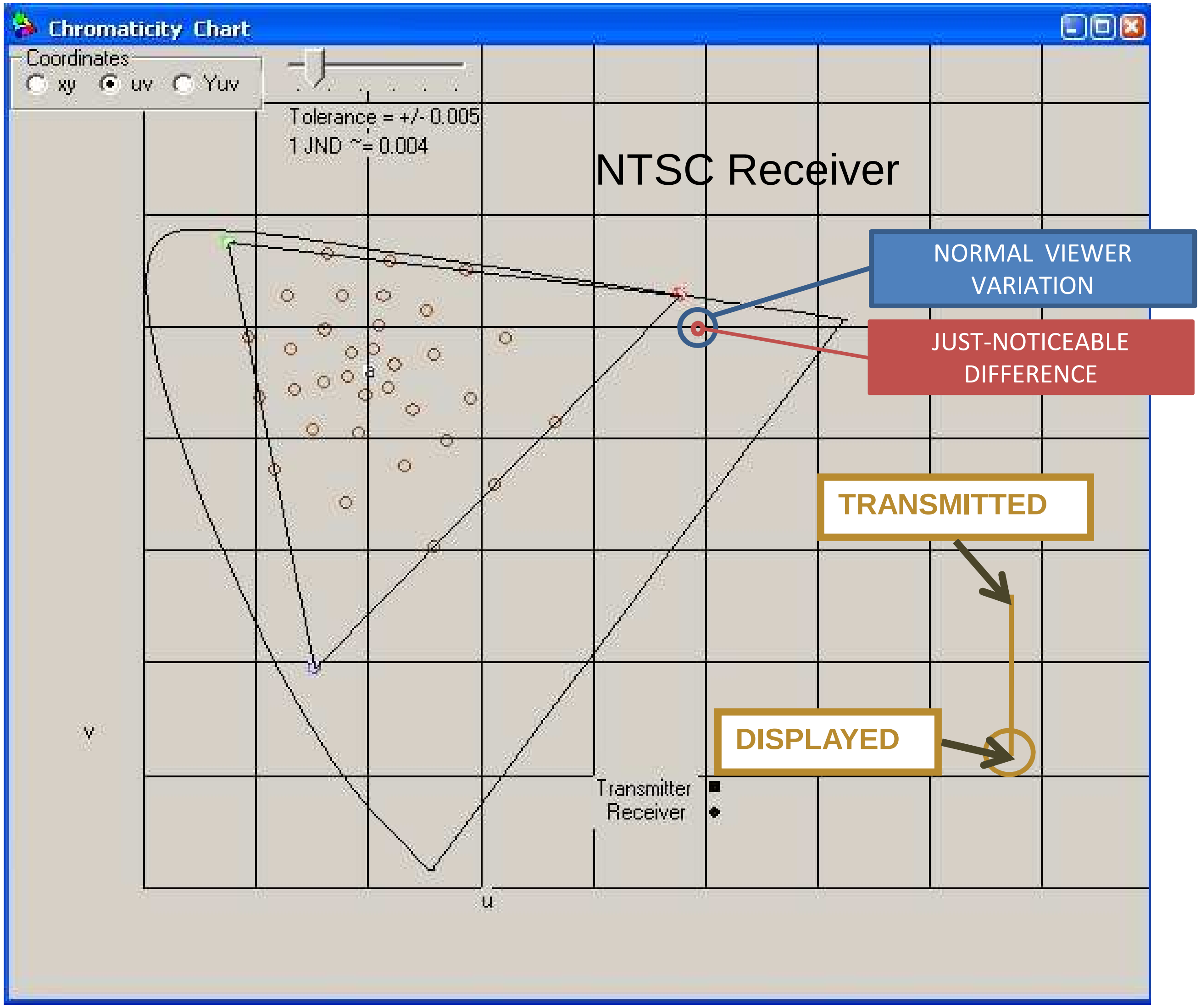
Receiver Effects

Receiver Effects

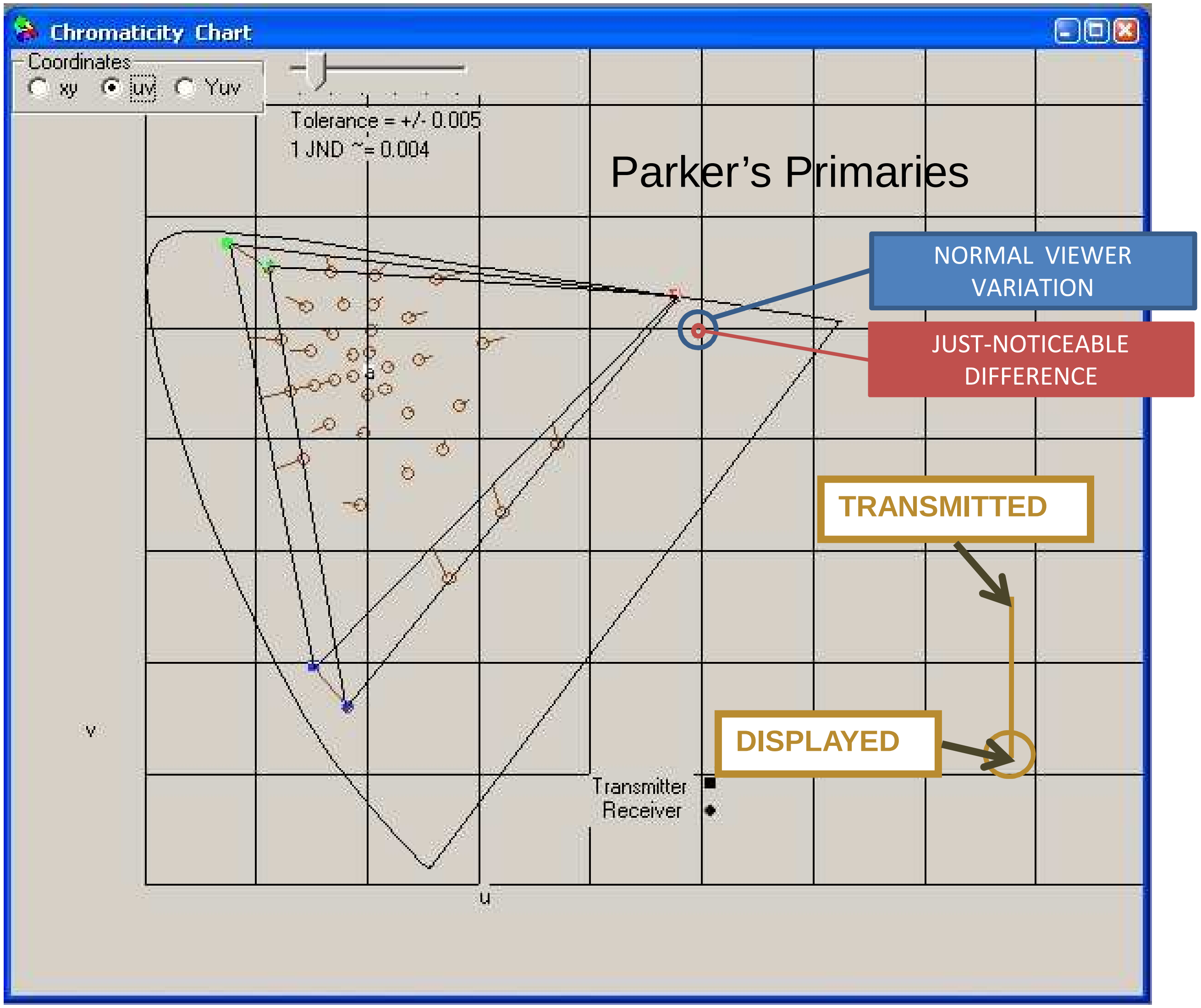
Primaries, White Point, Matrixing

- Papers on matrices for approximate color correction in receivers for non-NTSC phosphors and different white points were published by Parker (1966); Neal and DeMarsh (1974), Neal (1975), and Bretl (1979), among others
- This section illustrates Parker’s results and the tradeoff of color brightness errors for proper flesh tone reproduction

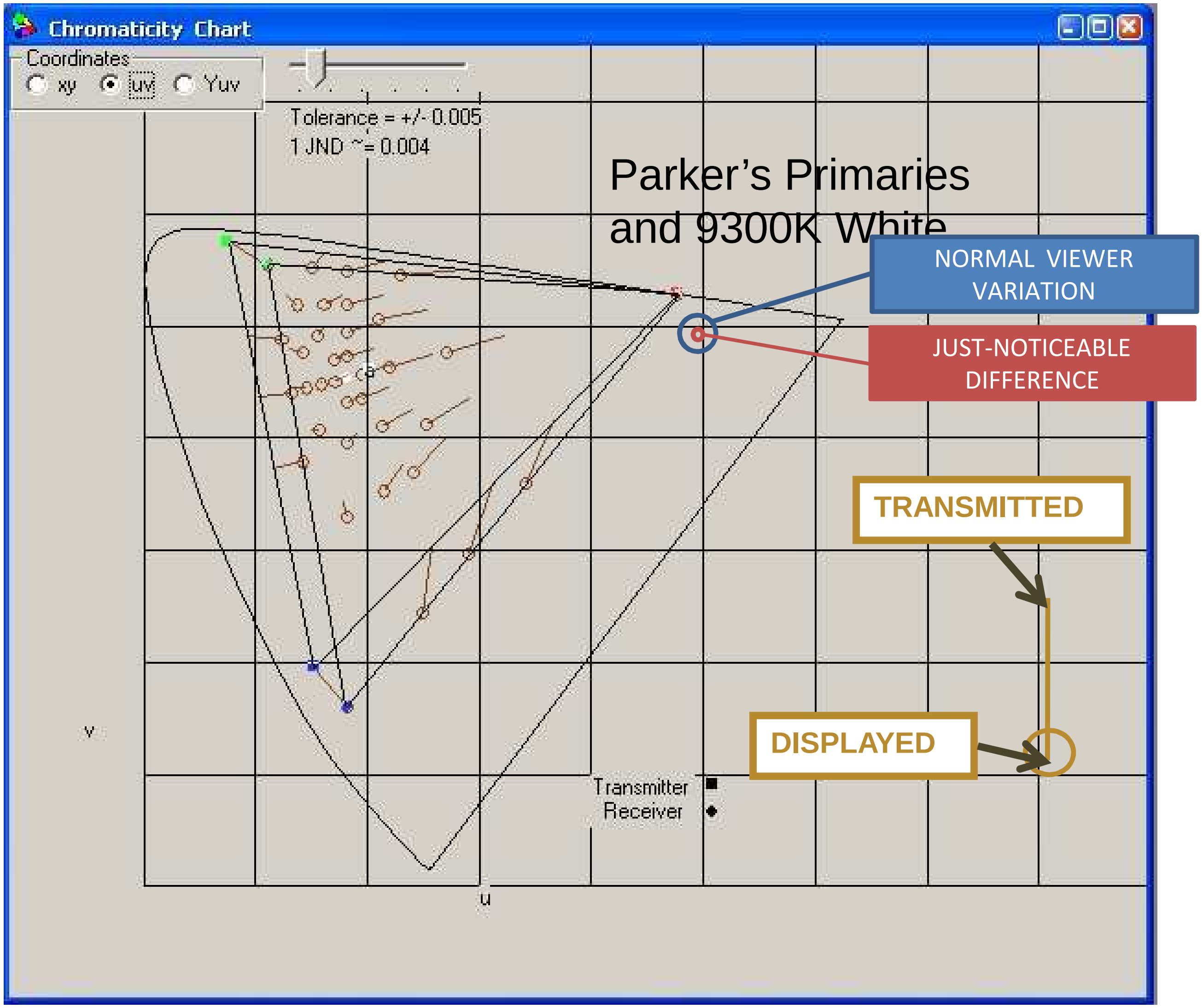
Effects of Receiver White Point and Primaries



Effects of Receiver White Point and Primaries

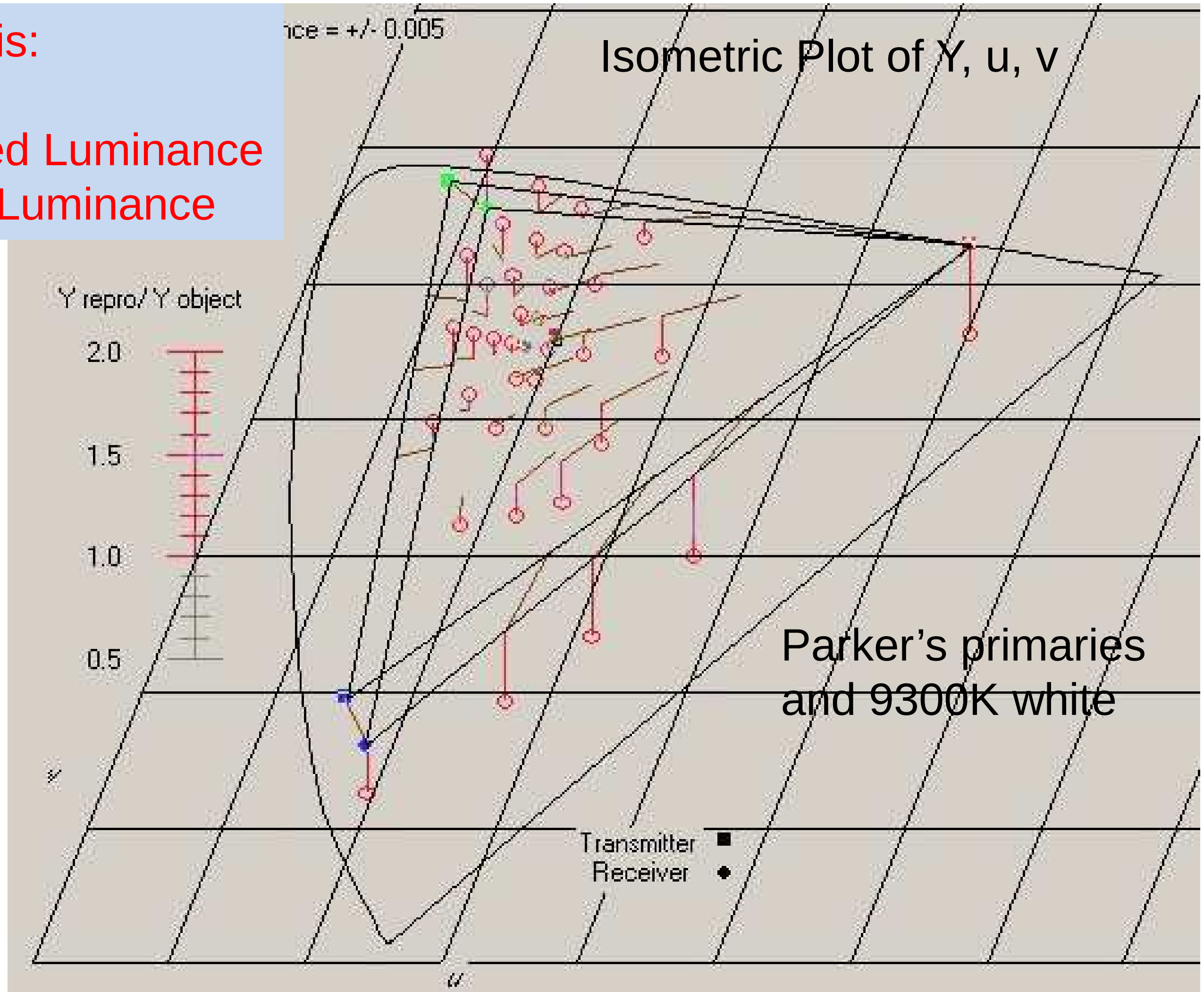


Effects of Receiver White Point and Primaries



Effects of Receiver White Point and Primaries

Vertical Axis:
Ratio of
Reproduced Luminance
to Correct Luminance



Simulating Effects of Receiver White Point and Primaries - Displaying on a Modern sRGB* Display

- A 3x3 matrix in the linear domain will simulate the change of white point and primaries, converting the input RGB values Rp, Gp, Bp to sRGB display values Rs, Gs, Bs

Parker 9300K + 27 MPCD to sRGB

	Rs =	Gs =	Bs =
Rn	0.8632	-0.0157	-0.0156
Gn	-0.1460	1.0726	0.0683
Bn	0.0254	-0.0046	1.1882

* sRGB primaries = HDTV primaries = ITU-R 709 primaries

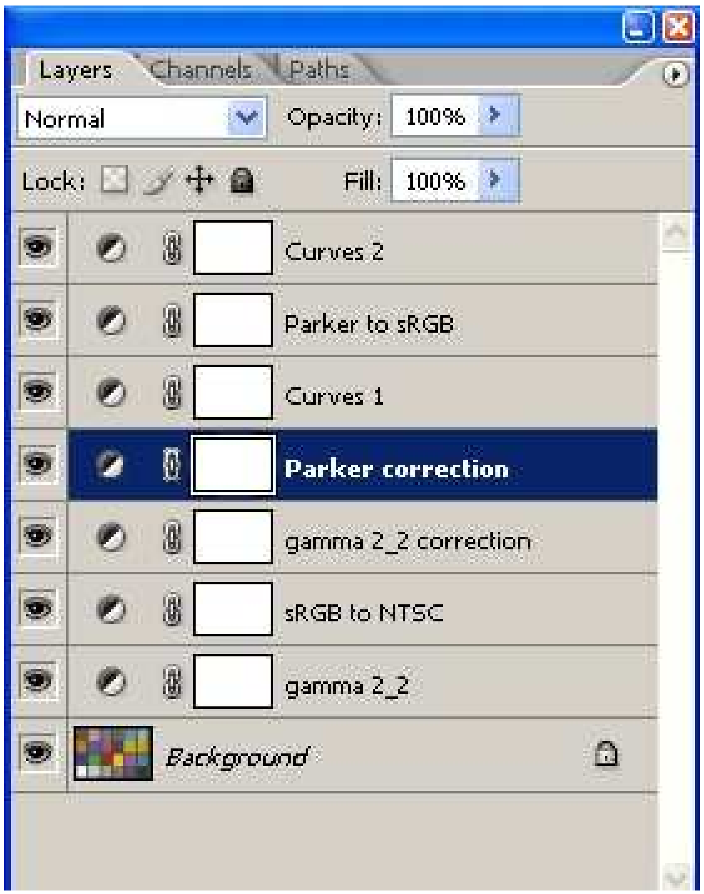
Simulating Effects of Receiver White Point and Primaries - Effects of Electrical Matrix in Receiver

- Parker’s 3x3 correction matrix is applied in the gamma–corrected domain

Parker's correction matrix for 9300K + 27MPCD

	Rprime=	Gprime=	Bprime=
R	1.5468	-0.0187	0.0095
G	-0.1977	0.8960	-0.2231
B	-0.3491	0.1226	1.2135

Simulating Effects of Receiver White Point and Primaries - Photoshop Layers



Order of Processing →

Curves: sRGB gamma correction

Channel Mixer (3x3 matrix) receiver primaries and white to sRGB

Curves: CRT gamma

Channel Mixer (3x3 matrix) per Parker

Curves: NTSC gamma correction

Channel Mixer (3x3 matrix) to NTSC

Curves: remove sRGB gamma correction

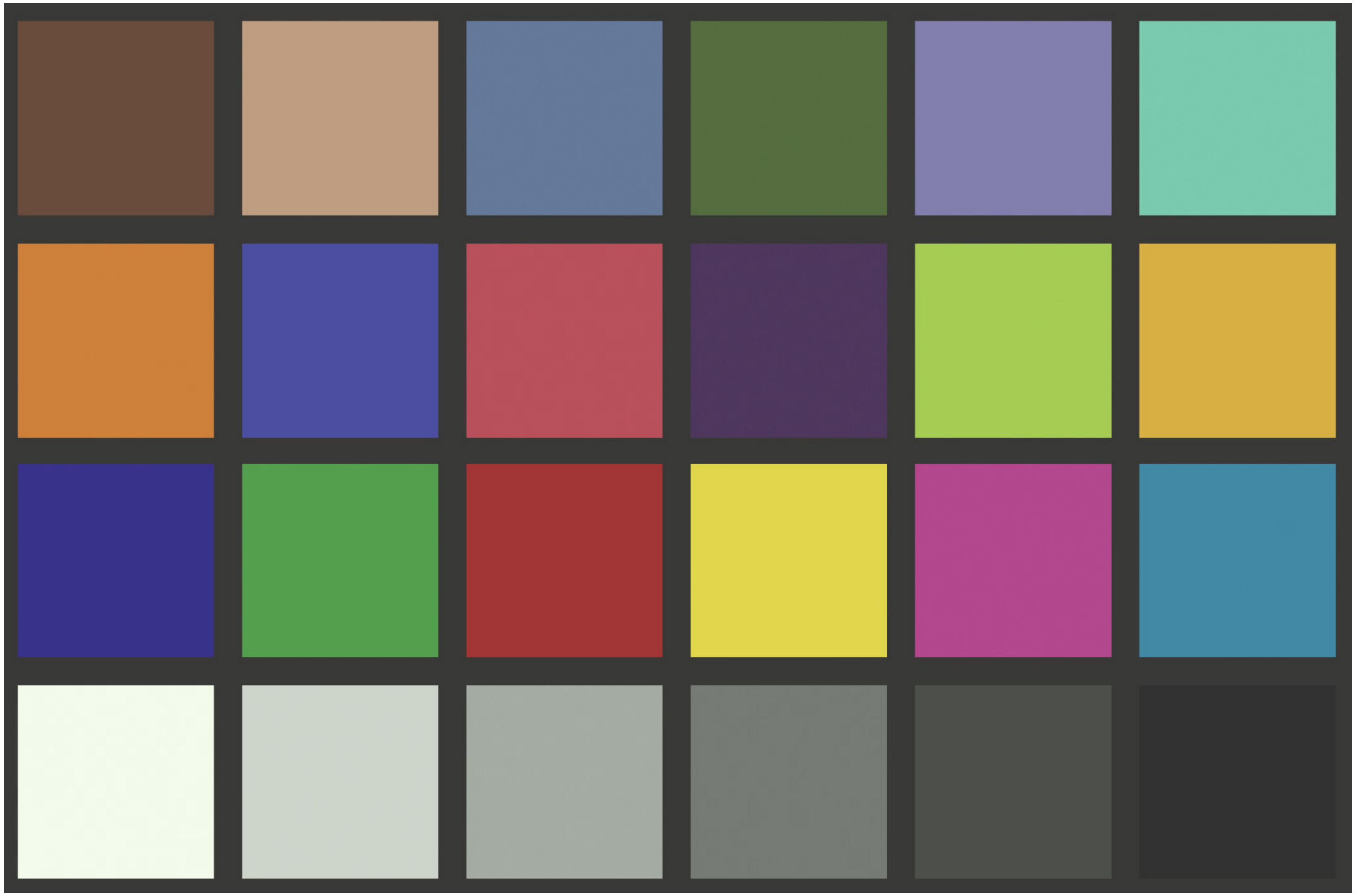
sRGB source image

Results with Test Chart

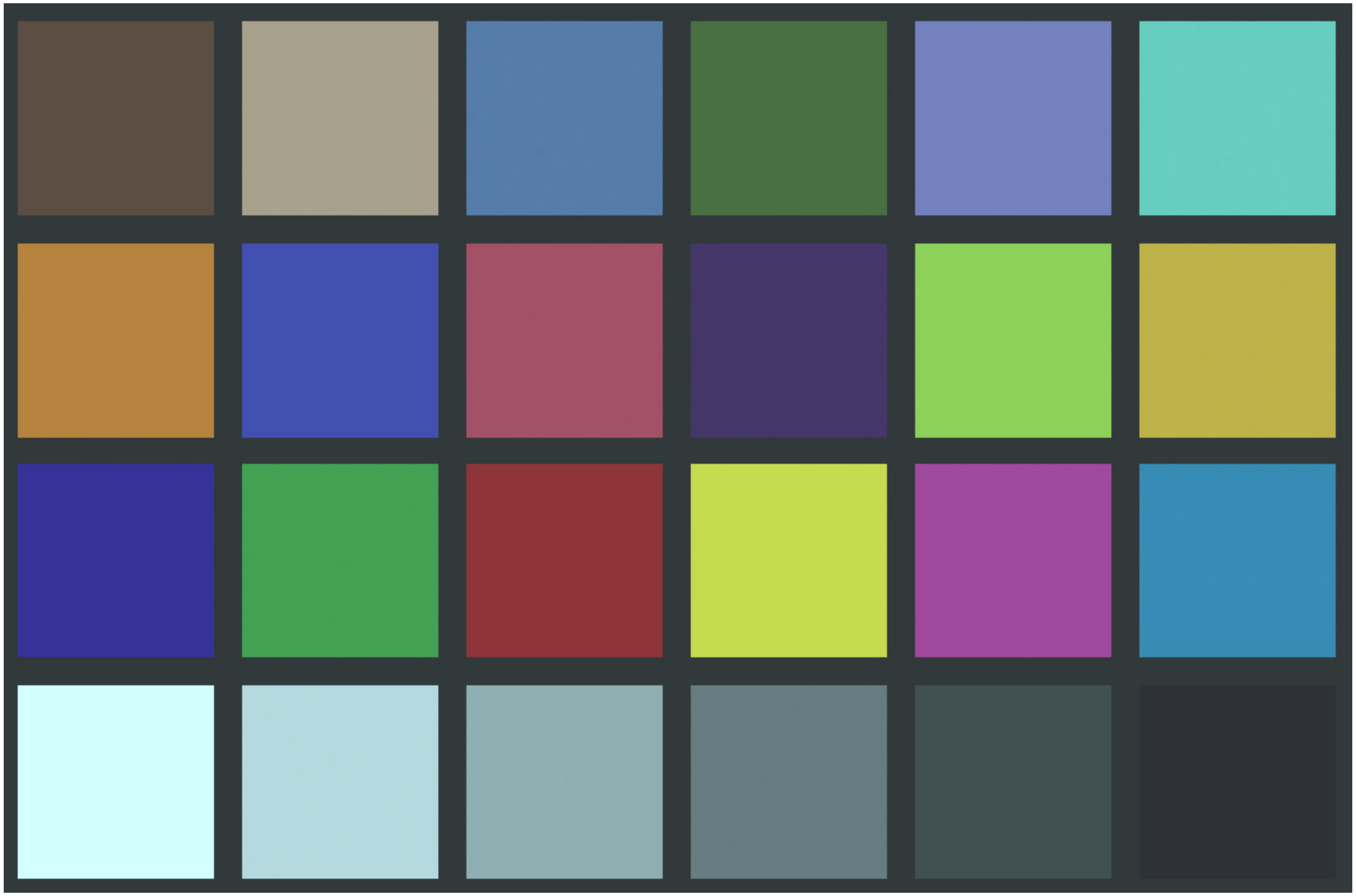
1. Presented on white background to make changes obvious
2. Presented on black background to allow adaptation (if any)

Original

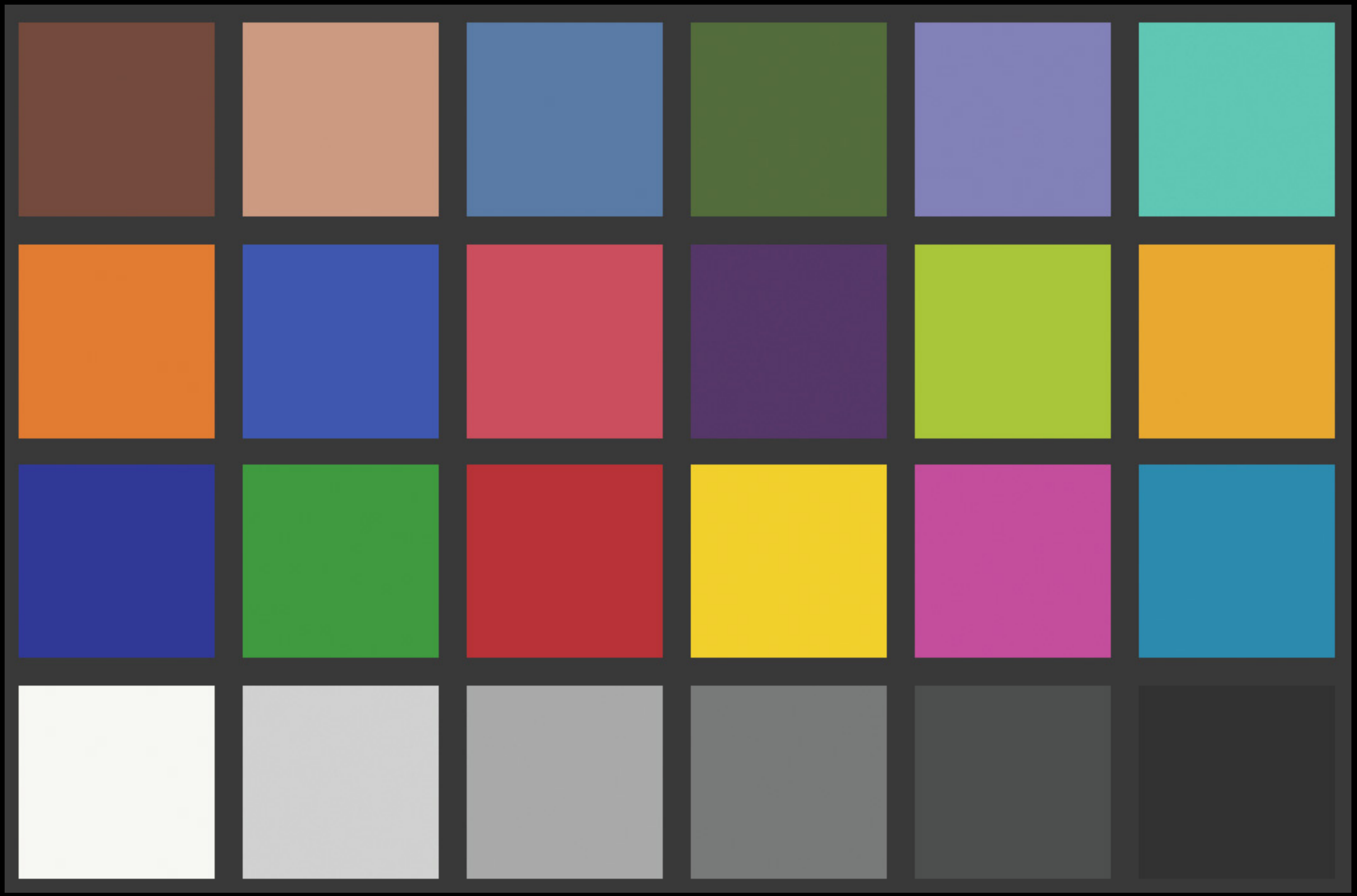
Parker’s Primaries



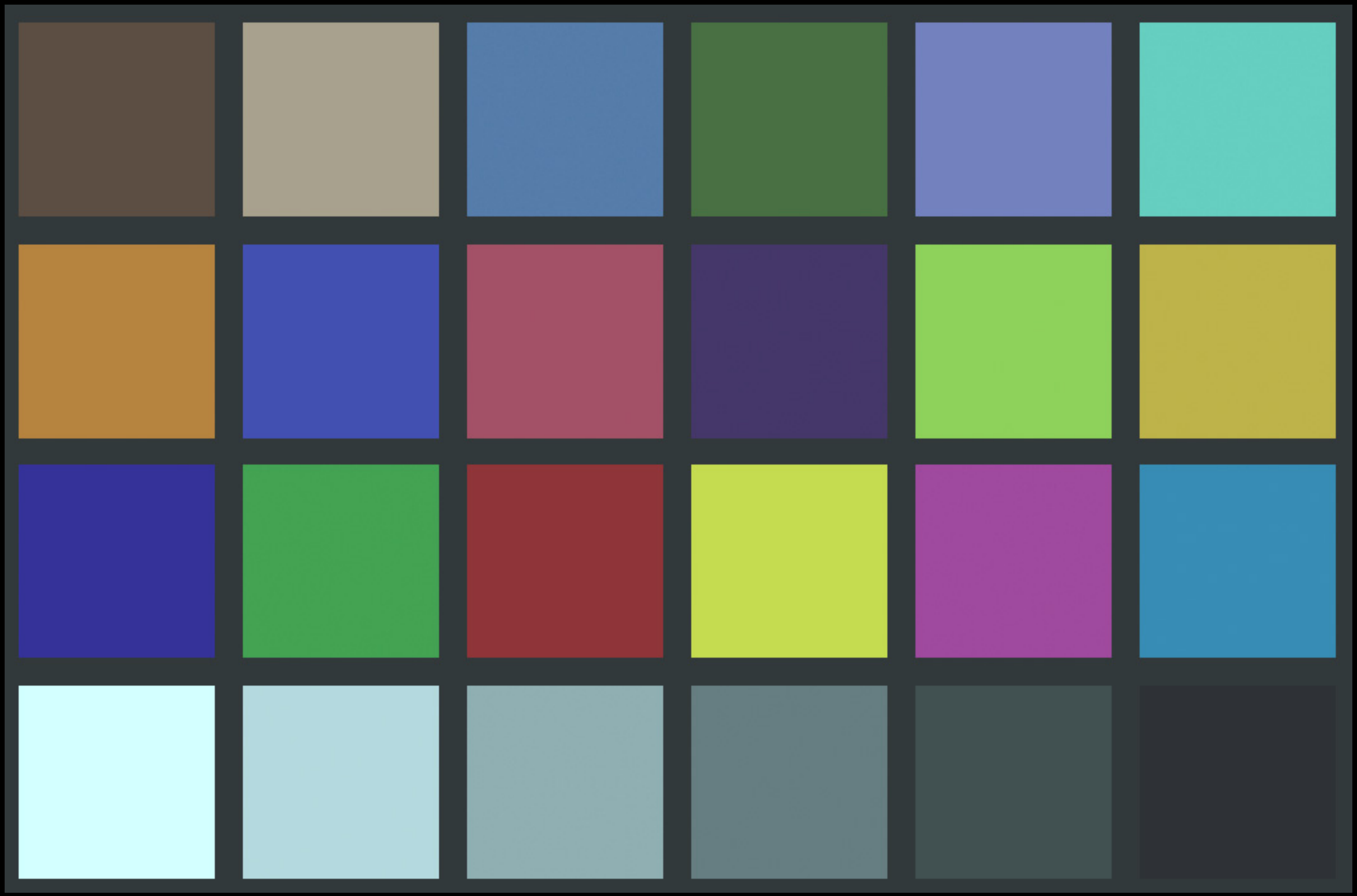
Parker’s Primaries and 9300K + 27 MPCD



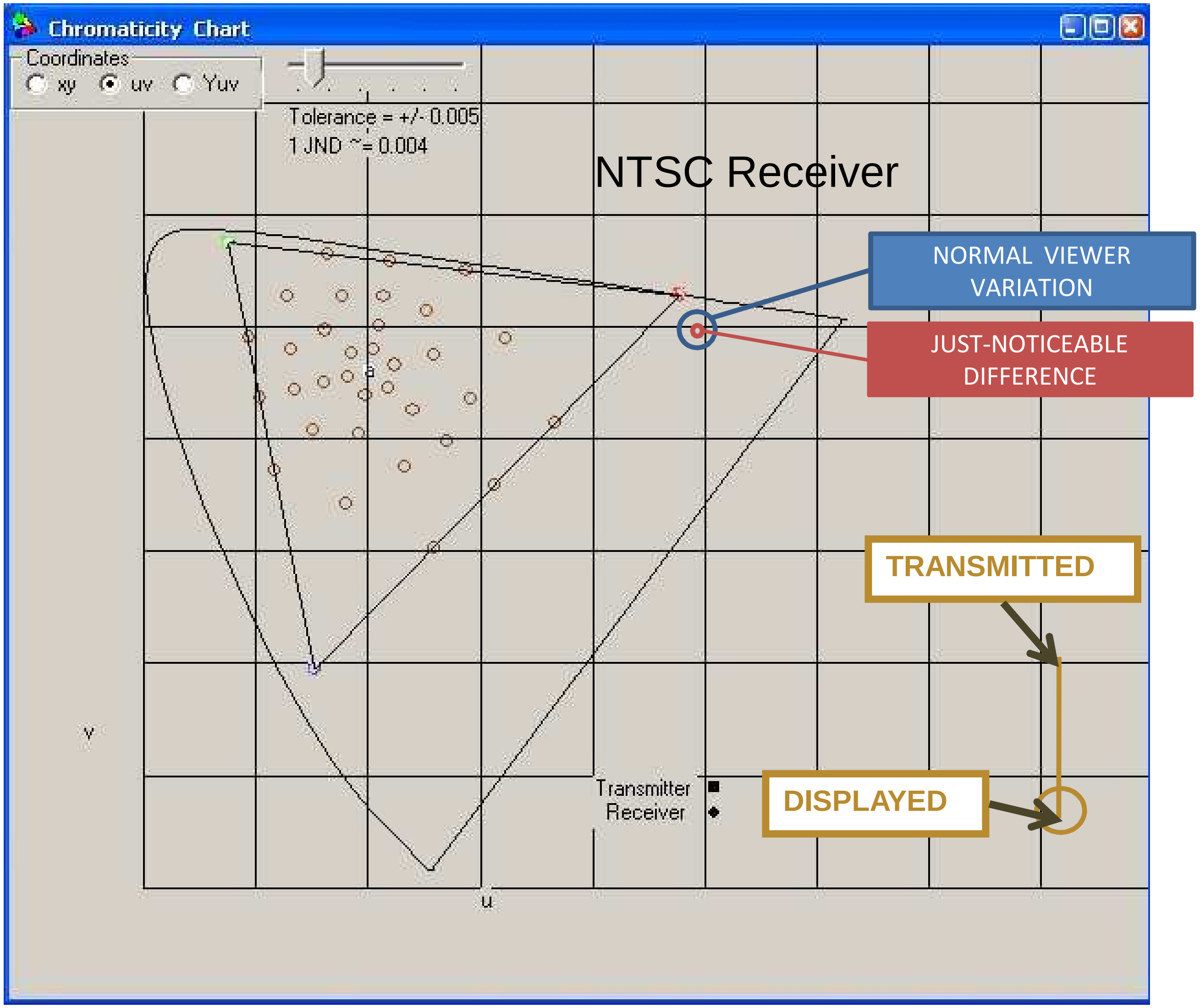
Original



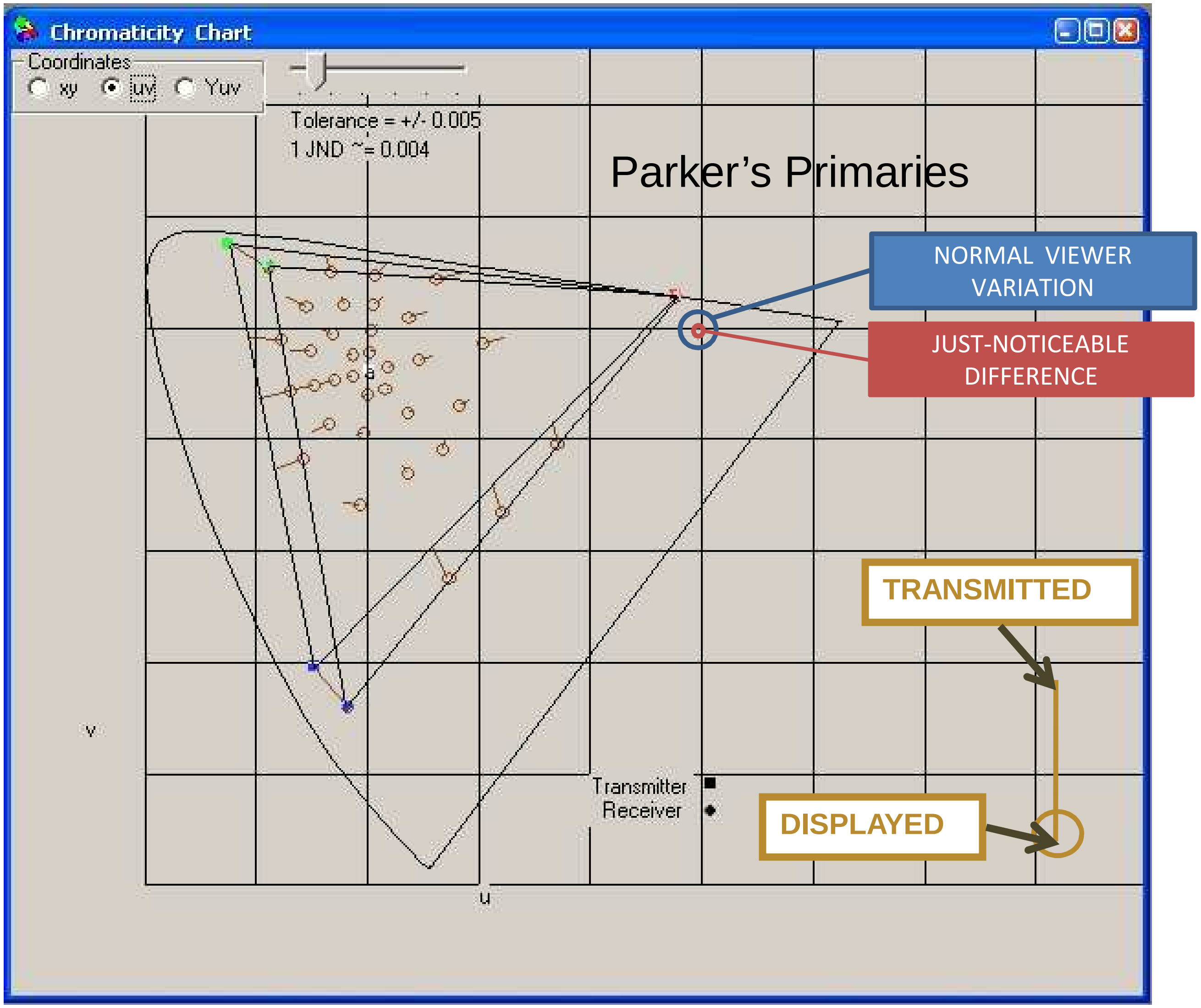
Parker's Primaries and 9300K + 27 MPCD



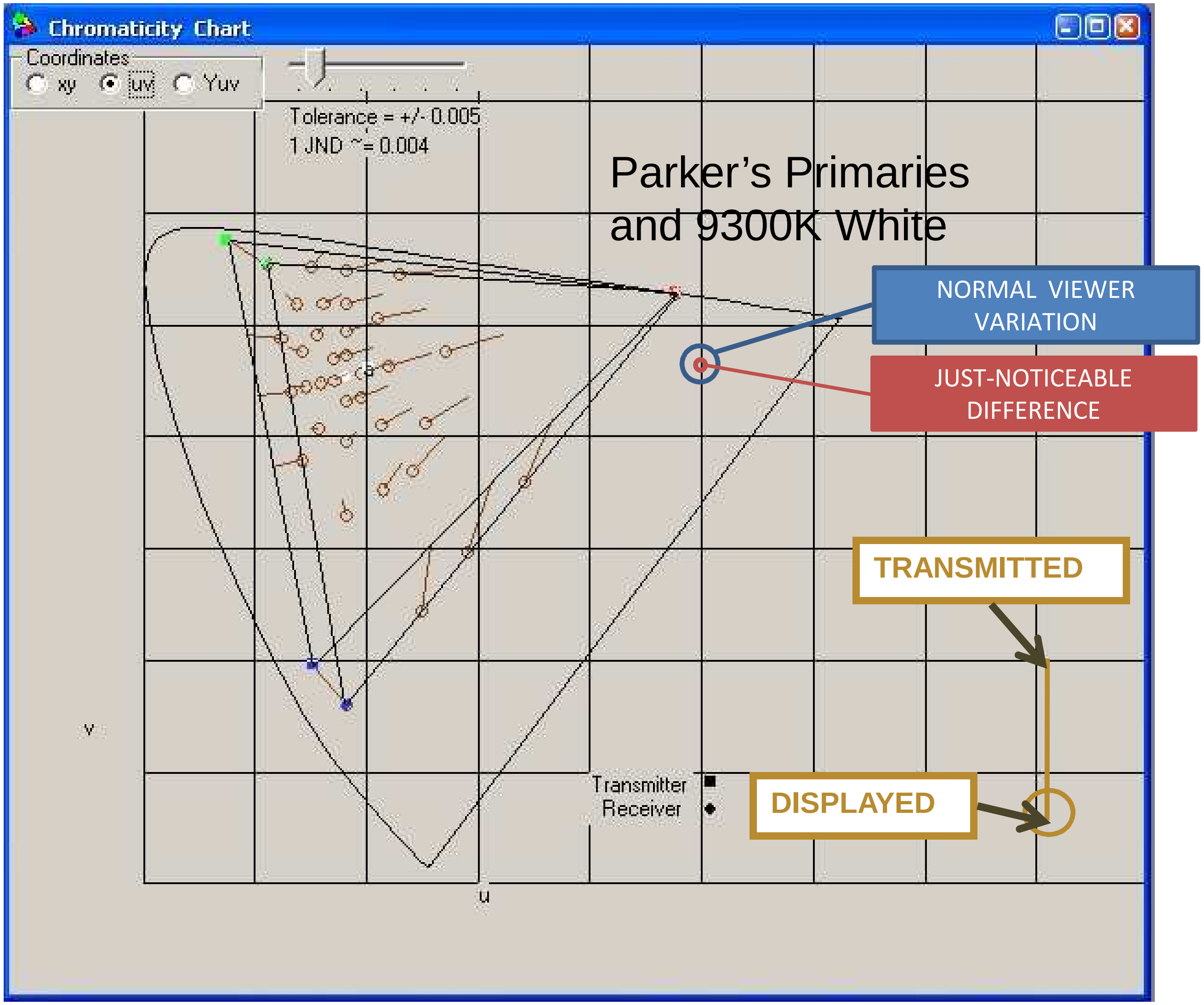
Effects of Receiver White Point and Primaries



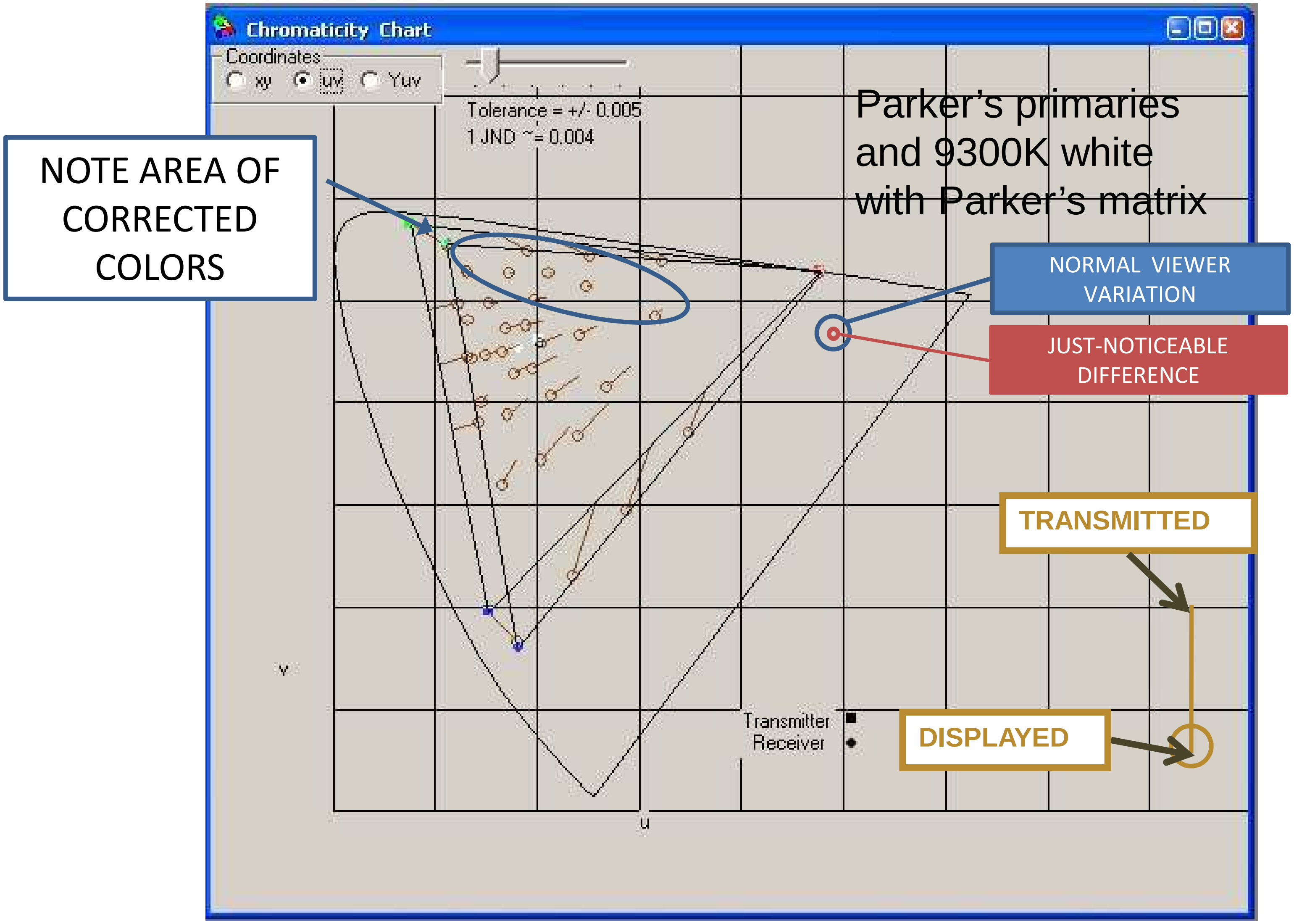
Effects of Receiver White Point and Primaries



Effects of Receiver White Point and Primaries

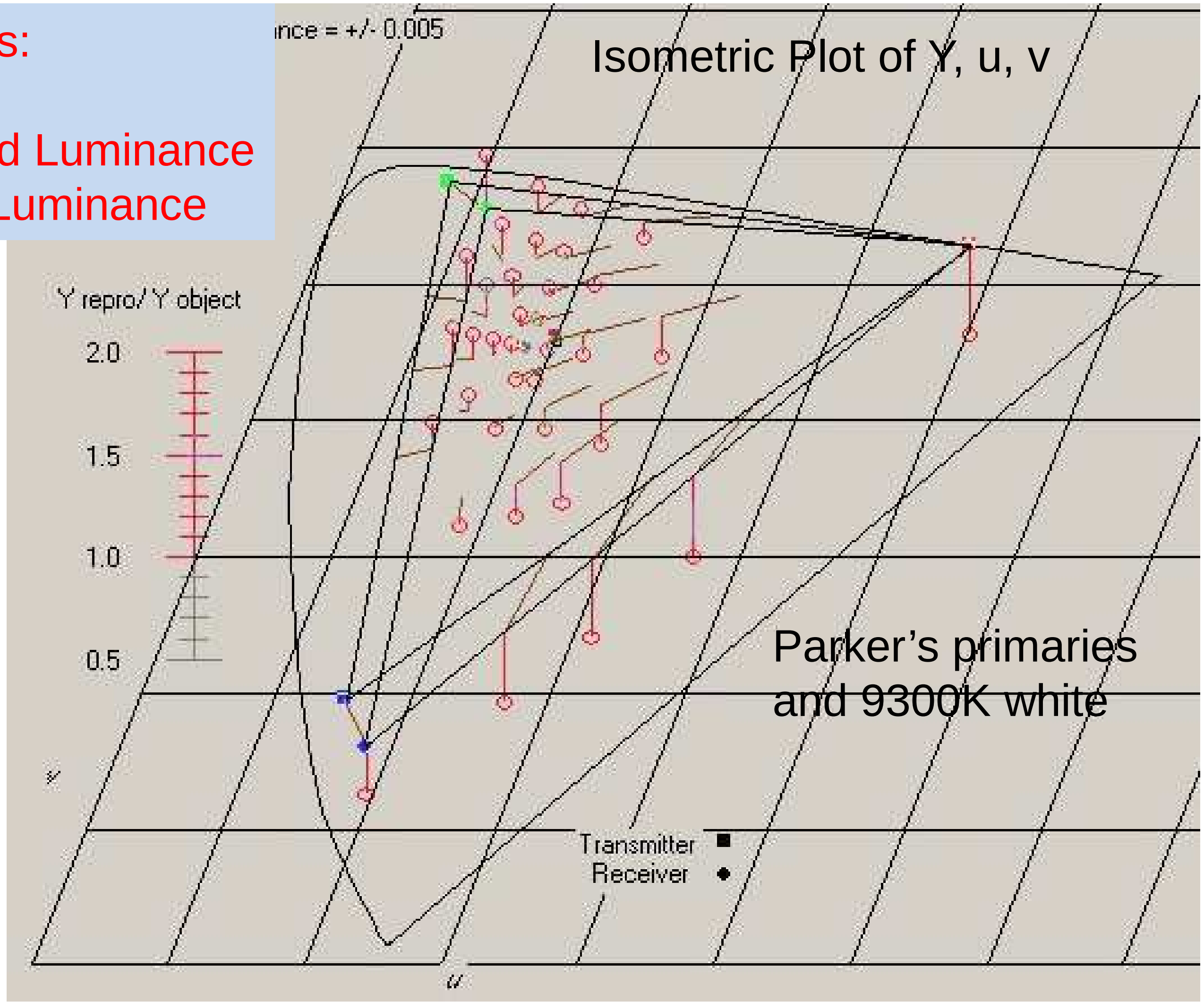


Parker's Primaries and 9300K + 27 MPCD with Parker's Correction Matrix – Assorted Colors



Effects of Receiver White Point and Primaries

Vertical Axis:
Ratio of
Reproduced Luminance
to Correct Luminance



Effects of Receiver White Point and Primaries

Vertical Axis:
Ratio of
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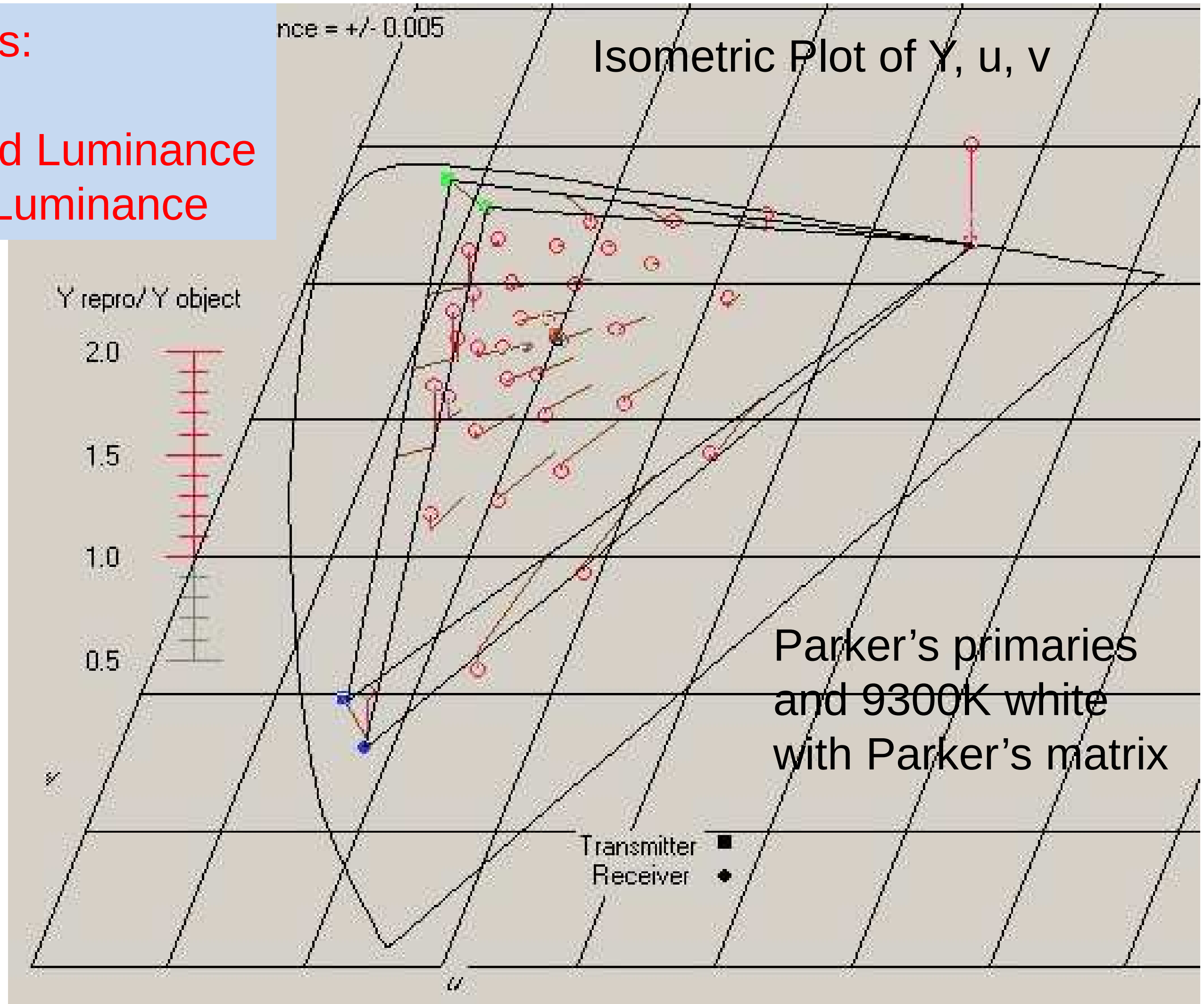
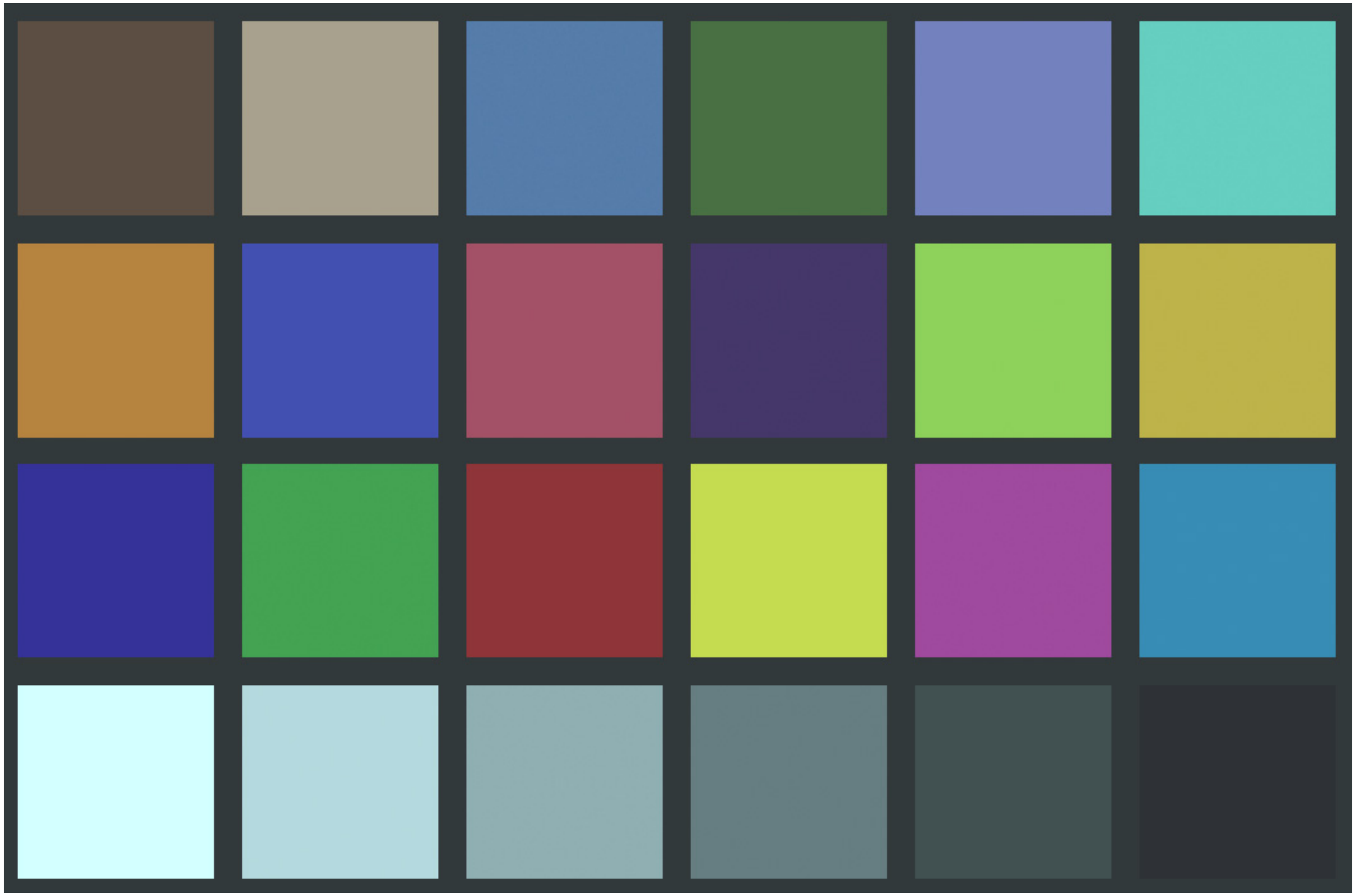
to Correct Luminance

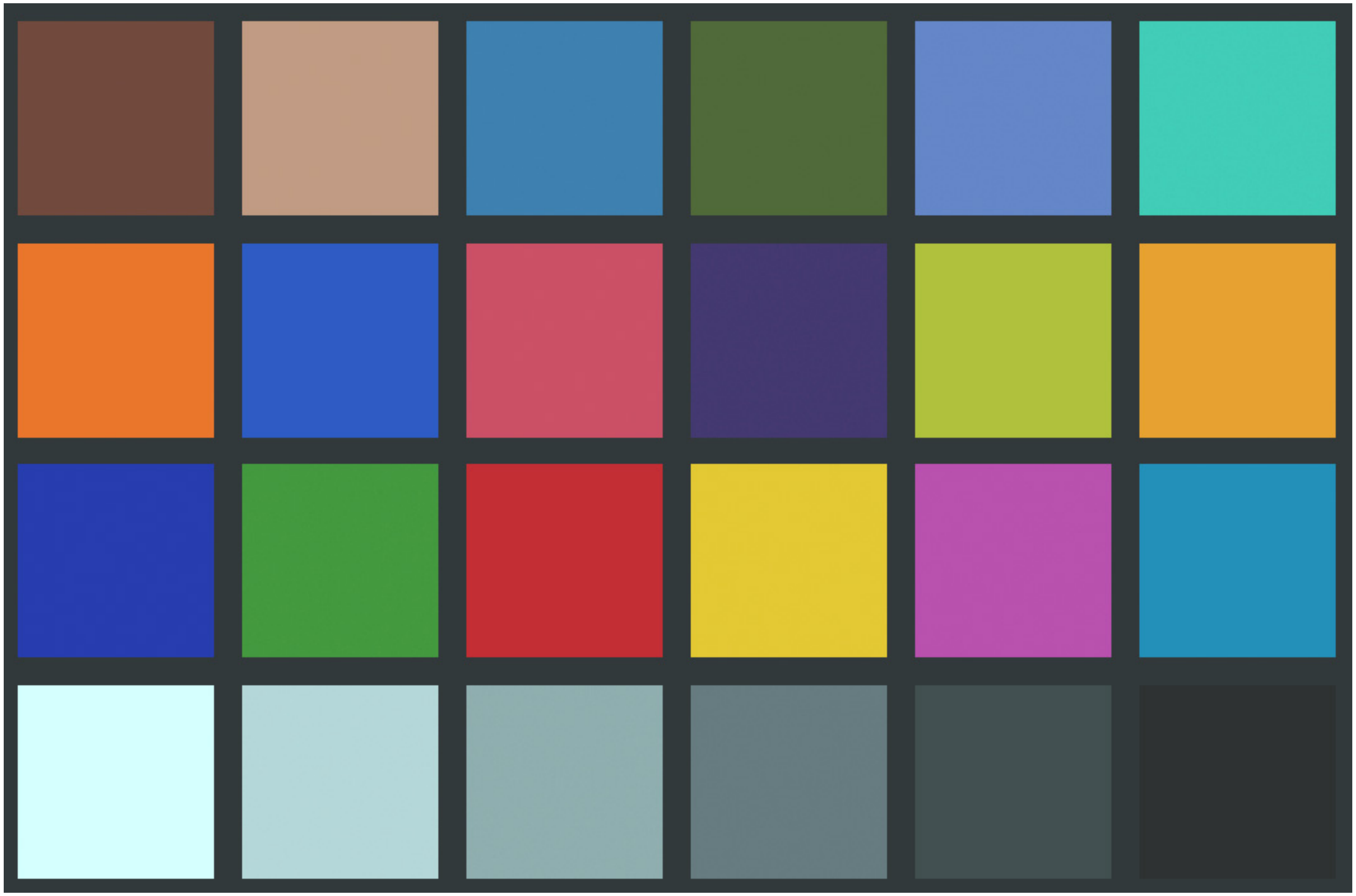


Original

Parker’s Primaries and 9300K + 27 MPCD



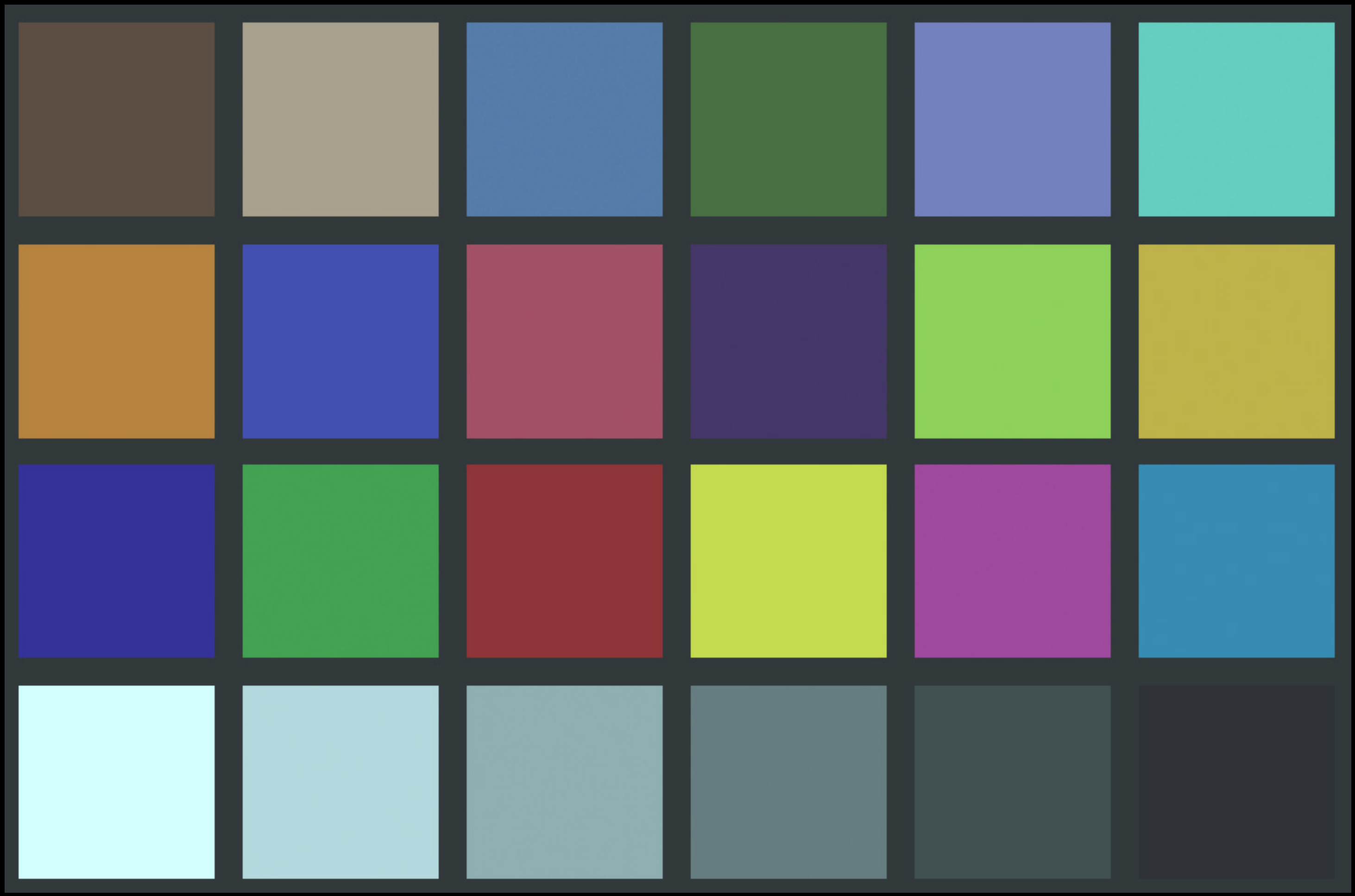
Parker's Primaries and 9300K + 27 MPCD with Parker's Correction Matrix



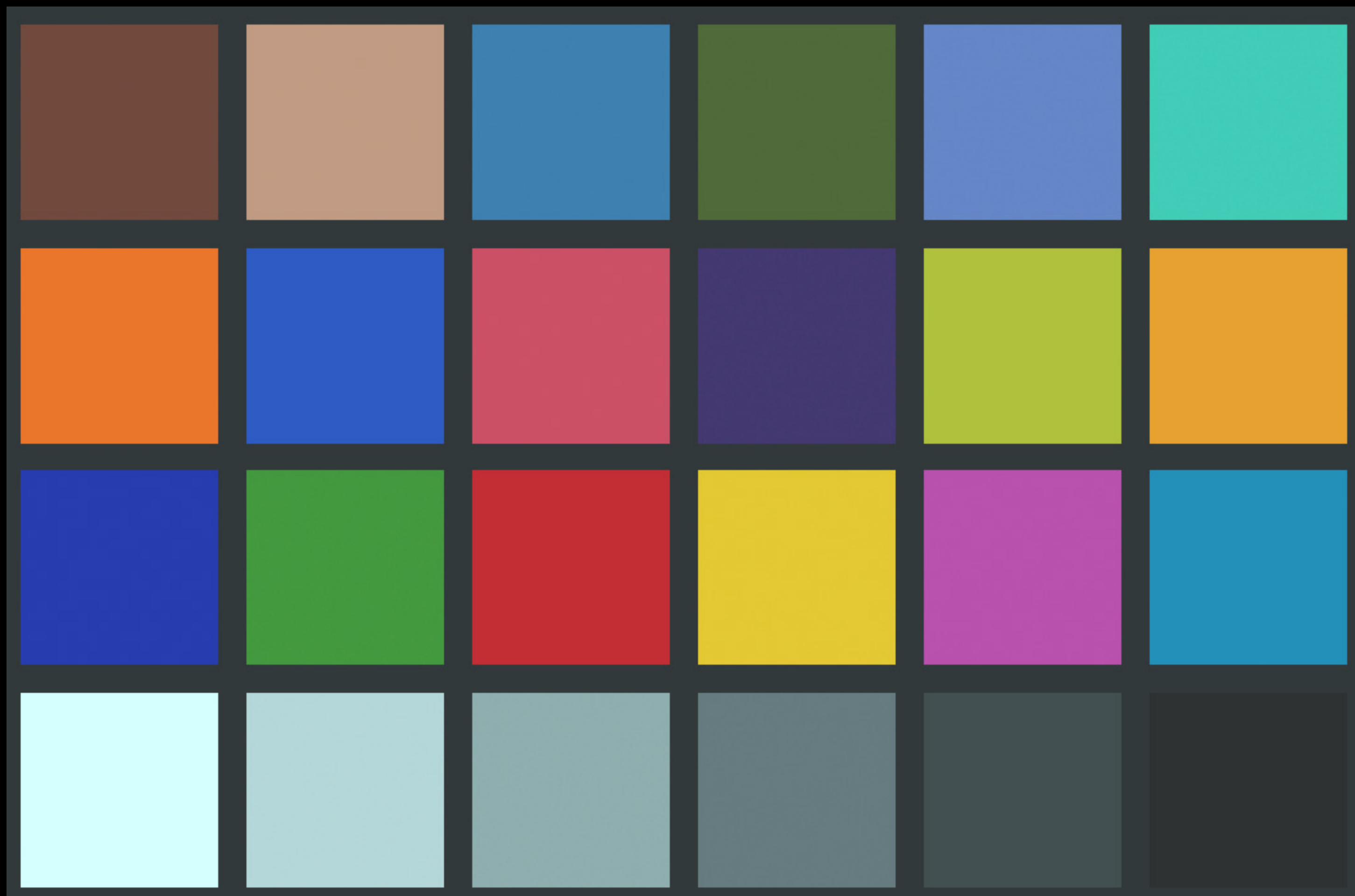
Original

Original

Parker’s Primaries and 9300K + 27 MPCD



Parker's Primaries and 9300K + 27 MPCD with Parker's Correction Matrix

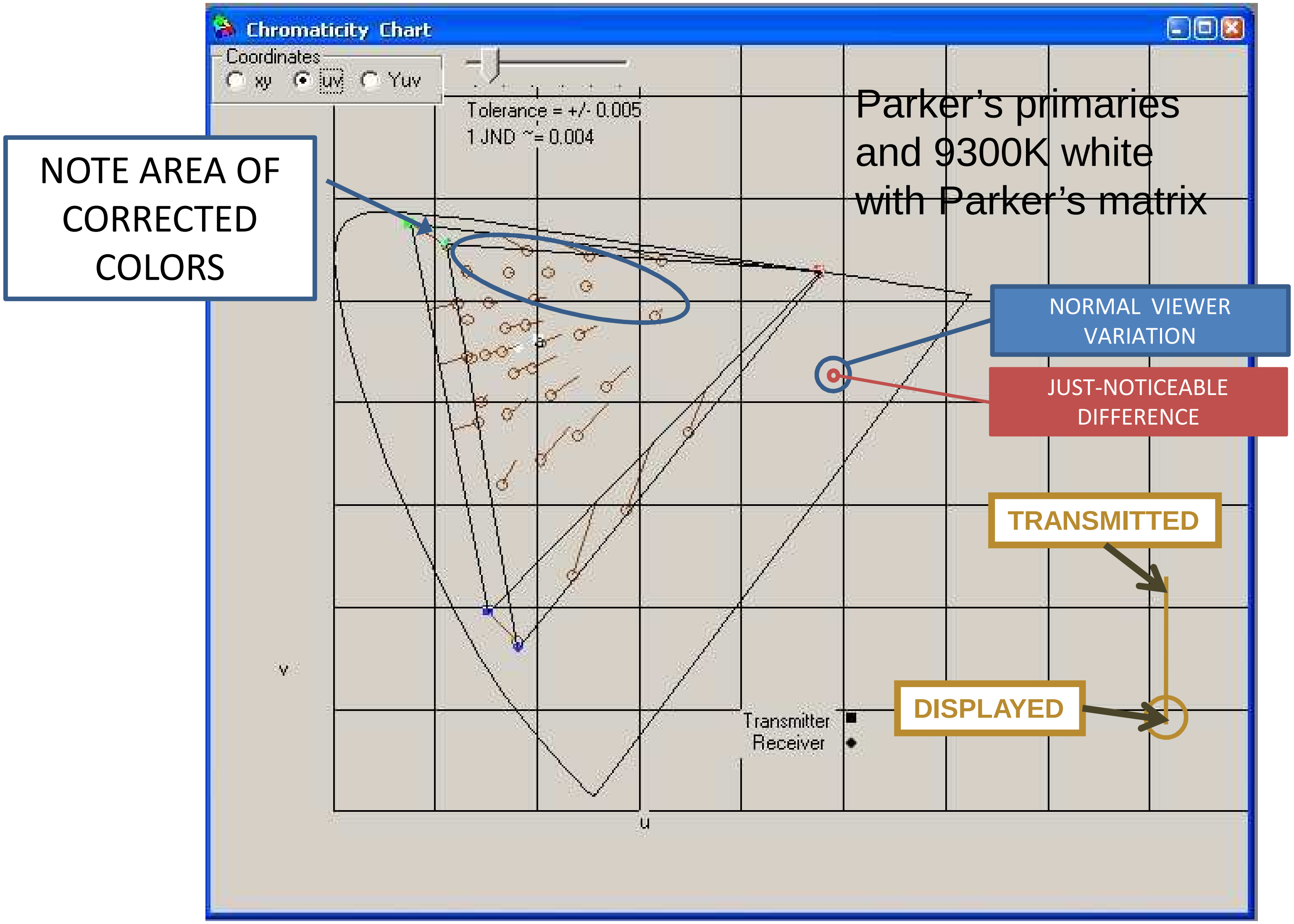


Original

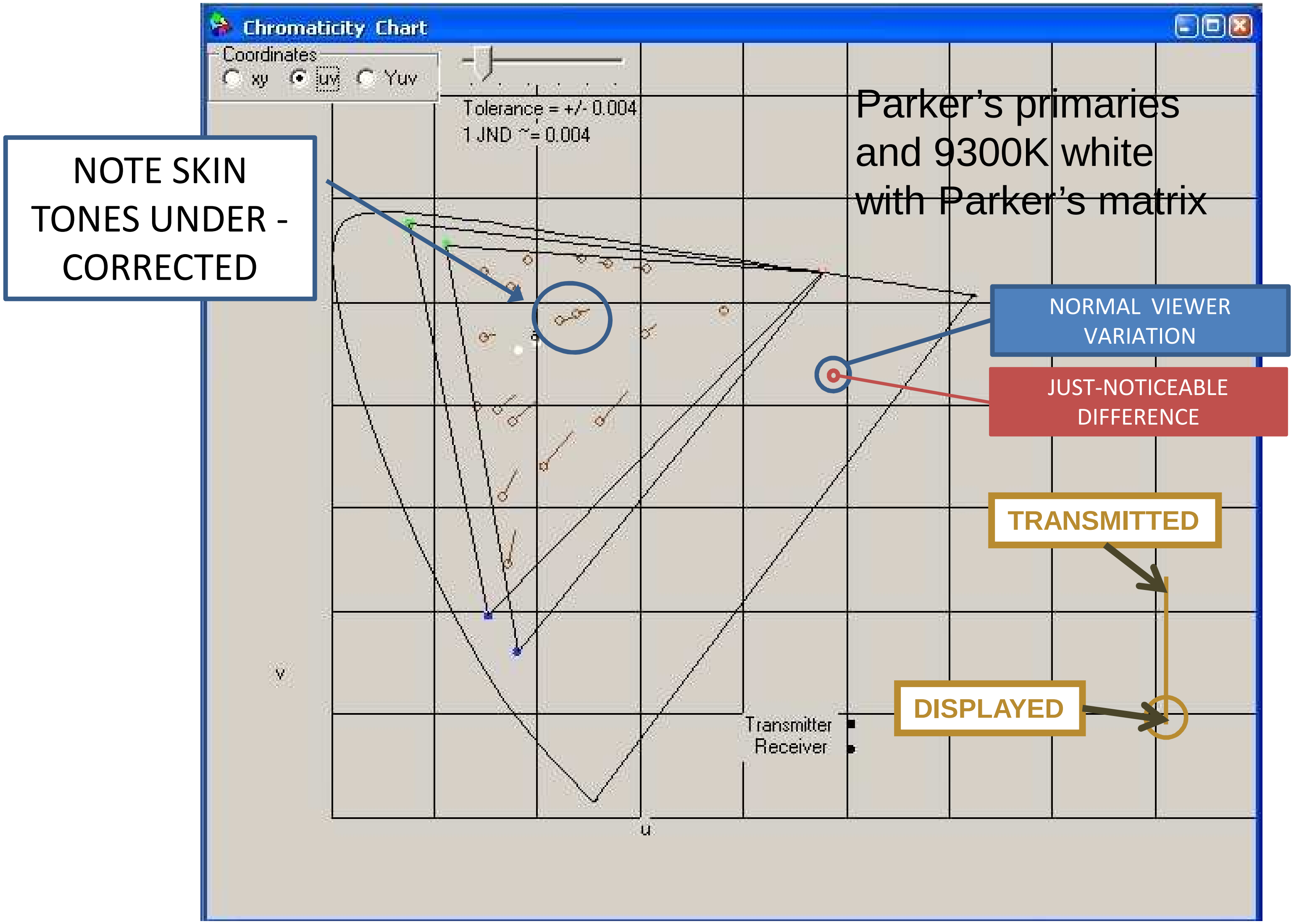
Higher-Saturation Version of Parker's Matrix

- Parker's matrix assumes skin tones that are more saturated than those on the color chart
- To correct the color chart skin tones, larger matrix terms are needed
- This increases the over-saturation and over-brightness of the more highly saturated colors, especially reds

Parker's Primaries and 9300K + 27 MPCD with Parker's Correction Matrix – Assorted Colors



Parker's Primaries and 9300K + 27 MPCD with Parker's Correction Matrix – ColorChecker Colors



Parker's Matrix vs. Higher-Saturation Matrix

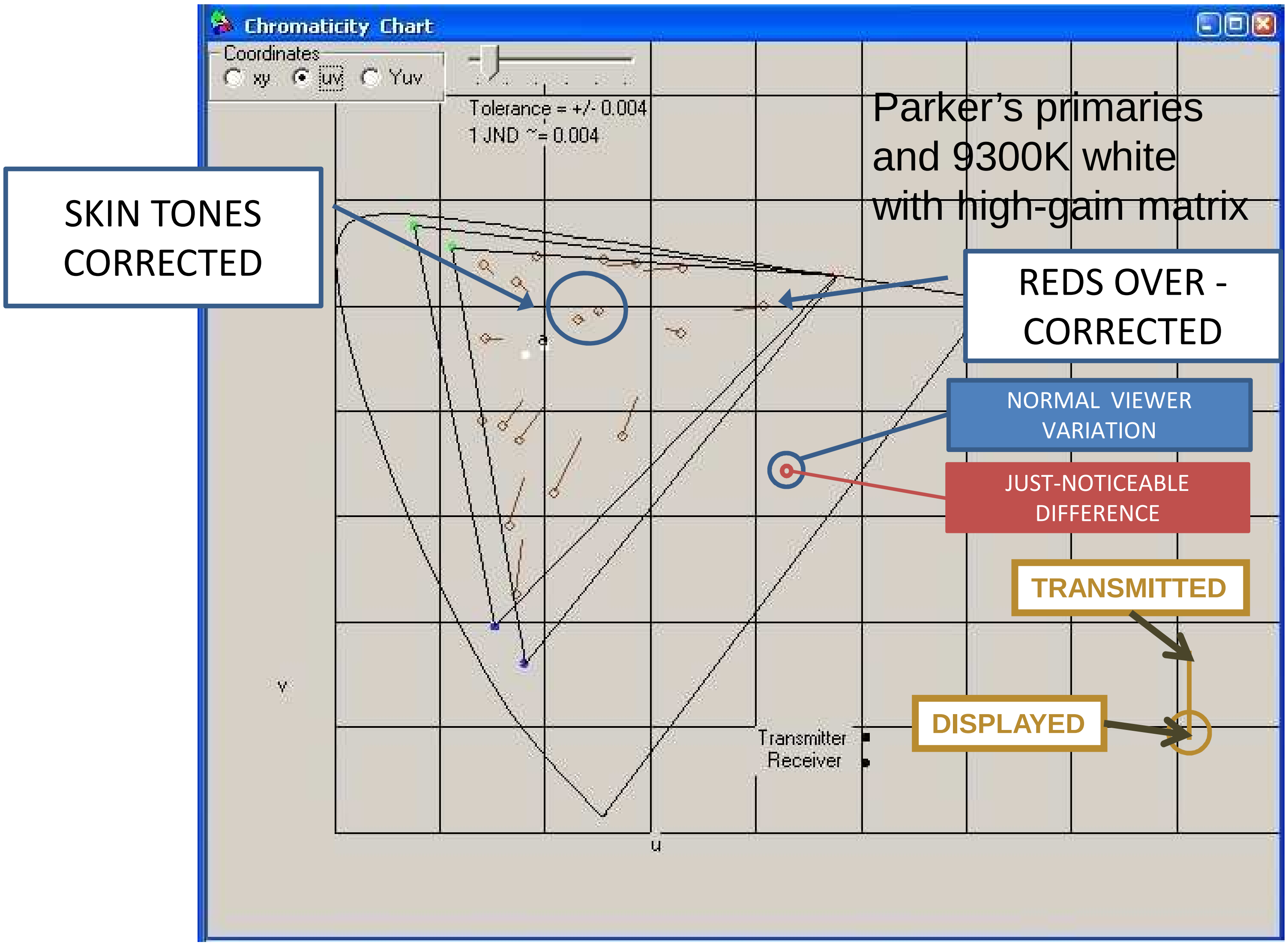
Parker's correction matrix for 9300K + 27MPCD

	Rprime=	Gprime=	Bprime=
R	1.5468	-0.0187	0.0095
G	-0.1977	0.8960	-0.2231
B	-0.3491	0.1226	1.2135

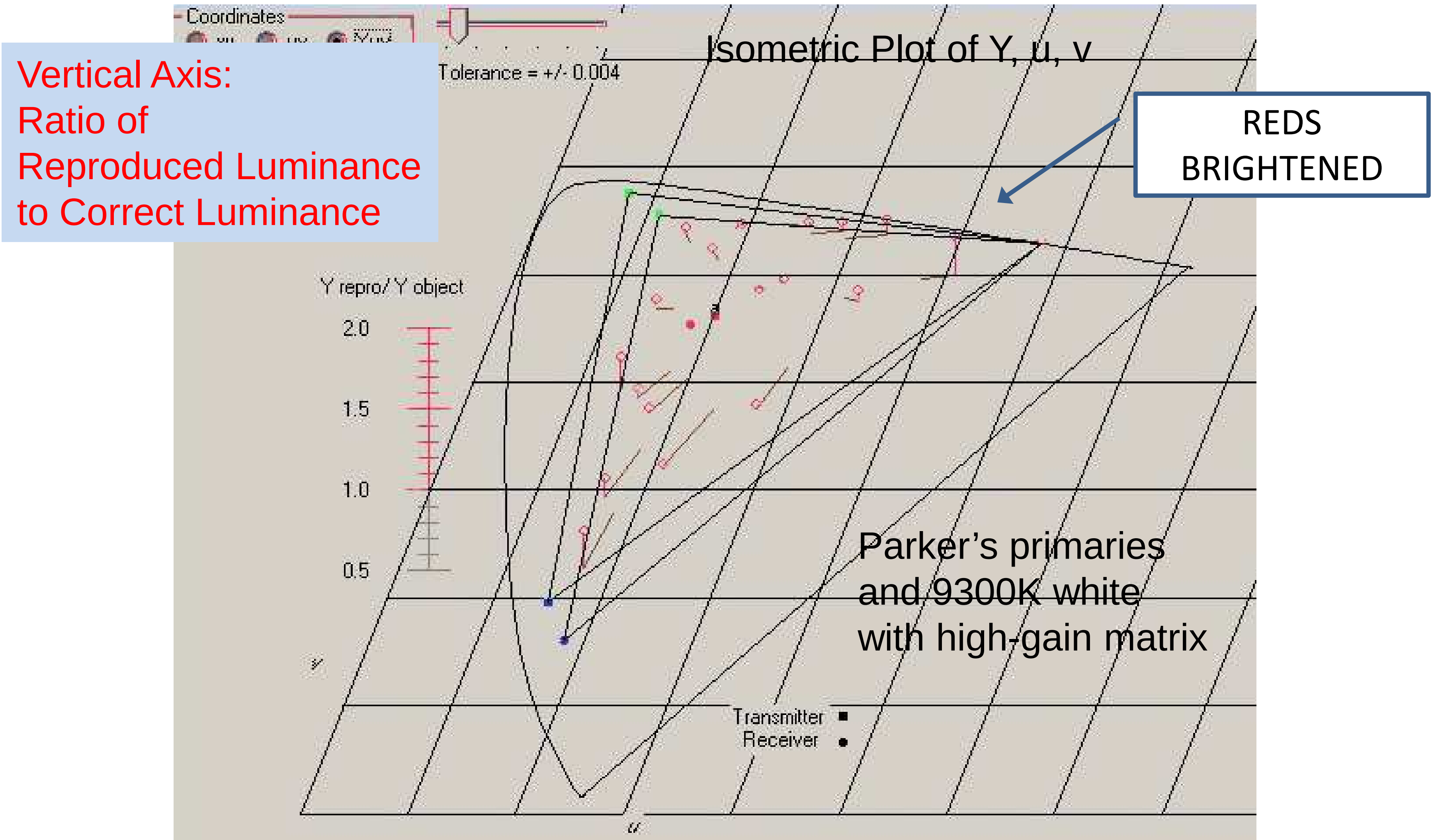
Higher-saturation correction matrix for 9300K + 27MPCD

	Rprime=	Gprime=	Bprime=
R	1.7800	-0.0812	0.0476
G	-0.3760	0.9562	-0.3827
B	-0.4036	0.1251	1.4303

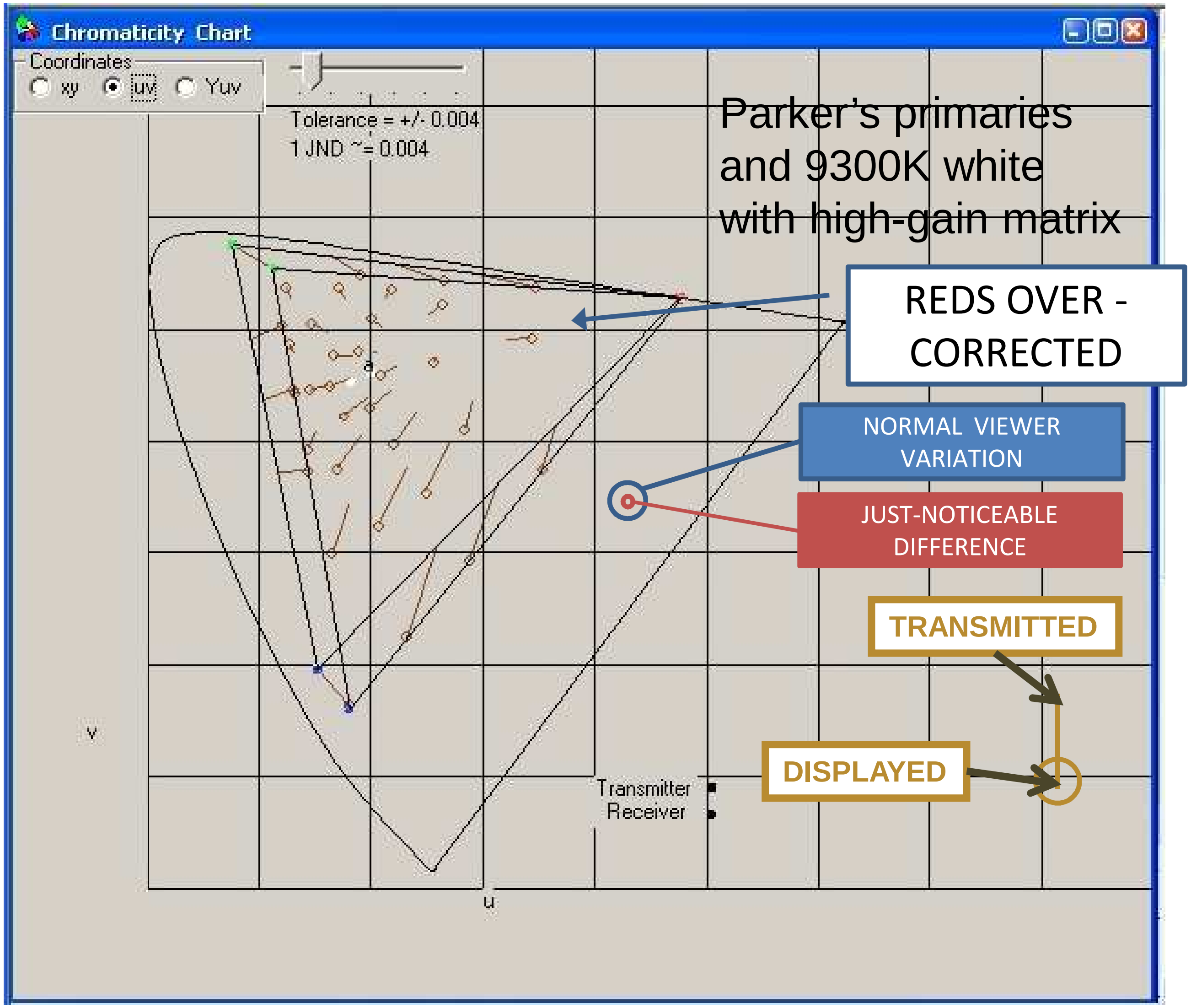
Parker's Primaries and 9300K + 27 MPCD with High-Gain Correction Matrix – ColorChecker Colors



Parker's Primaries and 9300K + 27 MPCD with High-Gain Correction Matrix – ColorChecker Colors

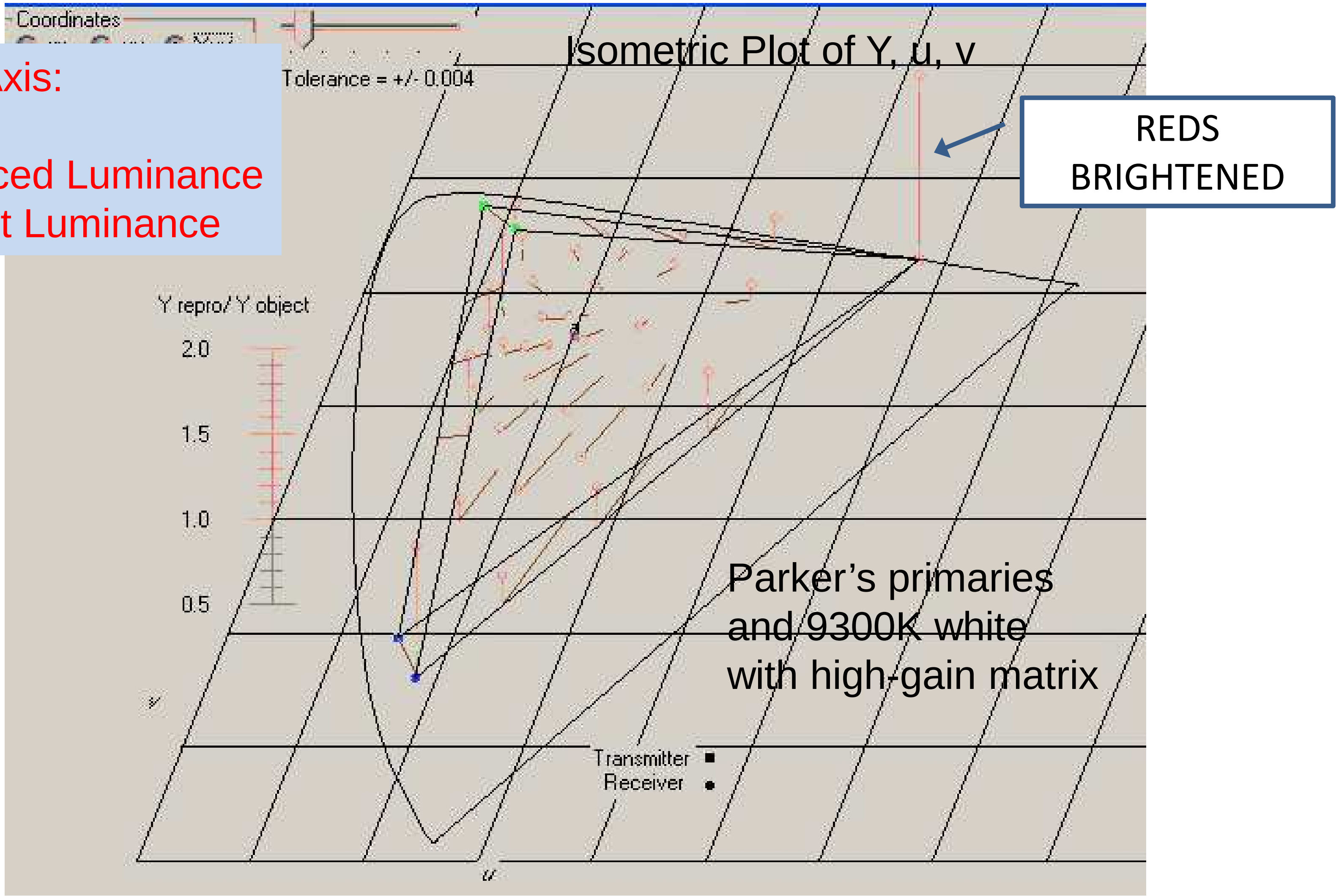


Parker's Primaries and 9300K + 27 MPCD with High-Gain Correction Matrix – Assorted Colors



Parker's Primaries and 9300K + 27 MPCD with High-Gain Correction Matrix – Assorted Colors

Vertical Axis:
Ratio of
Reproduced Luminance
to Correct Luminance



Original

Parker's Primaries and 9300K + 27 MPCD with Higher-Saturation Correction Matrix

Original

Parker's Primaries and 9300K + 27 MPCD with Higher-Saturation Correction Matrix

Vegetable Market - Original

Vegetable Market – Parker's Primaries and White

Vegetable Market - Original

Vegetable Market – Parker's Matrix

Vegetable Market - Original

Vegetable Market – High Gain Matrix

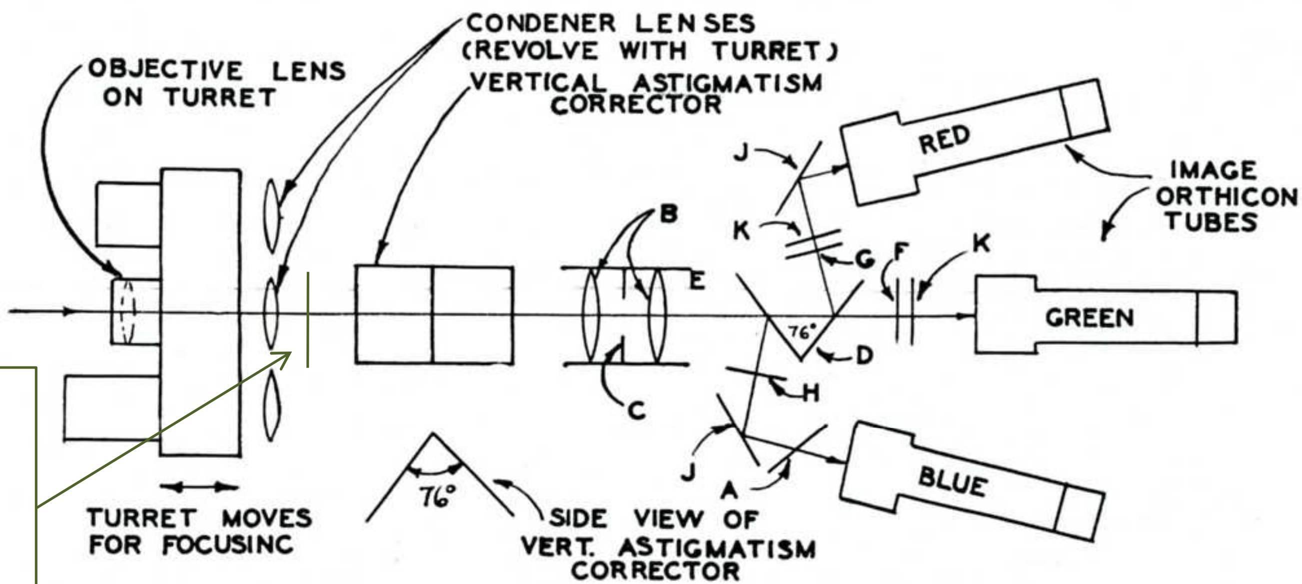
Camera Analysis

For the Remainder of this Presentation, an NTSC Standard Display is Assumed Unless Stated Otherwise

- **The following parts of this presentation generally assume an ideal NTSC display so that the effects of the early cameras' responses can be studied**
- **However - Two other early displays documented in the RCA petition to the FCC are also studied**

Image Orthicon Cameras for Color TV

Image Orthicon Color Cameras



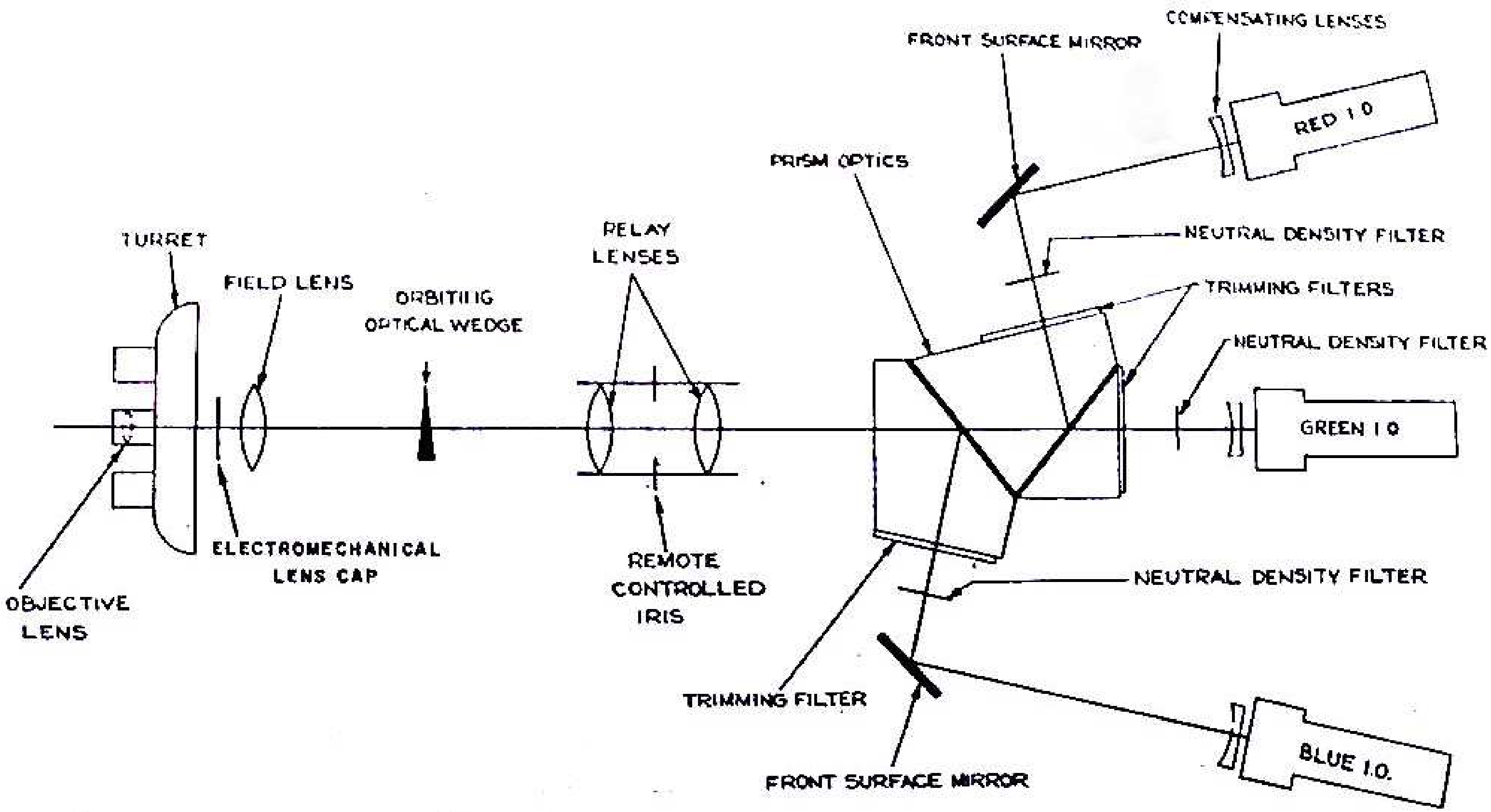
L. UV-IR FILTER (DICHROIC WITH UNSPECIFIED CUTOFFS, SHOWN IN [Ref38] AND [Ref39], SAID TO AID RED TRIMMING)

A. HOR. ASTIGMATISM CORRECTOR
B. RELAY LENSES, BOTH 9.5" F/4
C. REMOTELY-CONTROLLED IRIS
D. RED REFLECTING DICHROIC
E. BLUE REFLECTING DICHROIC
F. GREEN TRIMMING FILTER
G. RED TRIMMING FILTER
H. BLUE TRIMMING FILTER
J. FRONT-SURFACE MIRRORS
K. NEUTRAL-DENSITY FILTERS

Fig. 9 — Sketch of the optical system used in an RCA three-tube color television camera.

- **Pre-Production, 1949-1953, and Early Production Dichroic Plate Optics**

Image Orthicon Color Cameras

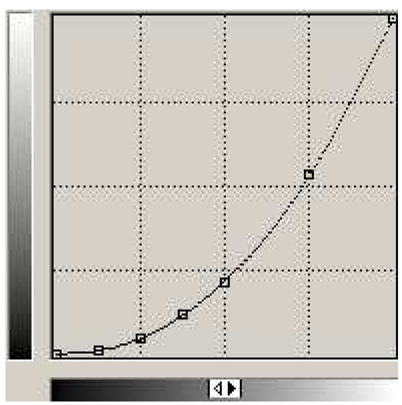


- **Later Production, Dichroic Prism Optics**

Gamma Correction and Noise

Gamma Correction Basics

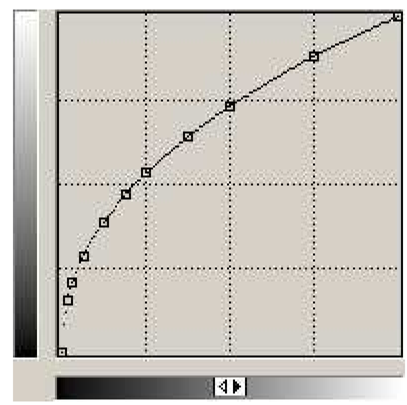
- Gamma (γ) is the exponent in the function that describes the beam current (hence brightness) in a CRT as a result of the video voltage input: $I = V^{\gamma}$
- Gamma *correction* is the inverse: $V = L^{(1/\gamma)}$
  and is applied in the camera to each primary channel



CRT Gamma

Note NTSC specification $\gamma = 2.2$

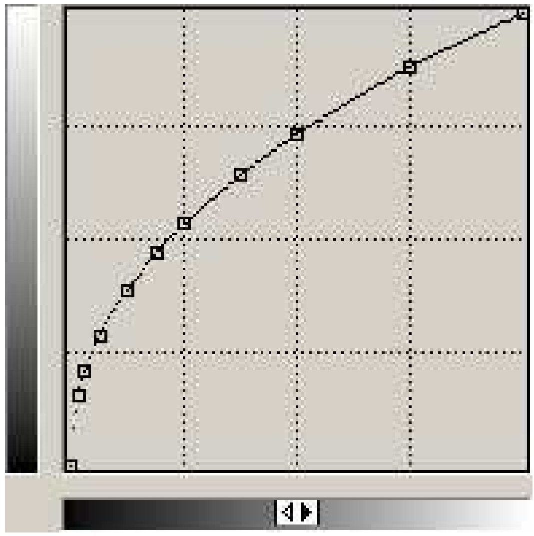
(Linear scales)



Gamma Corrector

Problems with Gamma Correction

- The "ideal" gamma corrector has infinite gain at black (impossible!)

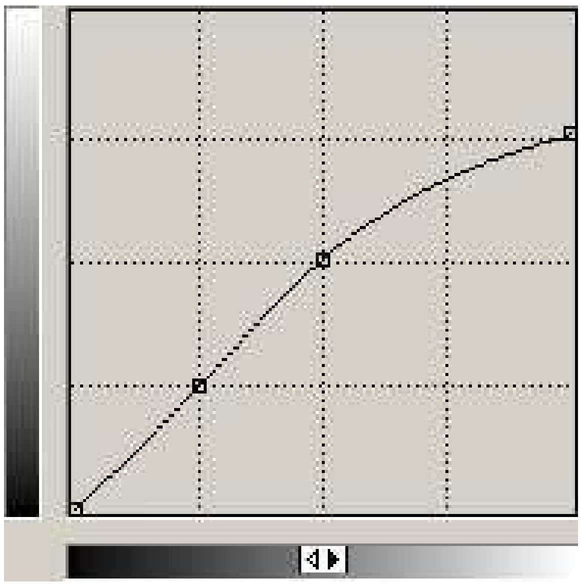


•Limiting the gain sets an implicit limit on contrast ratio of the system, since video below a certain level will be attenuated by the CRT gamma
•Even with limited gain, pickup device noise is amplified in the lowlights
•Noise obscures the shadow detail
•Noise is partially rectified and raises the black level

TK-41 Gamma Correction

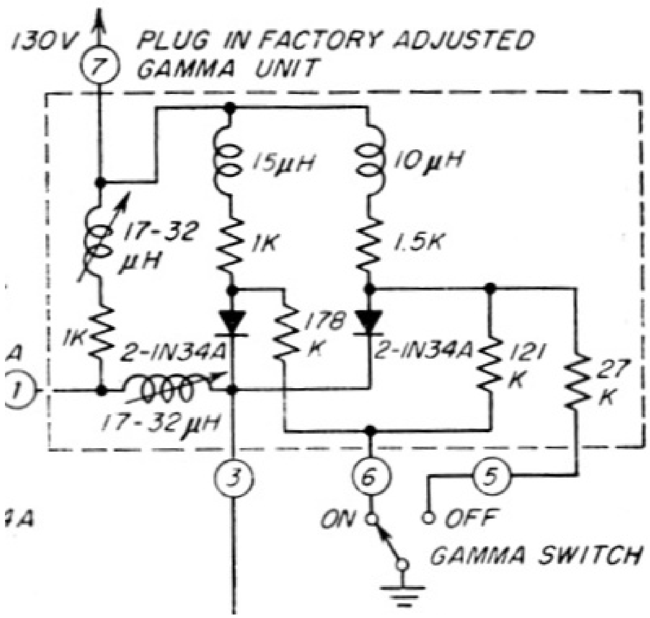
- Obtain some highlight correction from the image orthicon operating conditions (later abandoned)
- Correct electrically for $\gamma = 1.4$ instead of 2.2, to limit noise amplification
- Use a 2-break-point approximation in the electronic circuit

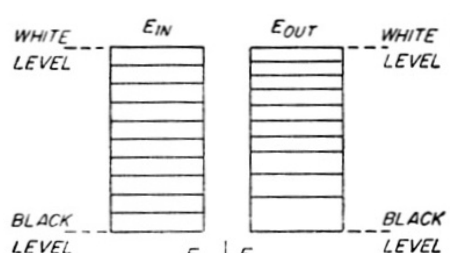
TK-41 Gamma Correction – Highlight Compression



- Highlight compression effect of image orthicon with target voltage = 2V
- Next, add some gain to bring maximum back to 100%
- This target compression was abandoned early on, and the target was set to 4V (no compression)

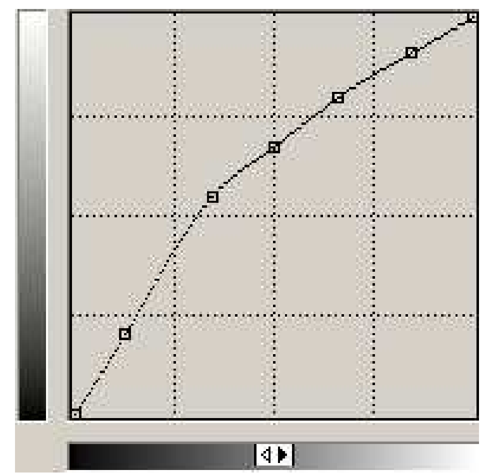
TK-41 Gamma Correction





E_{IN}	E_{OUT}
0.1	0.196
0.2	0.321
0.3	0.428
0.4	0.523
0.5	0.612
0.6	0.697
0.7	0.777
0.8	0.854
0.9	0.928
1.0	1.0

FIG. 17-75. Oscilloscope waveform pattern for power-law curve of 0.707.



Non–linear load
Two break points: 33% and 66%
Gain slopes 1:6, 0.8, 0.6

Aim: $\gamma = 1.4$
(Poor approximation near black)

Curve obtained:
Max slope = 1.6

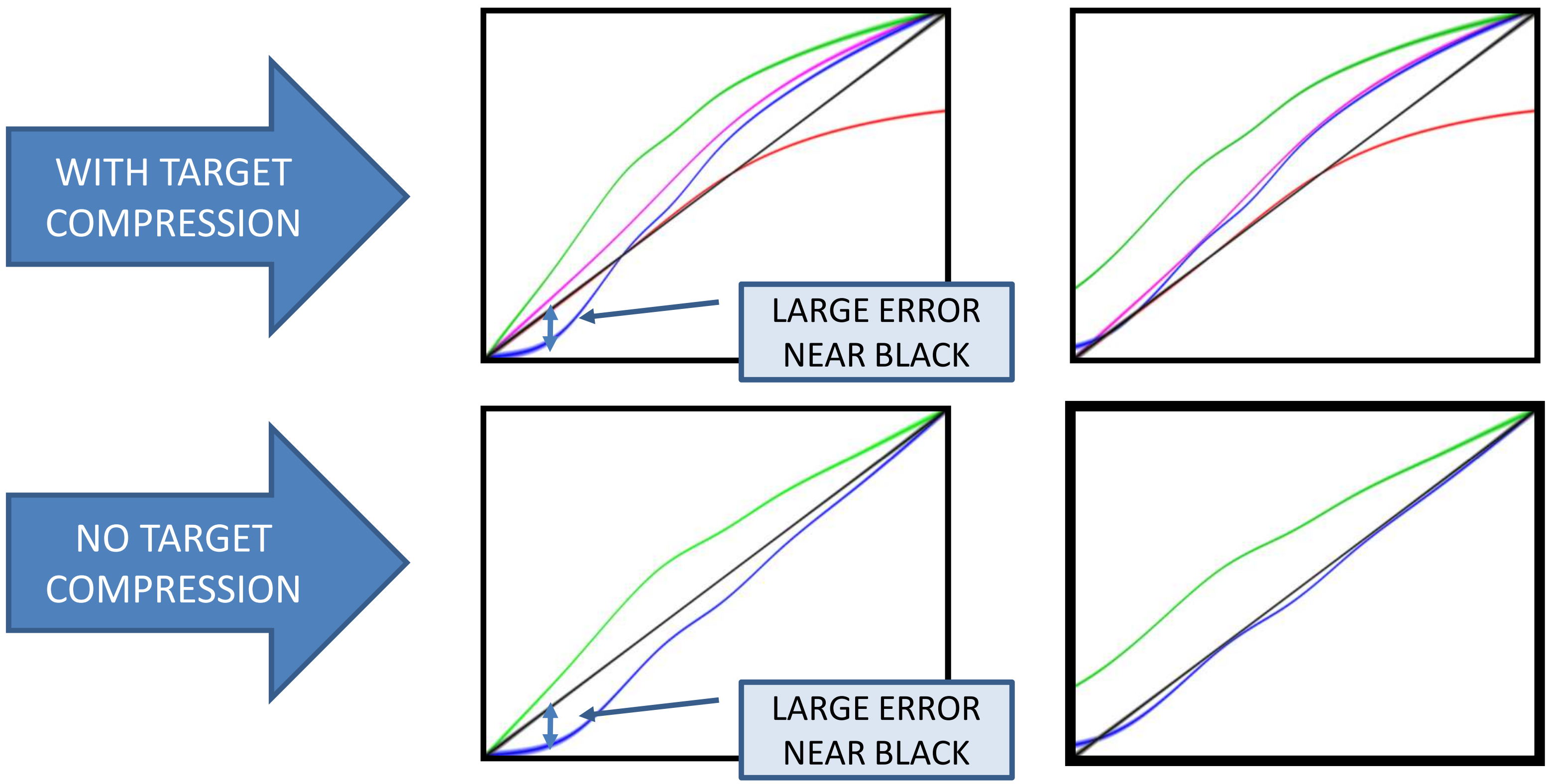
TK-41 Gamma Correction

- The combination of image orthicon highlight compression and the non-linear amplifier gives a maximum slope of 1.6/0.75 = 2.13
  - This compensates for the CRT at a level where its slope is 1/(2.13) = 0.469
  - This implies the video signal is 0.276 and the light output is $(0.276)^{2.2}$ = 0.0589
  - The system contrast range (for output roughly proportional to input) then is:
    1 / 0.0589 = **17:1**
- Note: modern systems (with much lower-noise cameras) typically specify a gamma correction curve that gives a system contrast ratio of several hundred – e.g., sRGB max slope = 12.92; implies contrast ratio = **462:1**

Making it Work

- The 0.707 power transfer function and 17:1 contrast ratio implied by the TK-41 circuit would not produce good pictures - images would look too dark
- Lifting the black level (an adjustment that was readily available to the video engineer) provides a much better reproduction of highlights and midtones, with some fogginess in the lowlights
- The author surmises this was the actual operating condition

Cascaded Gamma Correction Stages



RED: TARGET COMPRESSION

MAGENTA: TARGET COMPRESSION + GAIN COMPENSATION

GREEN: FOLLOWING TK41 GAMMA CORRECTOR

BLUE: FINAL CRT OUTPUT

WITH BLACK LIFT

NOTE

Chart scales are linear

Original

Original

TK-41 – Gamma Corrector OFF

Linear Camera (Without Gamma Correction) and No Added Noise

TK-41 – Gamma Corrector OFF, Noise Added

Linear Camera with 31 dB SNR

TK-41 – Highlight Compression, Noise Added

Camera with Target Voltage = 2 V and 31 dB SNR

TK-41 – Highlight Compression, Gain Restored, Noise Added

Camera with Target Voltage = 2 V, gain restored and 31 dB SNR

TK-41 – Highlight Compression, Gain Restored, Noise Added, Gamma Corrector ON

Camera with Target Voltage = 2 V and 31 dB SNR
Nominal Black Level and TK-41 Gamma Corrector Circuit

TK-41 – Highlight Compression, Gain Restored, Noise Added, Black Level Lifted 10%, Gamma Corrector ON

Camera with Target Voltage = 2 V and 31 dB SNR
plus 10% Black Lift and TK-41 Gamma Corrector

Original

Original

TK-41 – Improved Image Orthicon – Highlight Compression, Noise, 10% Black Lift, Gamma Corrector ON

Camera with Target Voltage = 2 V and 36 dB SNR (Tube Type 6474) plus 10% Black Lift and TK-41 Gamma Corrector Circuit

Original

Original

TK-41 –Linear Highlights, Noise, Black Lift, Gamma Corrector ON

Camera with Target Voltage = 4 V and 31 dB SNR (Tube Type 5820) plus 10% Black Lift and TK-41 Gamma Corrector Circuit

TK-41 – Improved Image Orthicon –
Linear Highlights, Noise, Black Lift, Gamma Corrector ON

Camera with Target Voltage = 4 V and 36 dB SNR (Tube Type 6474) plus 10% Black Lift and TK-41 Gamma Corrector Circuit

Original

Original

Higher-Gain Gamma Correction - 31 dB SNR

Linear Camera with 31 dB SNR and
Gamma Corrector with Max Slope of 9.75 (Contrast Ratio = 276:1)

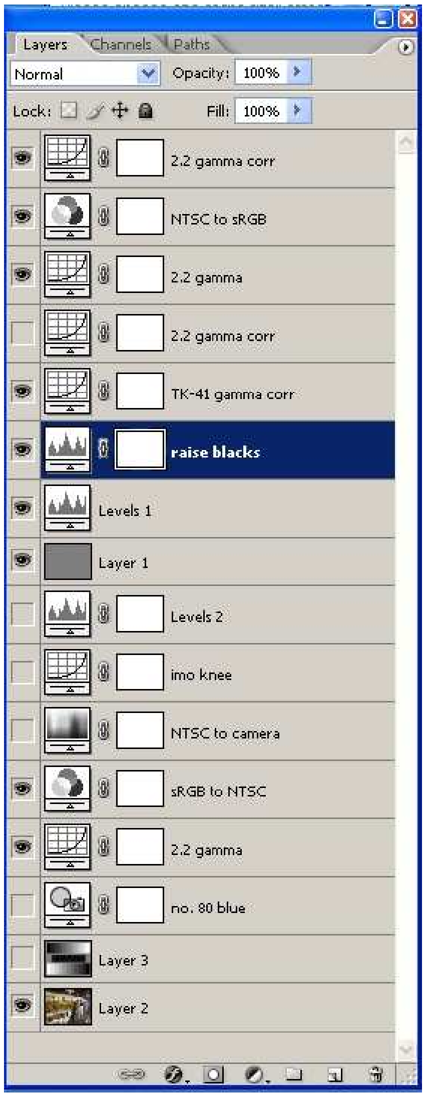
Higher-Gain Gamma Correction
Improved Image Orthicon – 36 dB SNR

Linear Camera with 36 dB SNR and
Gamma Corrector with Max Slope of 9.75 (Contrast Ratio = 276:1)

Original

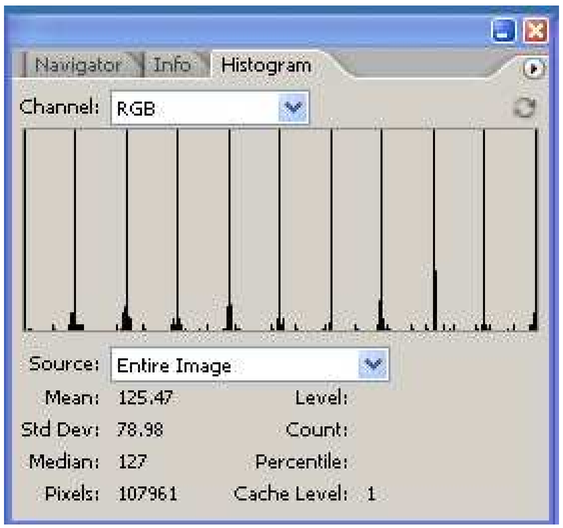
Original

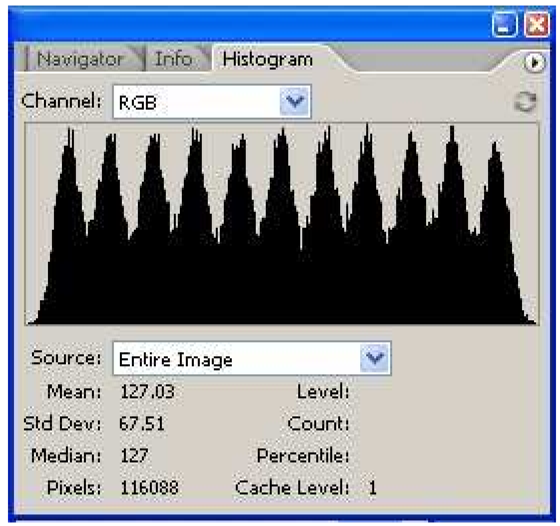
Simulation Technique – Photoshop Layers

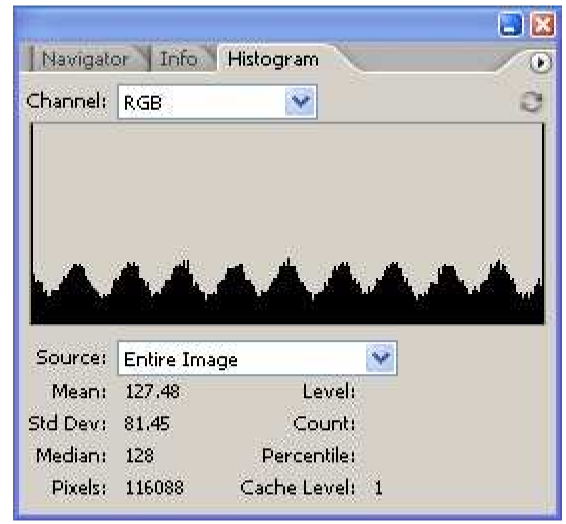


← 1/(2.2) gamma correction curve for sRGB output
← NTSC to sRGB matrix (channel mixer)
← 2.2 power curve of NTSC CRT
← 1/(2.2) gamma correction curve may be substituted for TK-41 curve
← TK-41 gamma correction curve
← Black lift prior to TK-41 gamma correction curve
← Restore image contrast lost due to noise layer opacity
← 127 mid-gray with 15% Gaussian noise – opacity 10% or 16% to vary noise
← Peak-to-Peak gain restoration for target compression
← Image orthicon target compression curve
← Approximate NTSC to Camera (Hue, Saturation, Lightness adjustments)
← sRGB to NTSC matrix (channel mixer)
← 2.2 power curve to linearize sRGB input
← Color balance filter if required
← Substitute grayscale image for histograms
← Base image (sRGB)

Histograms
Generation of Noise in Photoshop

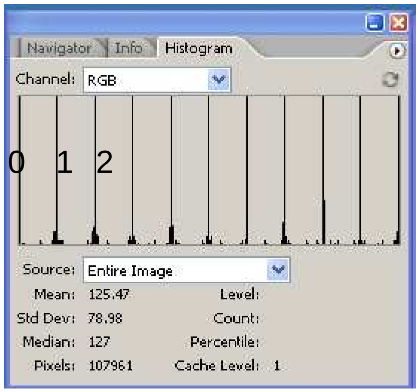


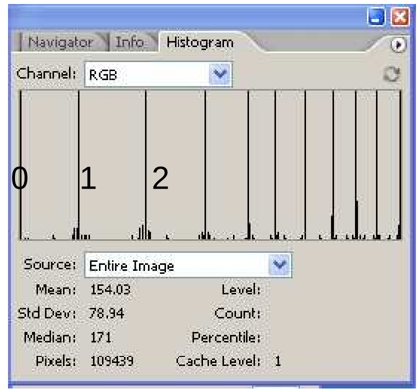


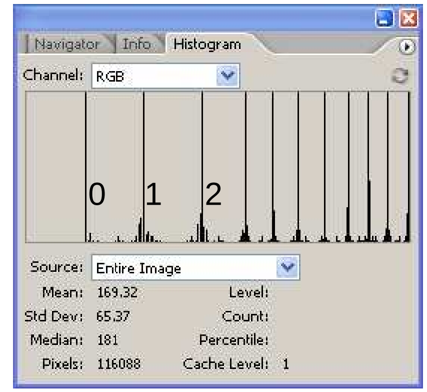


11-Step Grayscale → With 15% Noise Layer, 16% Opacity → With Level Adjustments SNR = 35:1 = 31 dB

Histograms

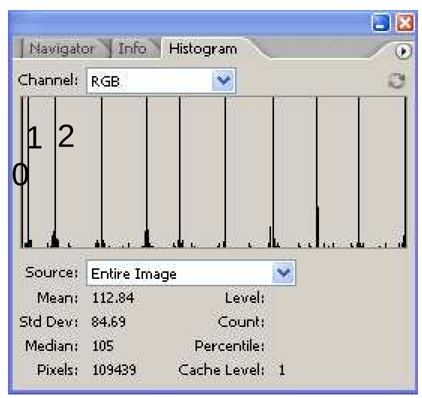


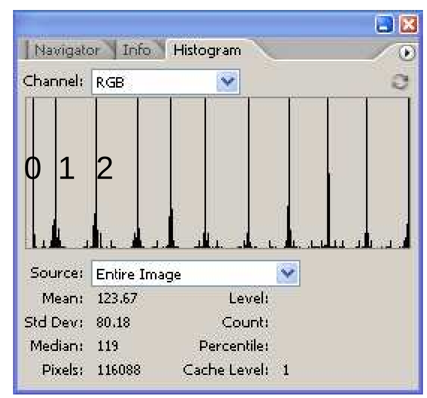




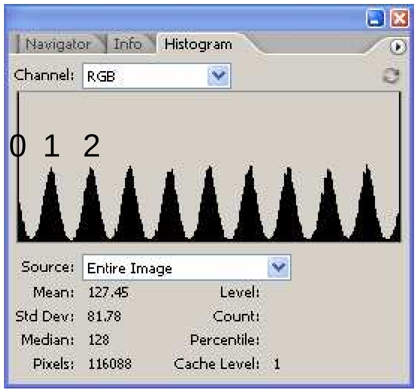
11-Step Grayscale → With TK-41 circuit → With TK-41 circuit + black lift

CRT Output →

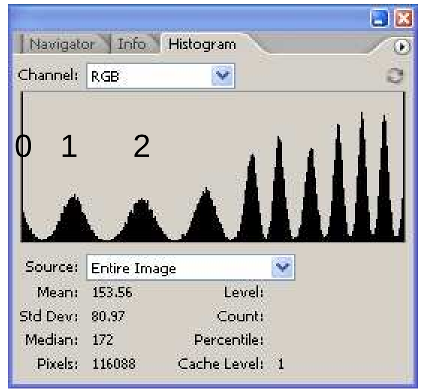




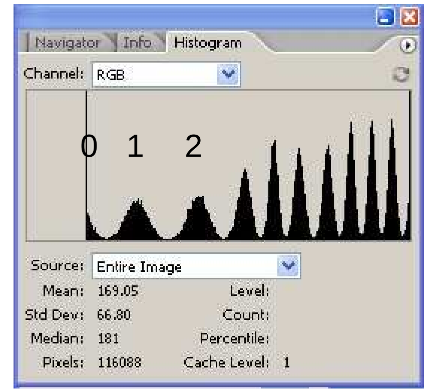
Histograms



11-Step Grayscale
with Noise
SNR = 36 dB

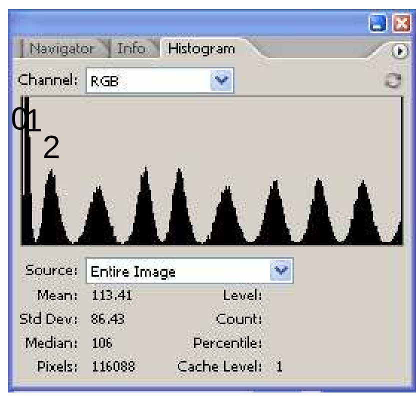


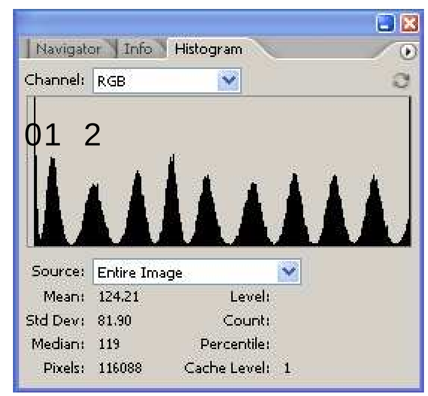
With TK-41 circuit



With TK-41 circuit
+ black lift

CRT Output →



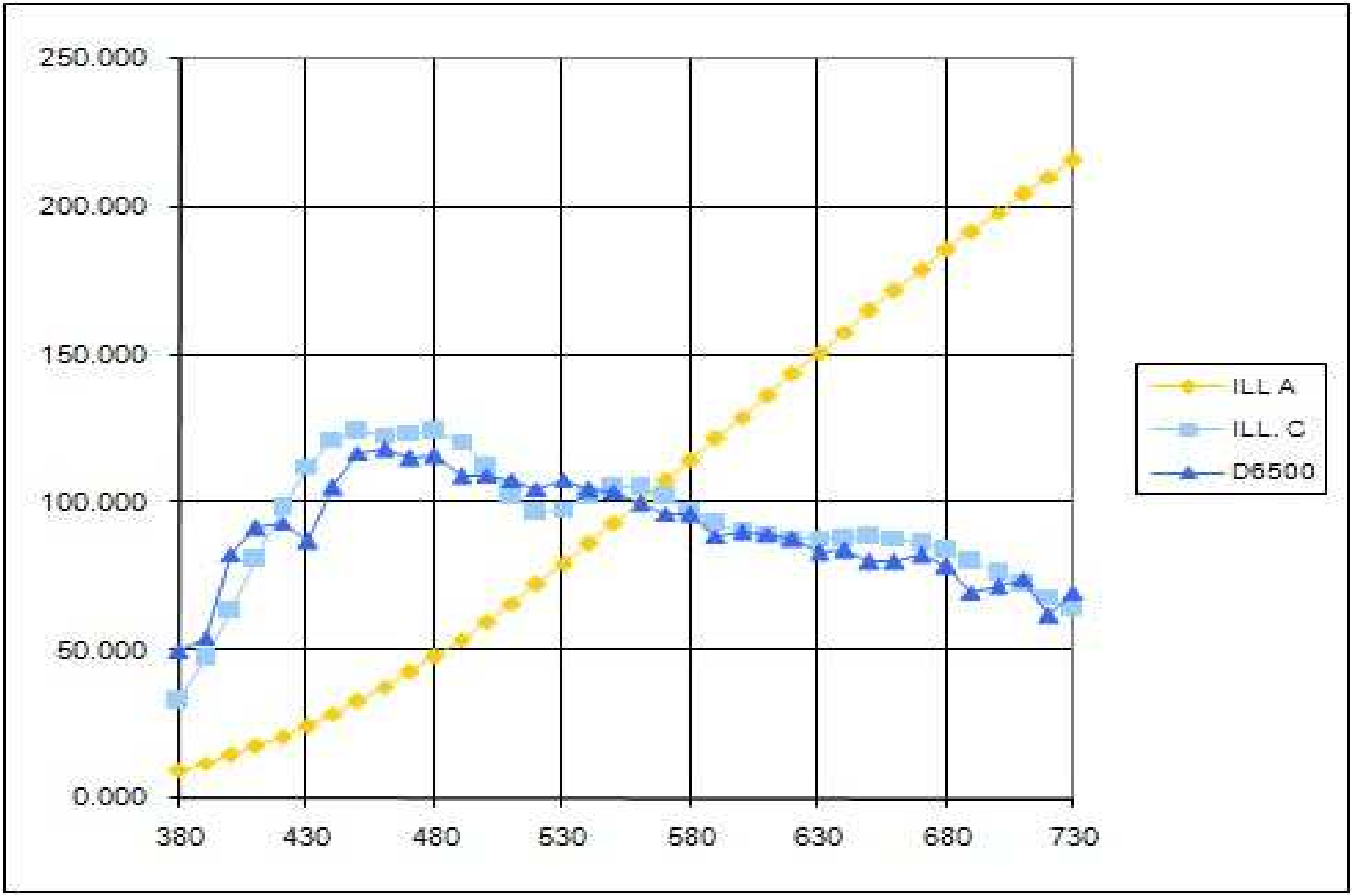


Analysis of Color Reproduction

Assumptions for Color Analysis

- **Illumination - Illuminant C**
  - **NTSC hypothetically should reproduce objects as seen under Illuminant C**
  - **Avoid the question of illuminant effects, study that separately**

Standard Illuminants

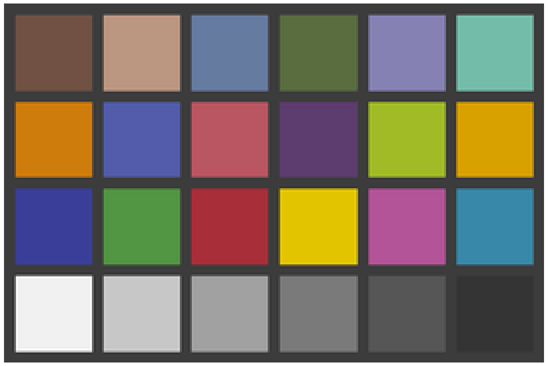


Sources of Camera and System Data

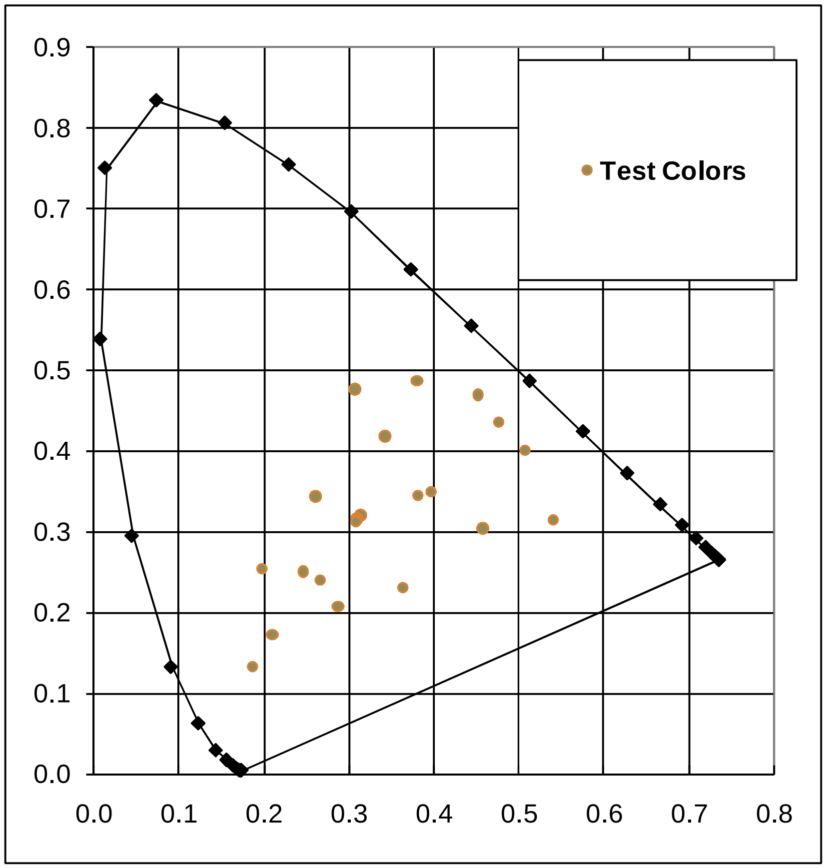
- "Red Book" - *Before the Federal Communications Commission, Washington D.C., Petition of Radio Corporation of America and National Broadcasting Company, Inc. for Approval of Color Standards for the RCA Color Television System*, June 25, 1953
- Color Television Engineering, John W. Wentworth, McGraw-Hill Book Company, Inc., 1955, pp.292-293
- Spectral Response of Color Cameras, I. Bosonoff and W. J. Derenbecher, Radio Corporation of America, April 10, 1953
- TK41C Prism Measurements, Jay Ballard, (private communication) 2007

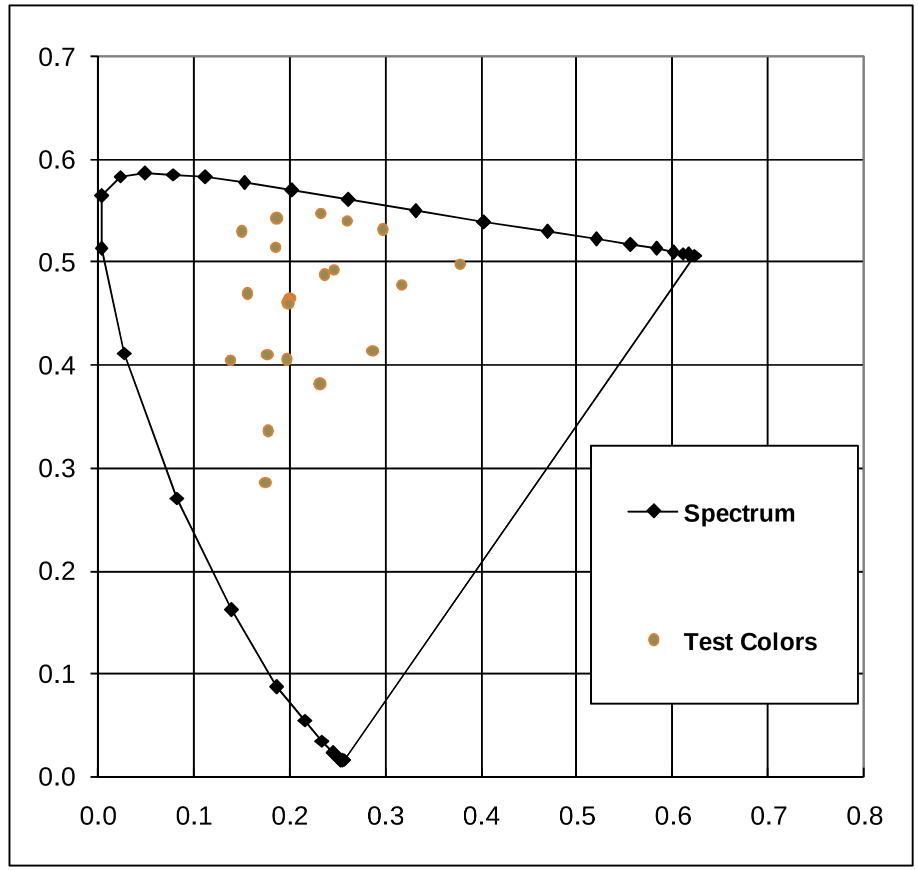
Test Objects

- Spectra of test objects used in earlier papers are usually unknown
- Use Gretag-Macbeth ColorChecker chart
  - SMPTE Standard 0303M-2002, Television – Color Reference Pattern
  - http://www.babelcolor.com/main_level/ColorChecker.htm#How_about_data



Test Colors – Gretag-Macbeth Chart



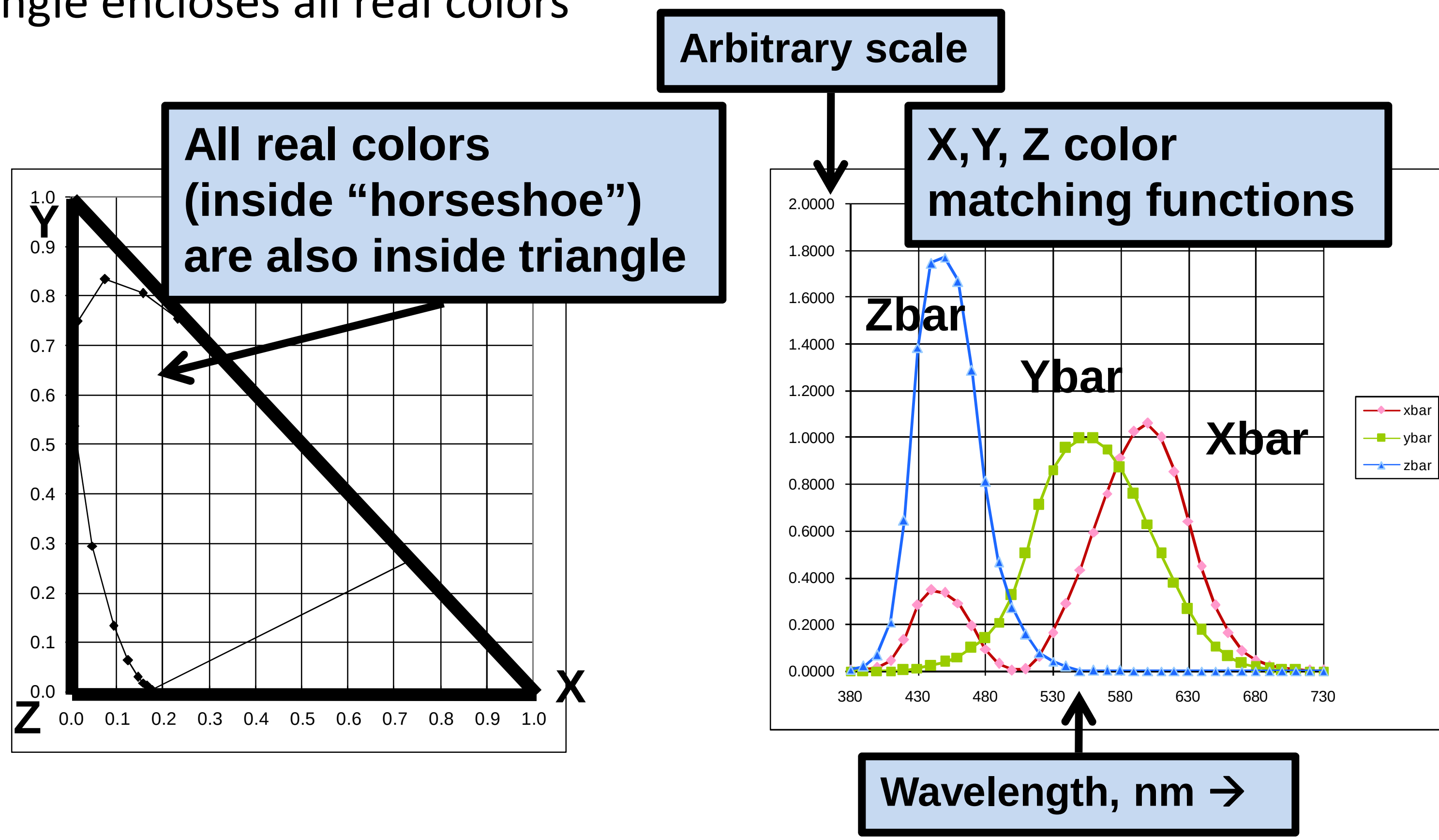


Display Primaries

- NTSC
  - Assumed aim for most of the studies here
- Trinoscope
  - Earliest display
  - High-purity primaries
- Reduced Gamut
  - Mentioned in Red Book, but apparently abandoned
  - Would require matrix with large negative coefficients
- sRGB
  - Used only to get to files viewable on modern display

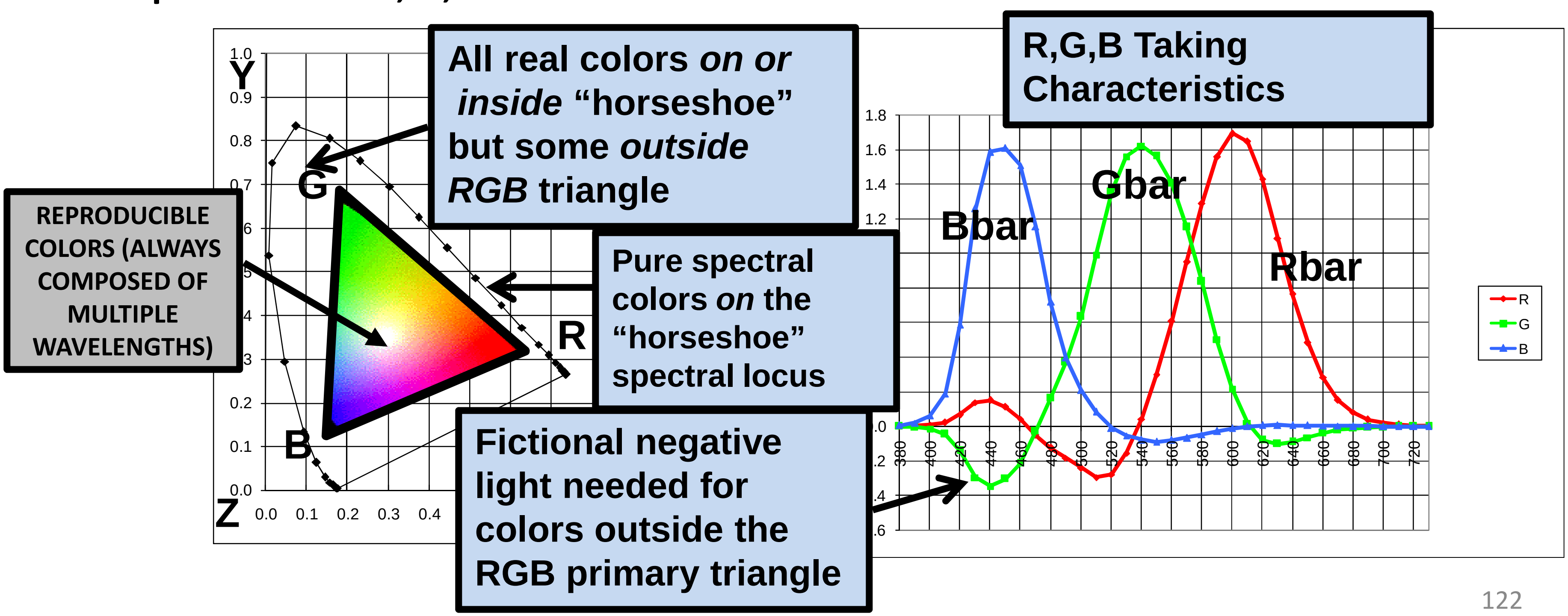
“Taking Characteristics” for Given Primaries

- “Taking Characteristics” are the spectral responses needed to specify the amount of each primary color to reproduce pure spectral wavelengths
- Start with CIE fictional primary colors X,Y,Z
- X,Y,Z can reproduce any color with positive quantities because their triangle encloses all real colors

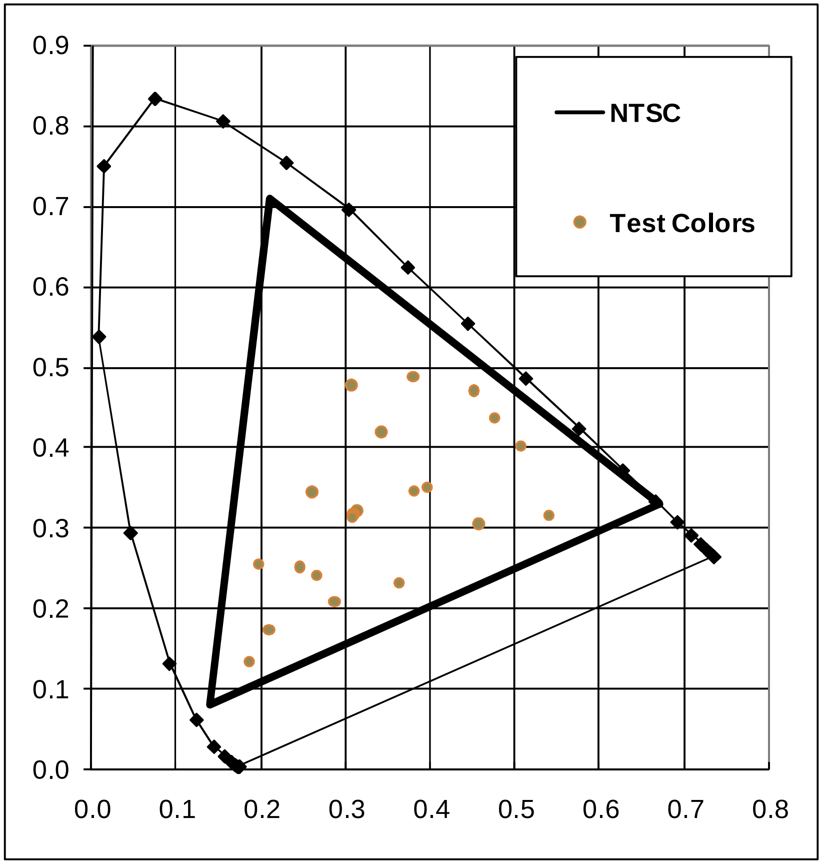


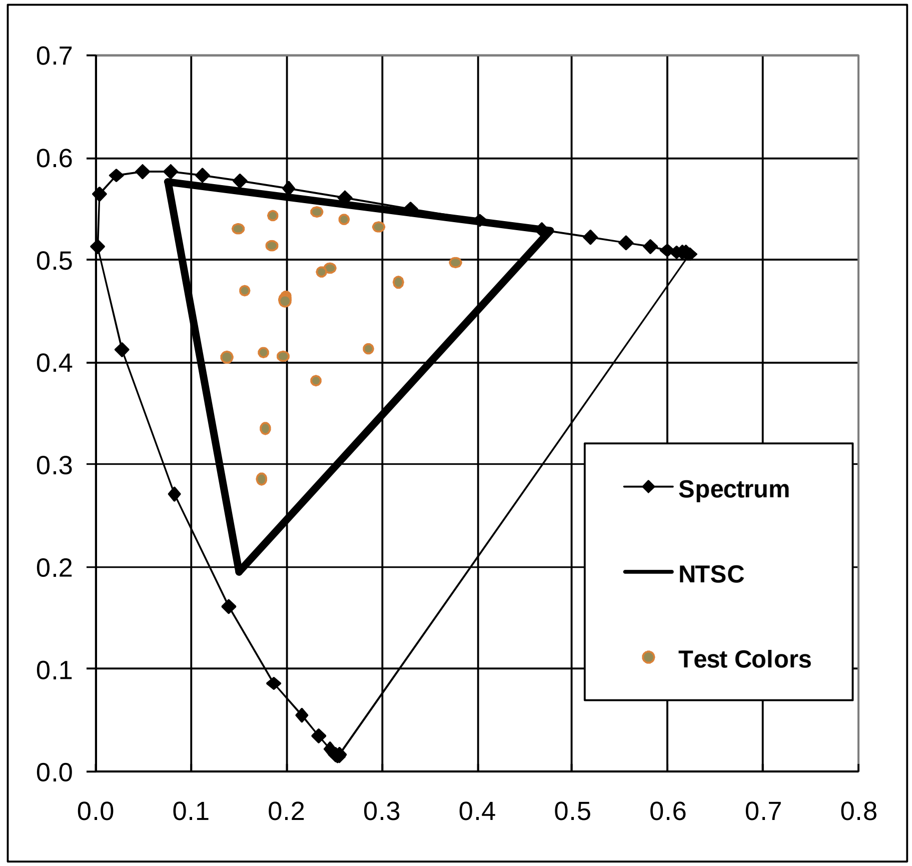
Taking Characteristics for Real Primaries

- **Spectral Sensitivity Curves needed for perfect reproduction of pure spectral wavelengths with real primaries**
- ***Linear combination* of the CIE XYZ curves**
- **R,G,B require fictional negative amounts of light to reproduce any color outside the RGB triangle**
- **For correct reproduction of colors *inside* the triangle, we still need the negative camera responses to certain wavelengths to get the correct net positive quantities of R, G, and B**

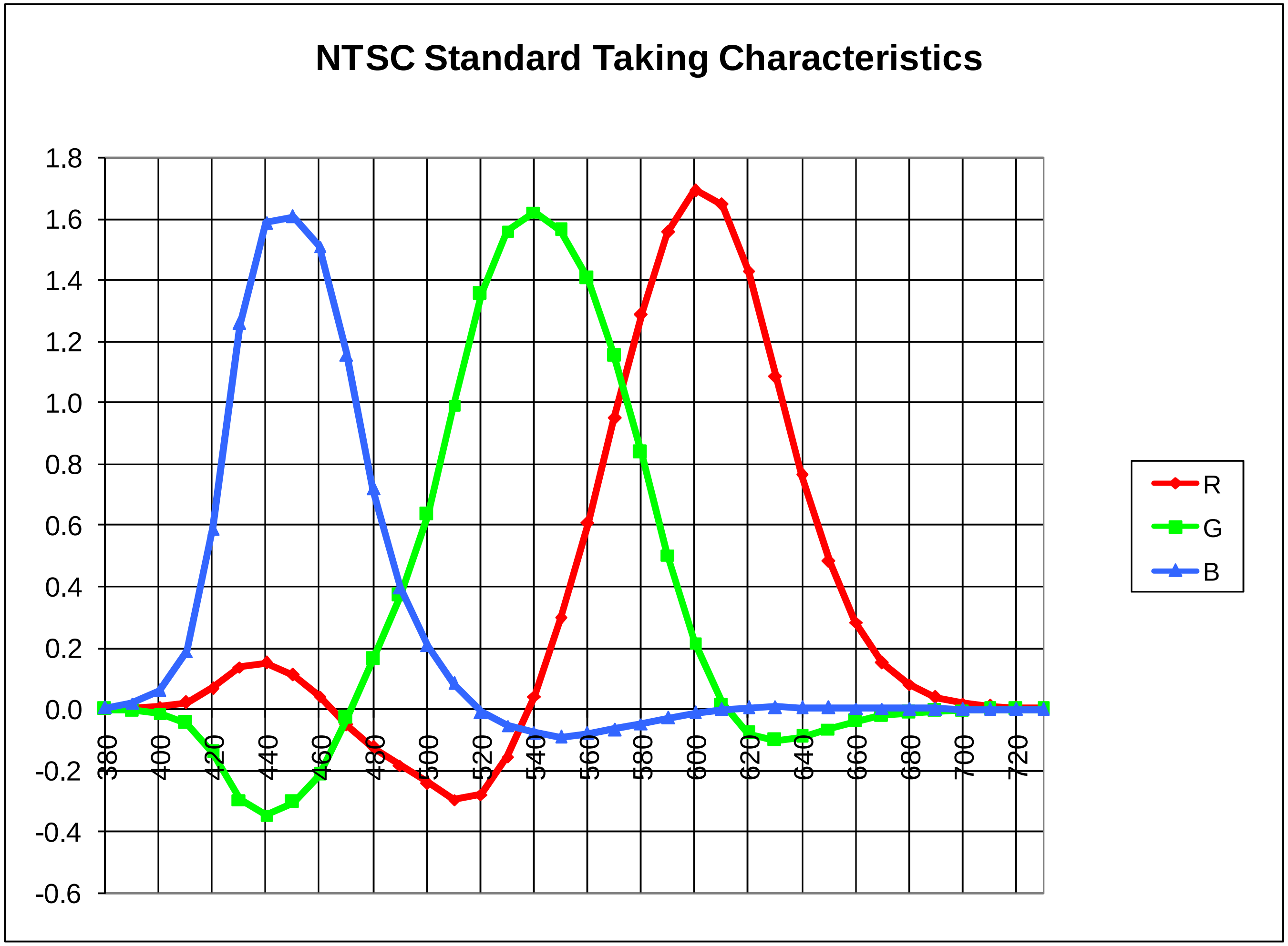


Display Primaries - NTSC





Taking Characteristics - NTSC



Taking Characteristics - NTSC

- Things to note
  - To be perfectly correct, a camera with three sensors needs a 3x3 matrix to generate negative responses to certain wavelengths
  - The negative lobes for NTSC are not huge
  - For many/most object spectra, the effects of the negative lobes may be approximated by using only positive lobes that are somewhat narrower than the positive lobes of the ideal taking characteristics
  - This is the same technique used in all color photographic film until the invention of 4-layer film with an inhibitory cyan-sensitive layer (equivalent negative response to cyan wavelengths!), and the same technique that could be used in early color TV cameras

Other Early Display Primaries

- Trinoscope
  - Used for practical demonstrations before color picture tube was developed
- Narrow-gamut display
  - Studied in theory to determine effects, but apparently never produced

RCA Trinoscope #1

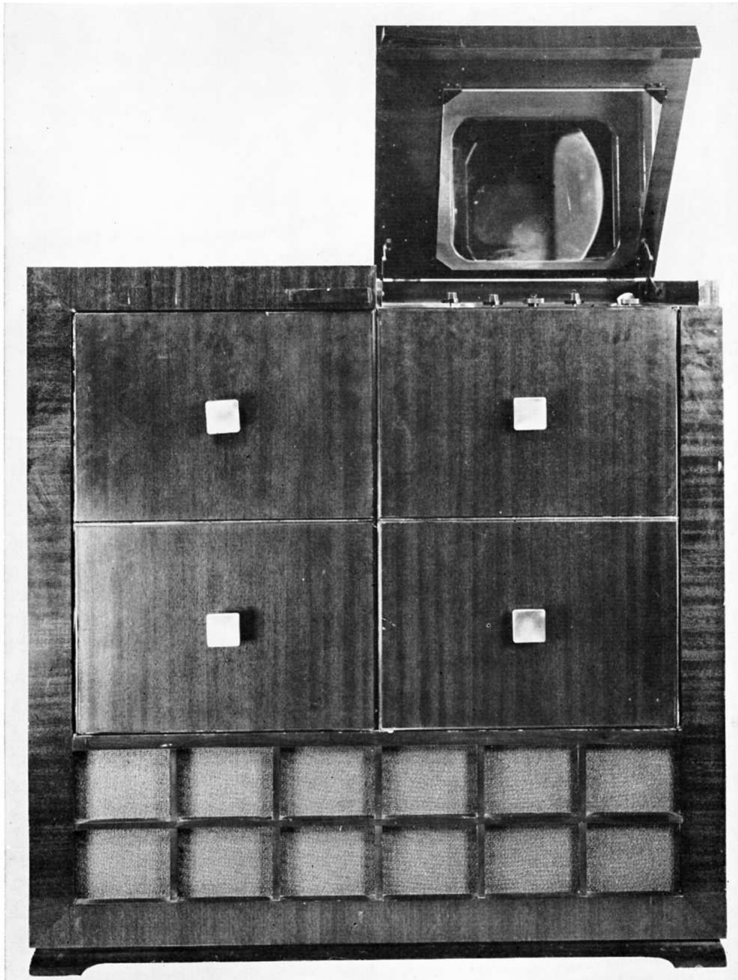


Fig. 1 – Trinoscope Receiver Model No. 1

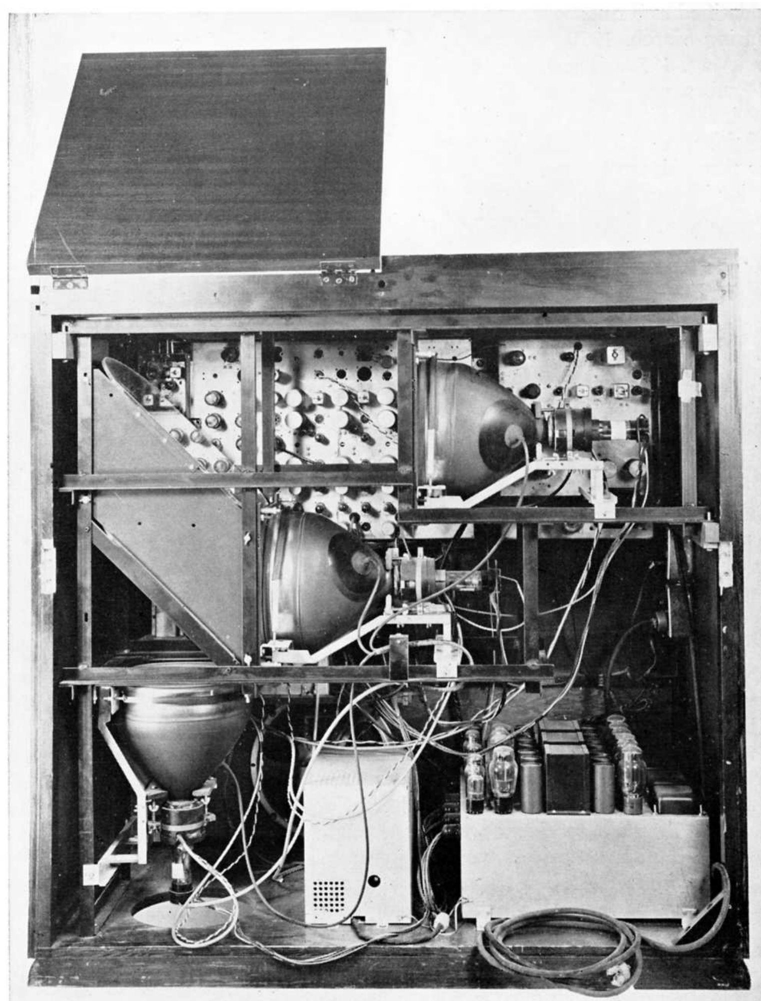


Fig. 2 – Trinoscope Receiver Model No. 1

RCA Trinoscope #2

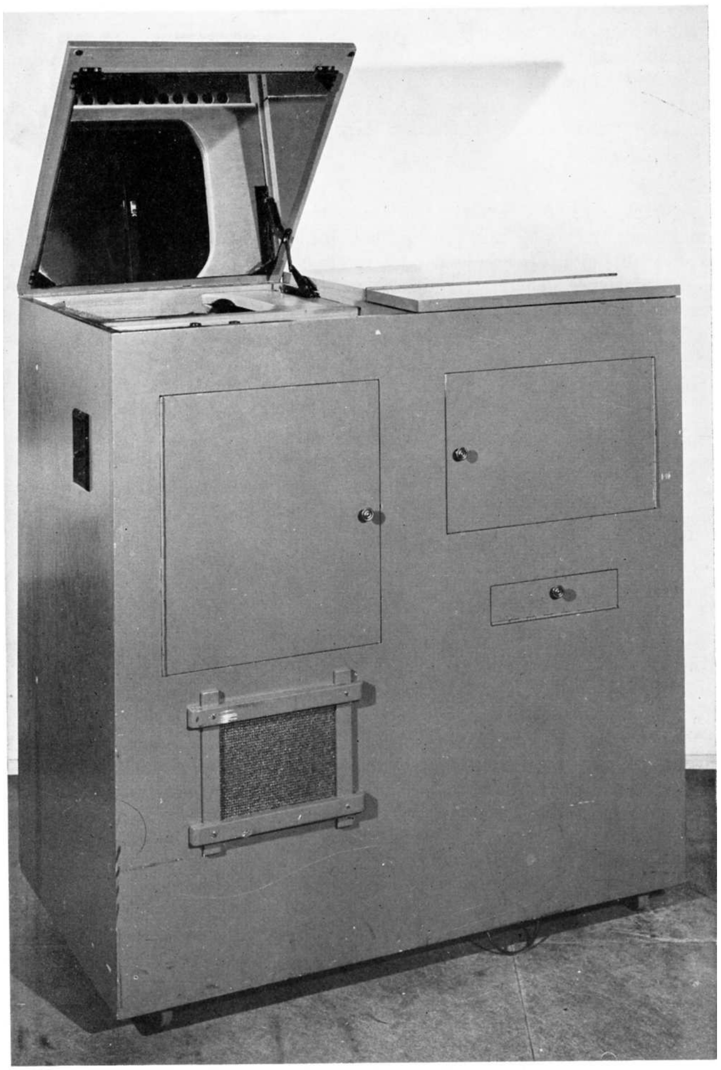


Fig. 3 – Trinoscope Receiver Model No. 2

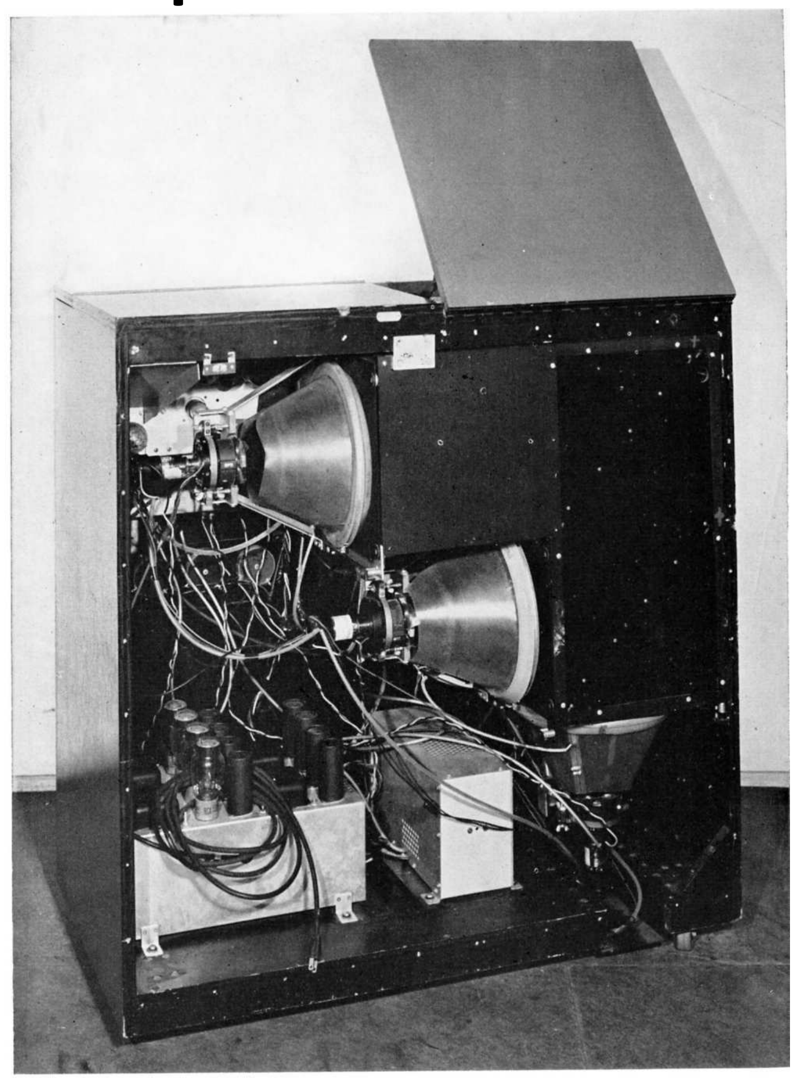


Fig. 4 – Trinoscope Receiver Model No. 2

Mitsubishi Trinescope 1964

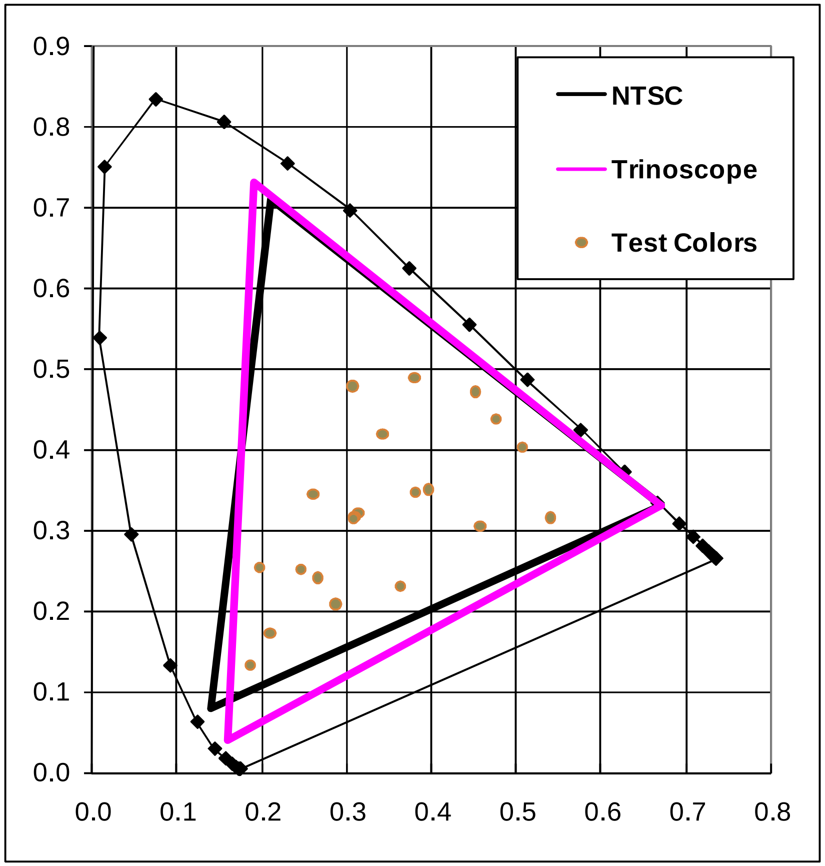
New York
World's Fair
1964-65

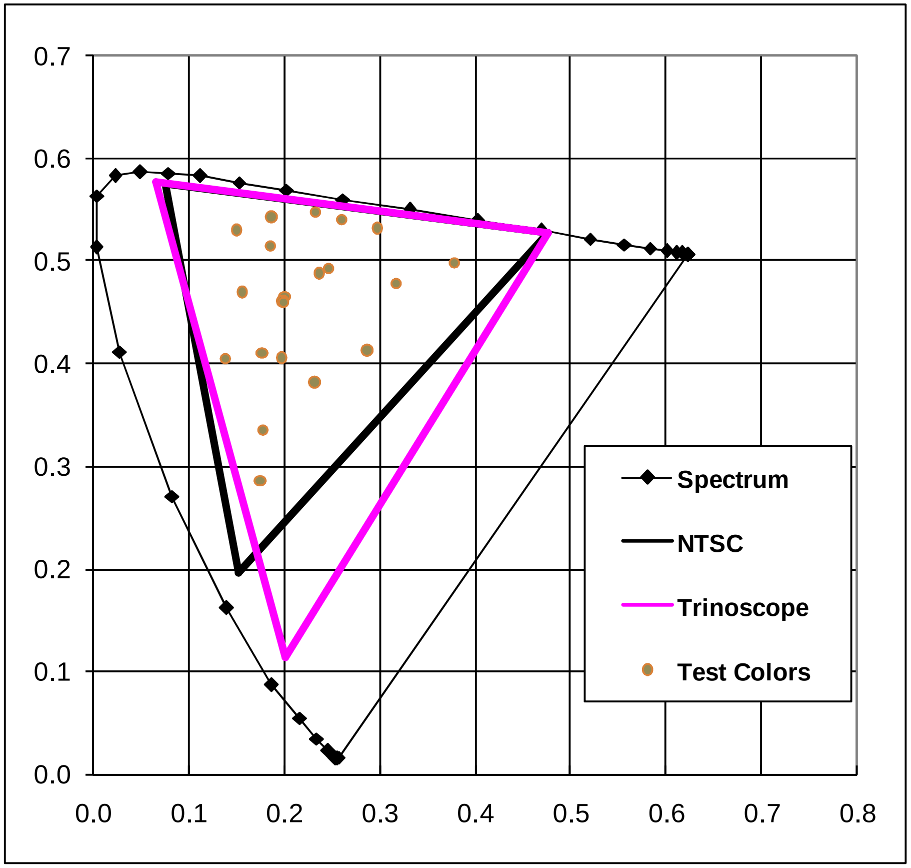
Photo:
Wayne Bretl

Operating
In 2007

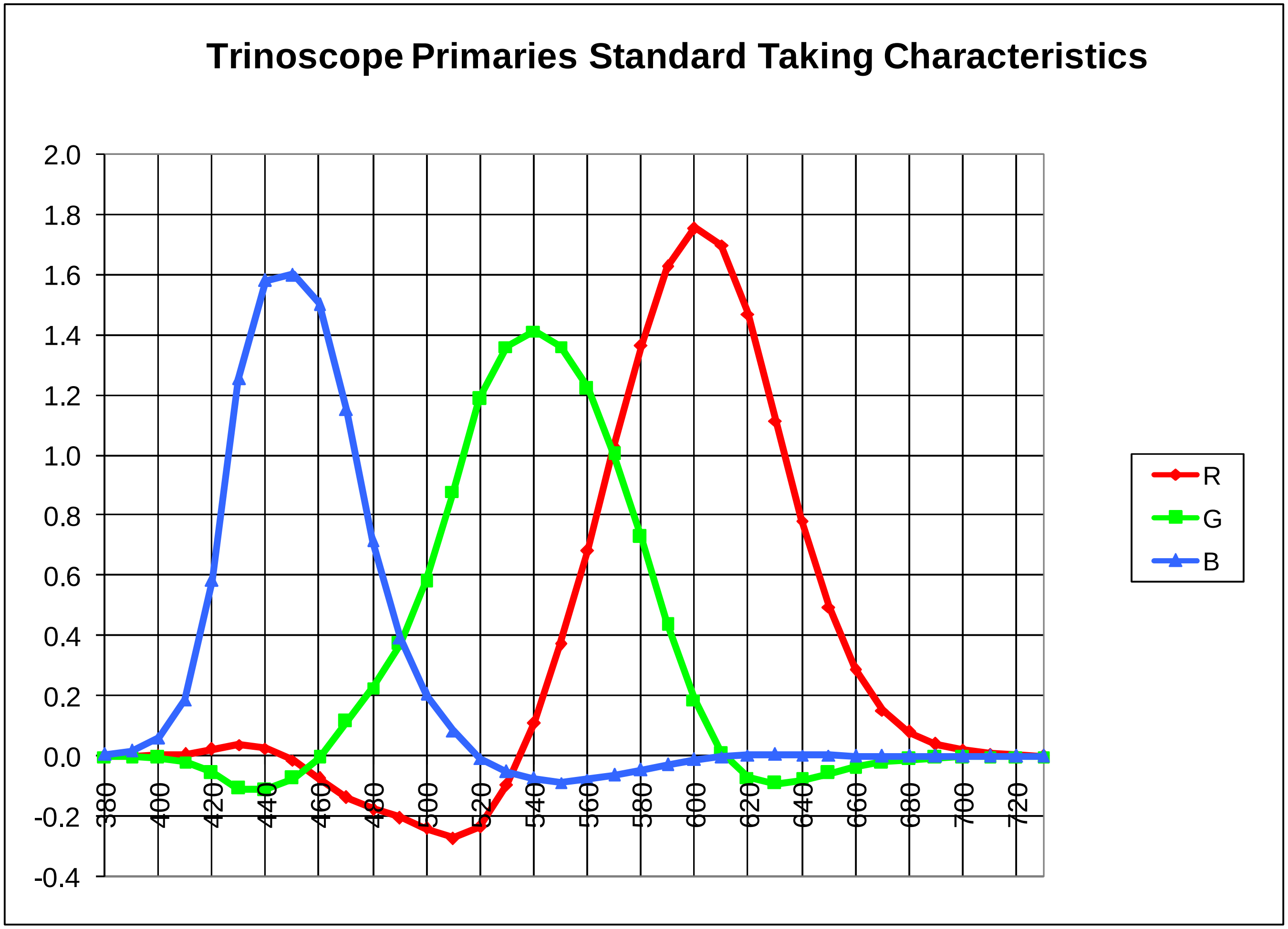
Photo:
Erich Loepke
(Member *trinescope*
on audiokarma.org)

Display Primaries - Trinoscope

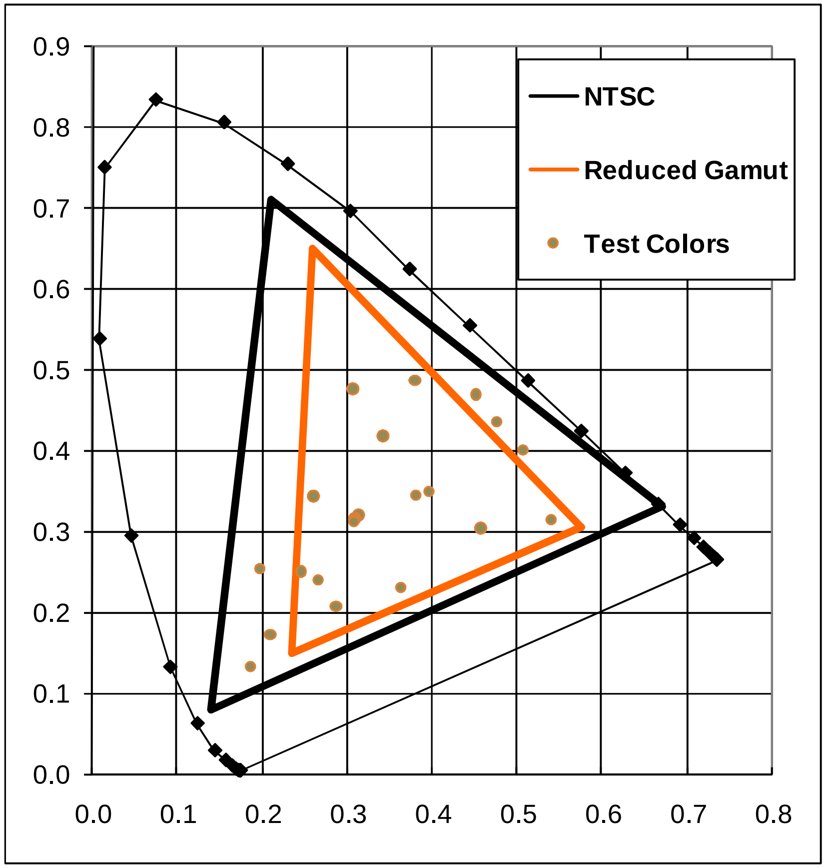


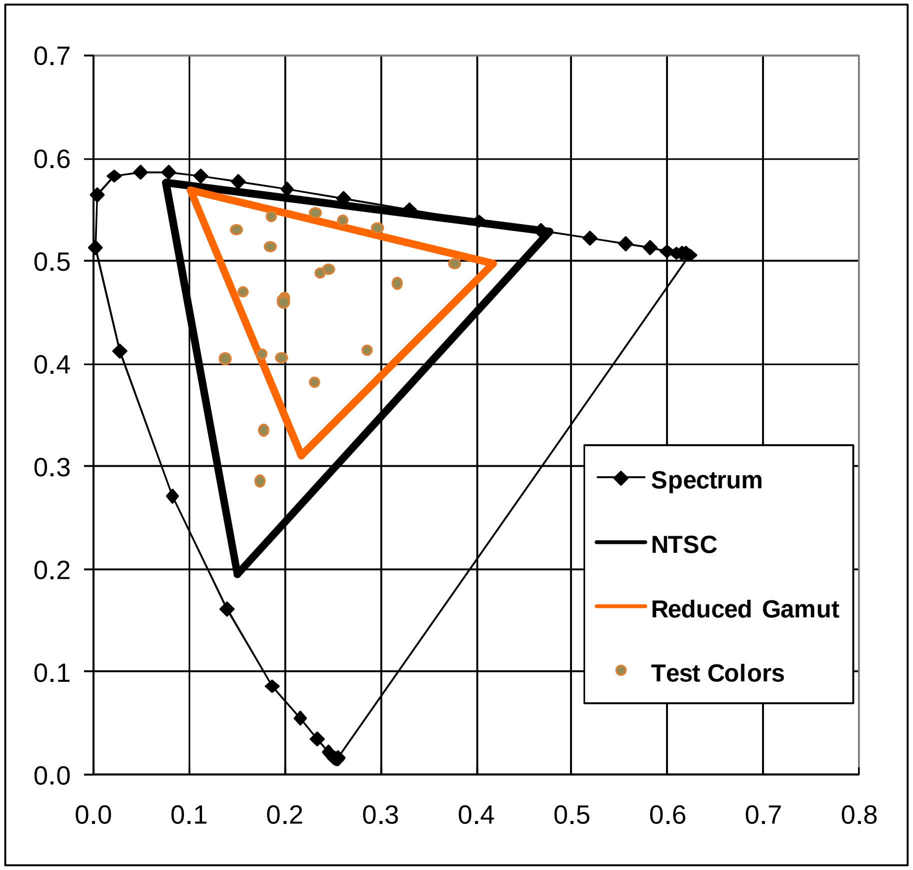


Taking Characteristics - Trinoscope

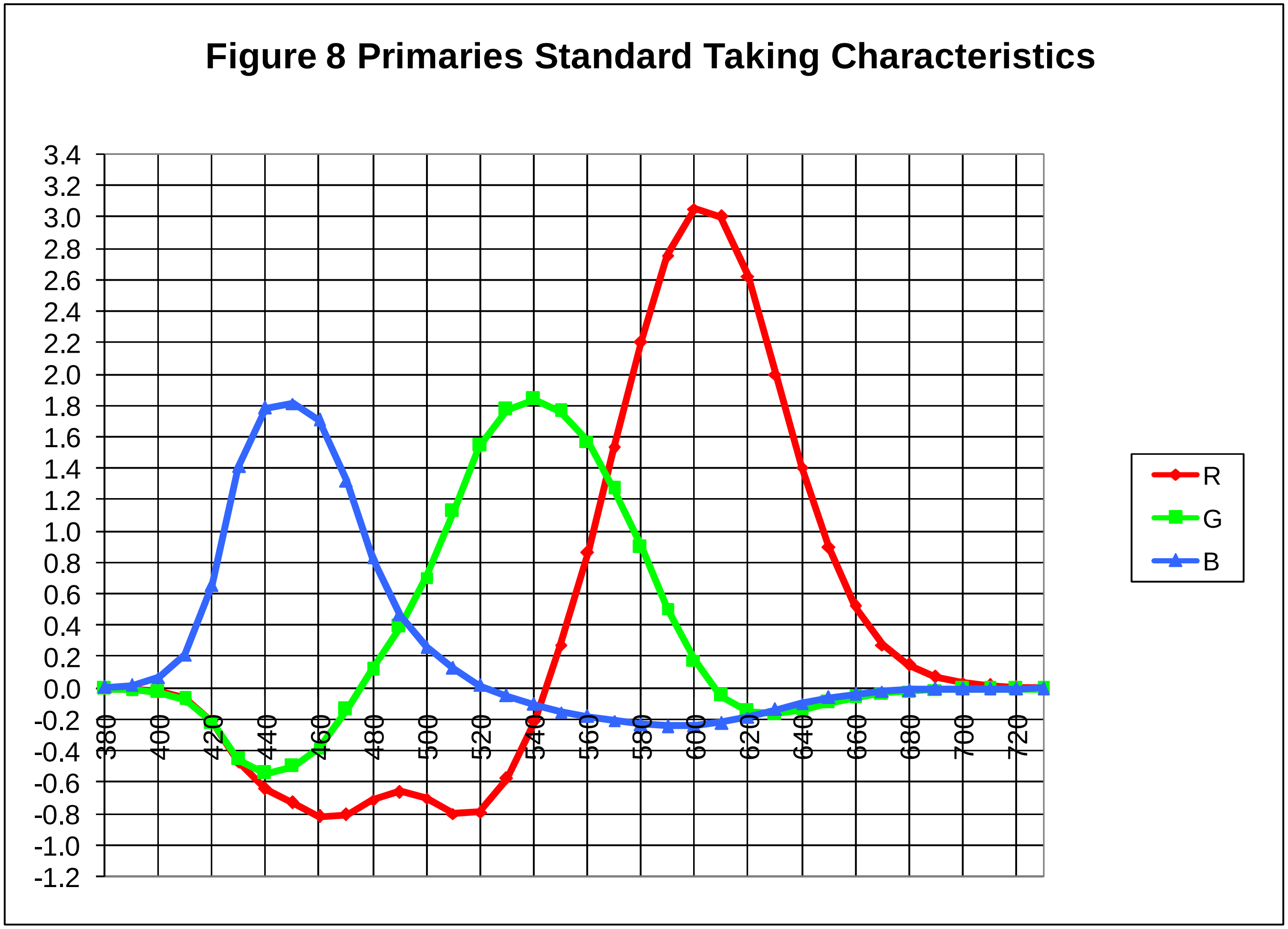


Display Primaries – Reduced Gamut

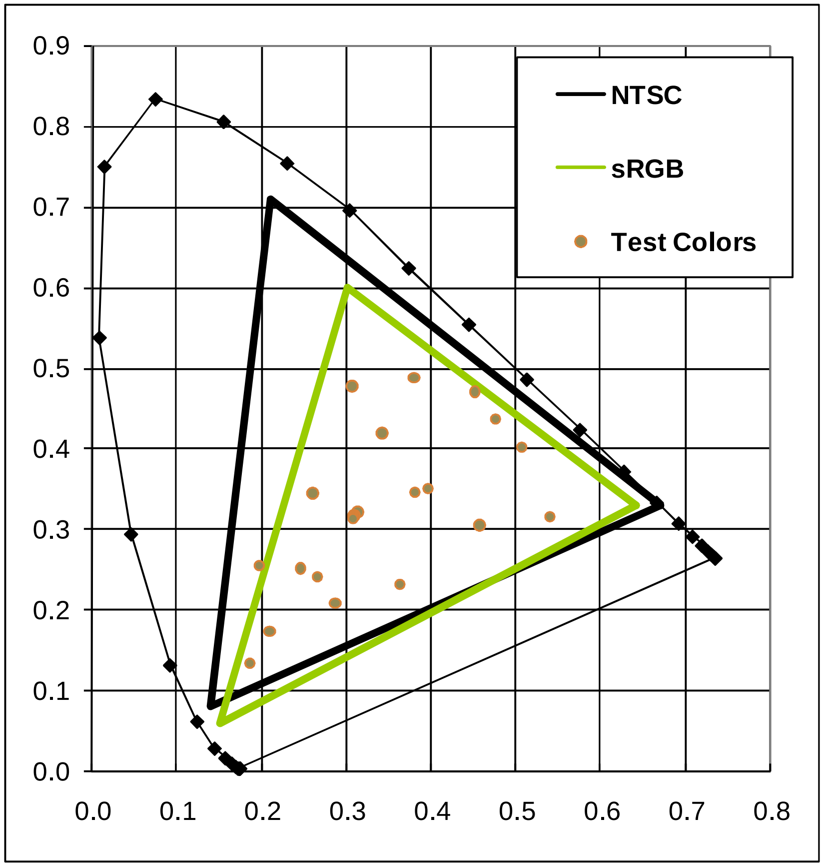


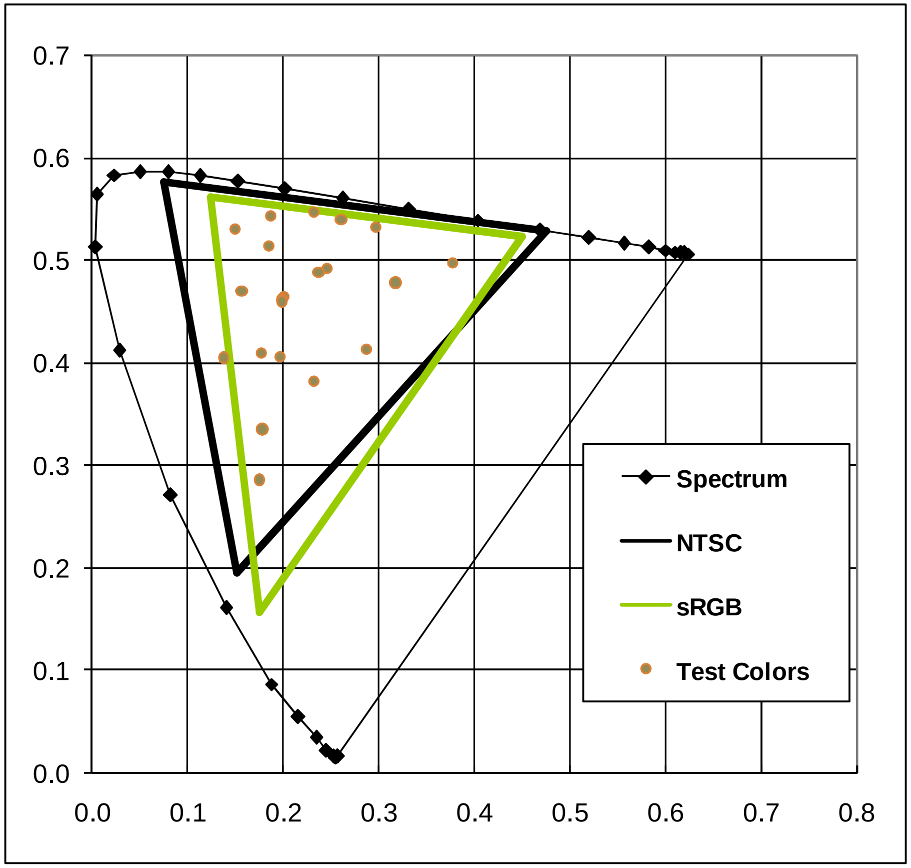


Taking Characteristics – Reduced Gamut

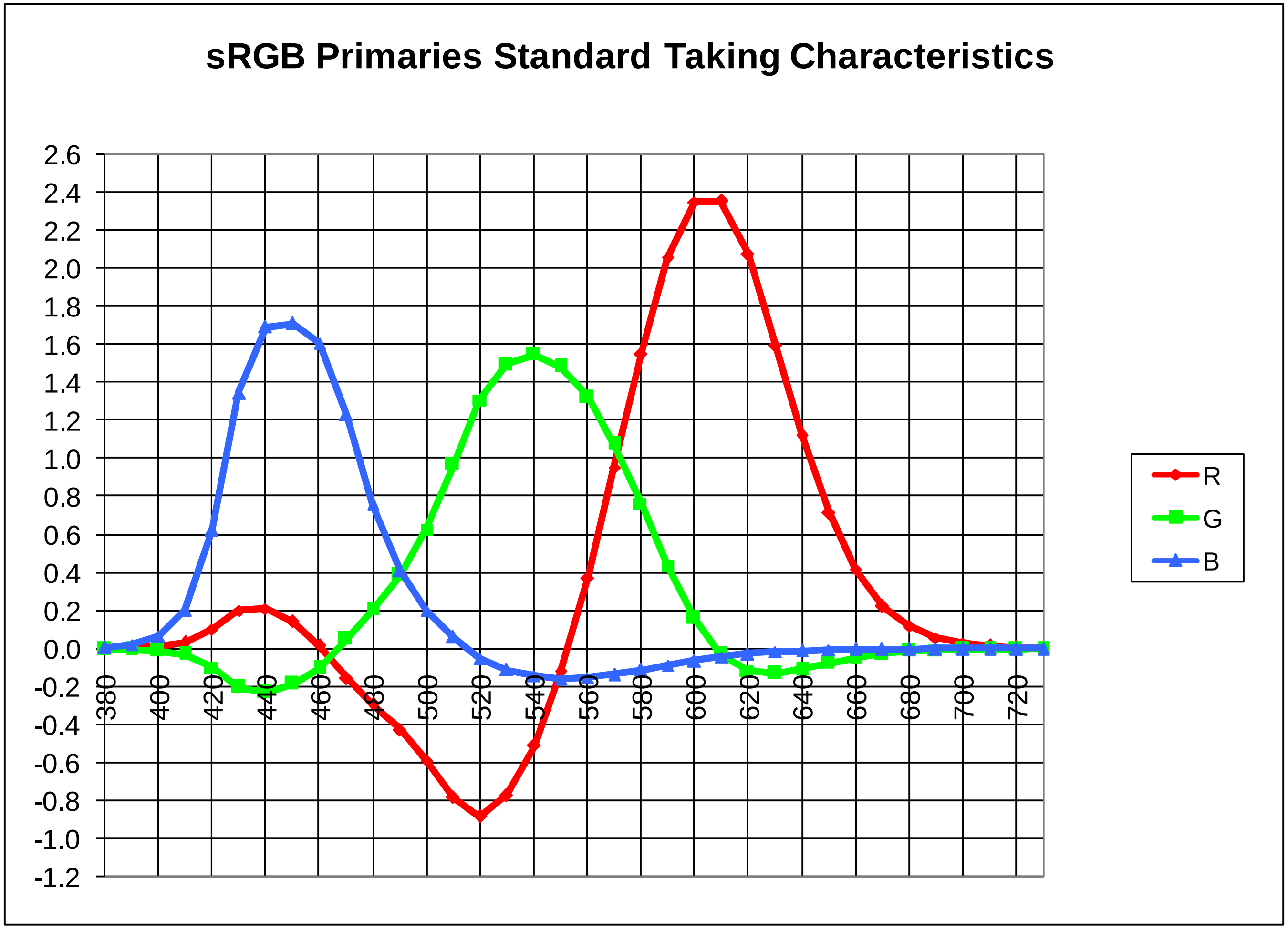


Display Primaries - sRGB

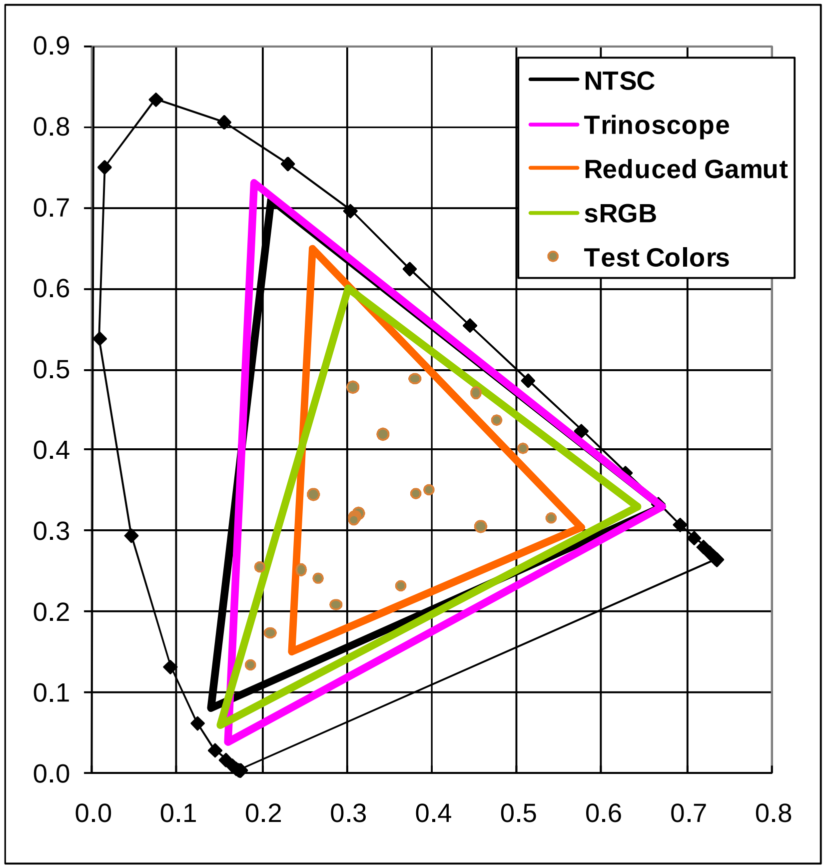


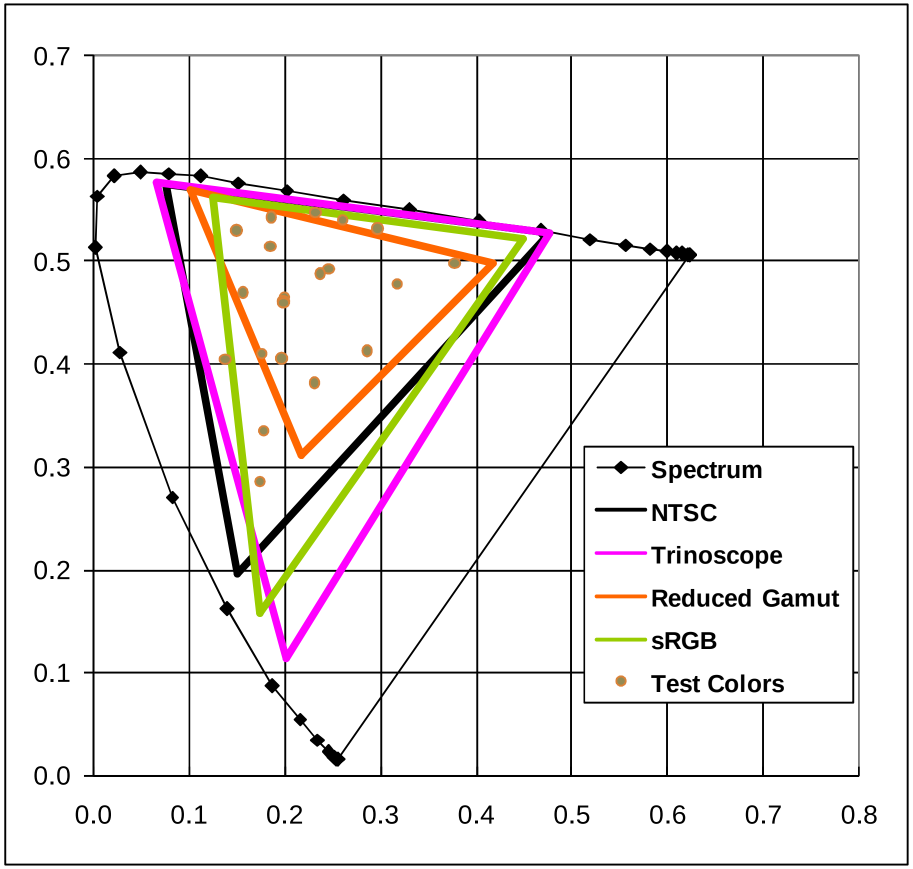


Taking Characteristics – sRGB



Display Primaries





Calculations

- All measured and standard quantities entered into spreadsheet at 10 nm intervals from 380 to 730 nm
  - Measured camera responses
  - Filter transmission curves
  - CIE color matching functions
  - Color chart spectra

Calculations

- Camera response for each color patch
  - Form product spectrum of Illuminant, object, and camera responses
  - Numerically integrate the R,G,B responses of the camera
  - Numerically integrate for an ideal white patch (100% reflectance at all wavelengths)
  - Normalize all results so that R=G=B on the ideal white

Calculations

- Displayed color for each color patch
  - 3x3 matrix transform from target display primaries (usually NTSC) to sRGB primaries
  - Gamma correct the sRGB values

Calculations

- Eye response for each color patch
  - Form product spectrum of Illuminant, object, and CIE color matching functions
  - Numerically integrate to get X, Y, Z
  - Calculate (x, y) and (u’, v’)

Possible Improvements via Linear Matrixing

- Lack of negative lobes in response and other inaccuracies can be corrected approximately by a least-squares-fit linear 3x3 matrix
- Works best if the original camera characteristics are close to ideal
- Can be skewed by unusual test object spectra in combination with non-ideal camera characteristics
- Ideally, the best fit is calculated in a uniform color space

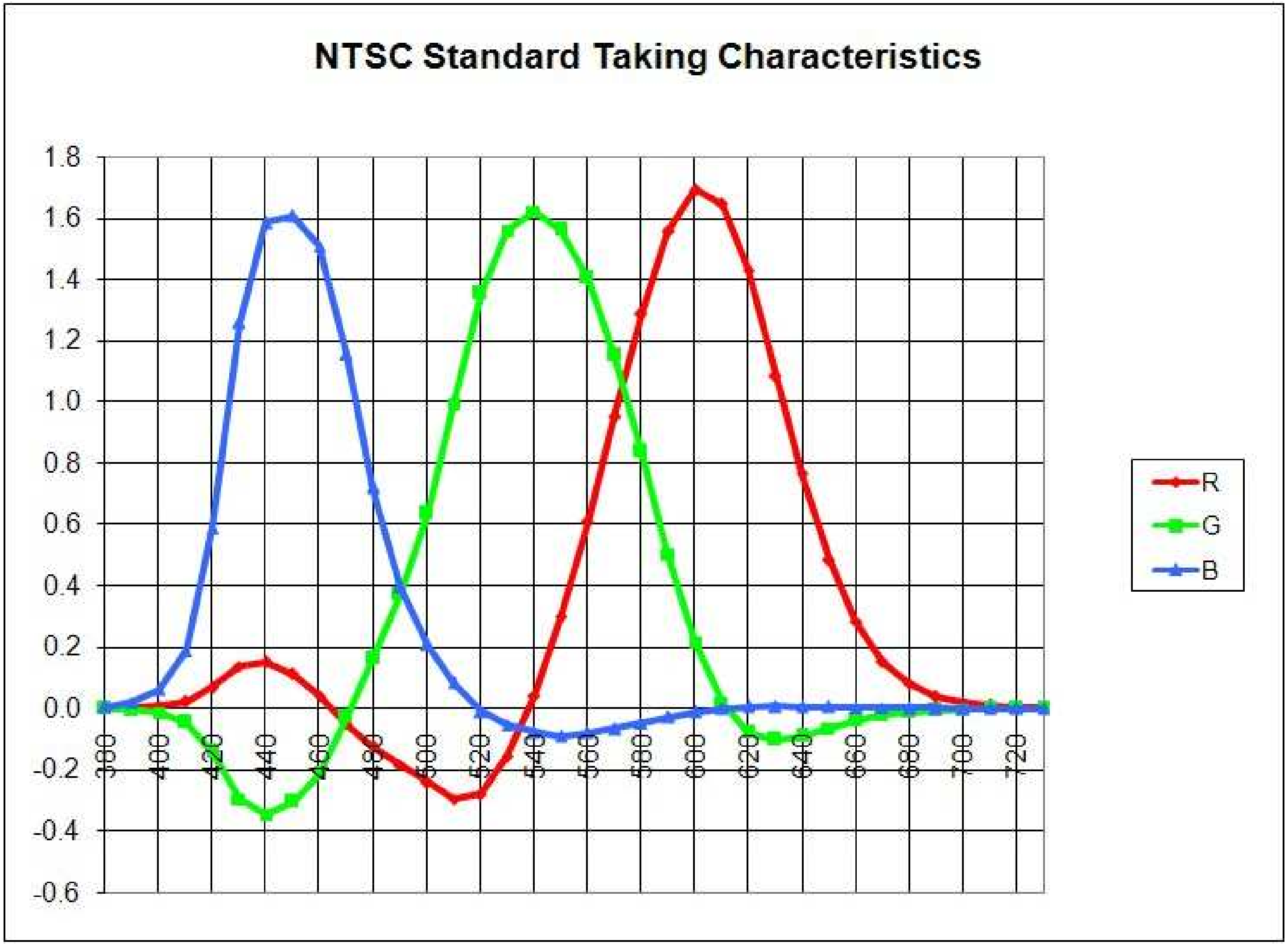
Possible Improvements via Linear Matrixing

- Was not used in image orthicon cameras due to increase in noise, complexity
- Calculations are made here
  - to see what improvements could have been made
  - for comparison with both the original camera output and the ideal reproduction
  - Done in R,G,B space for simplicity

Camera Taking Characteristics

- Calculated NTSC ideal curves
- *or* Real curves from published over-all camera RGB spectral responses
- *or* Calculated from products of real curves of individual system components, either published or measured

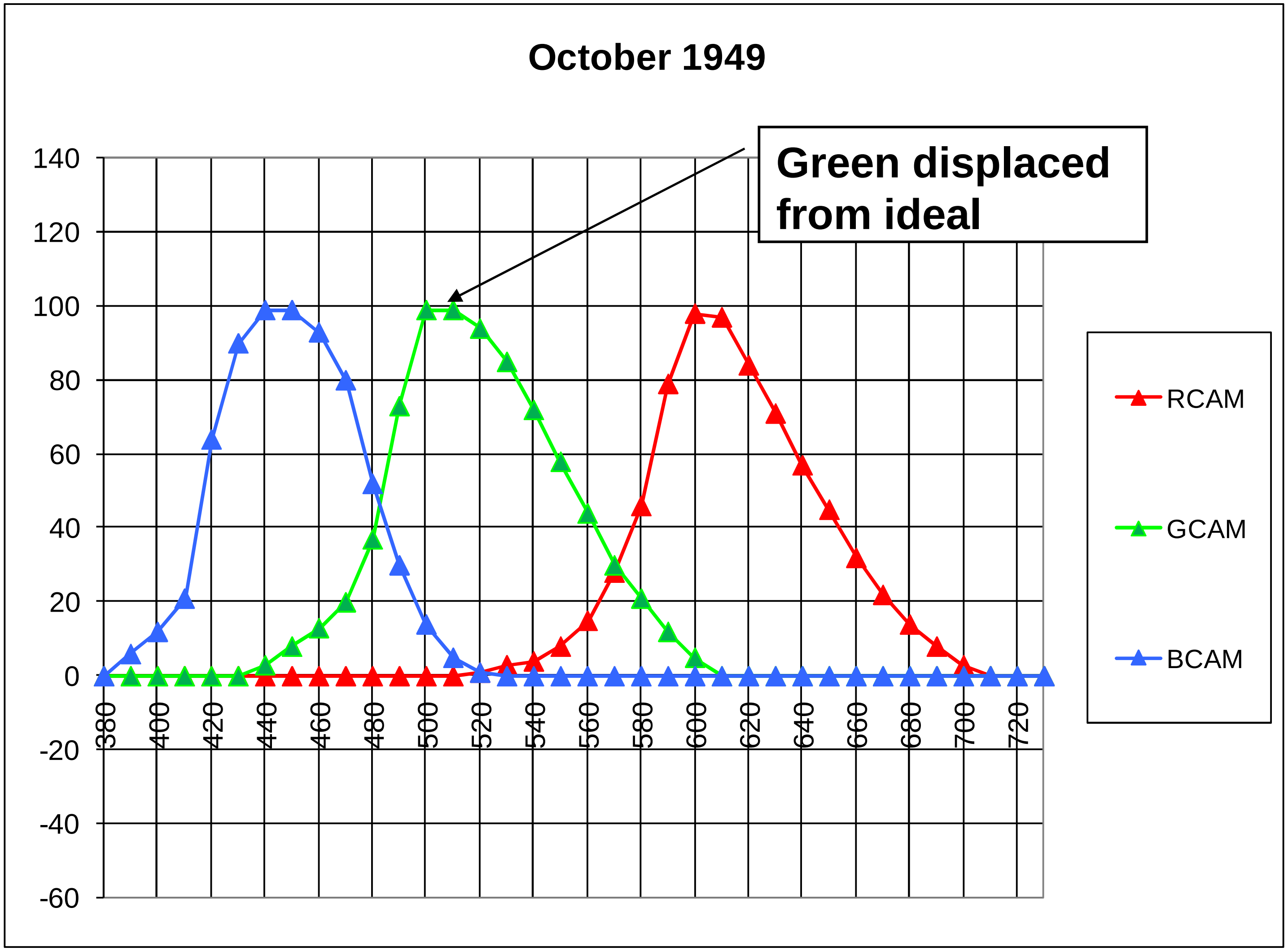
Ideal NTSC taking characteristics



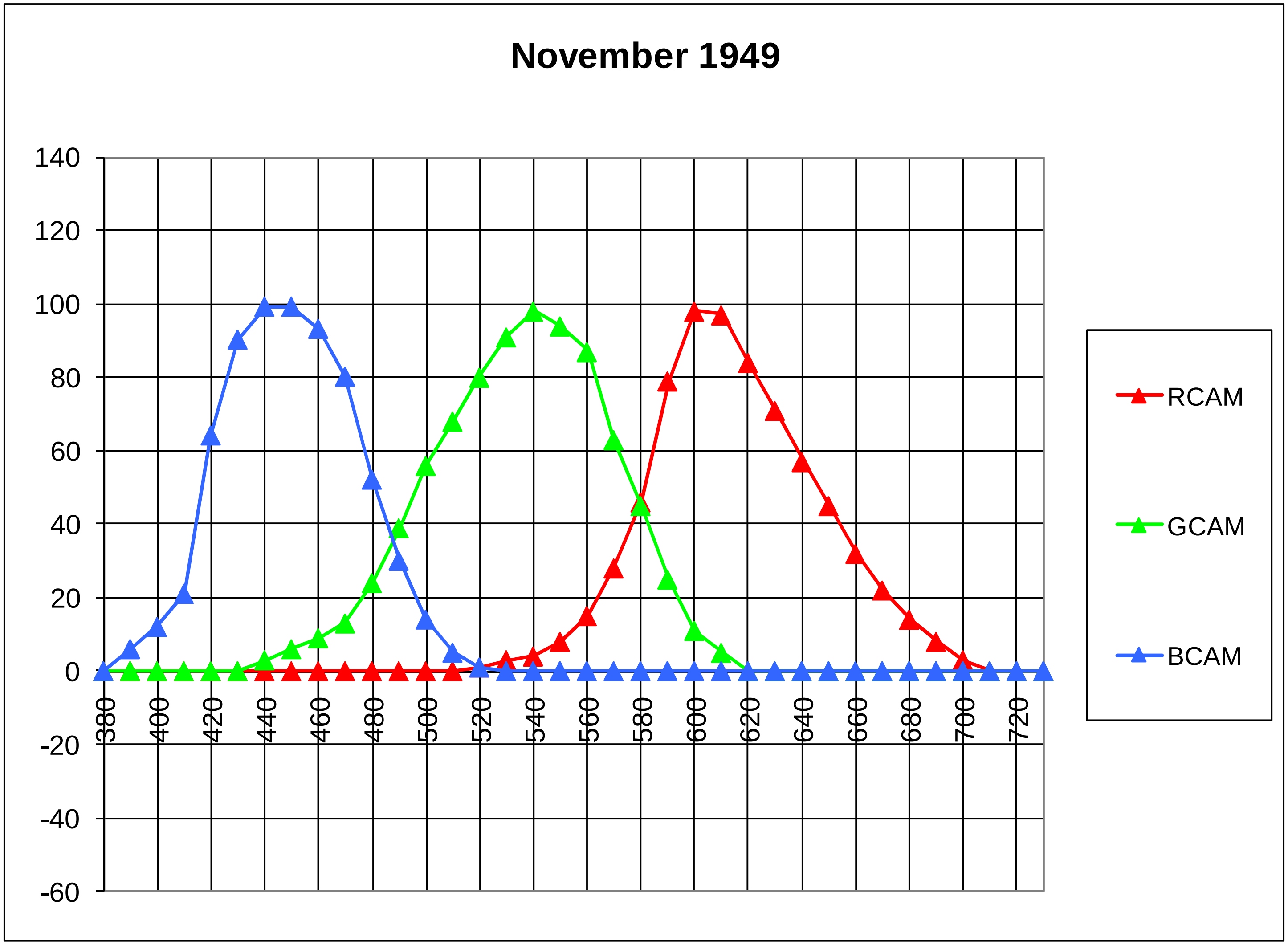
1949 Cameras

- Camera used in October 1949 demo had green curve displaced toward short wavelengths – tended to move yellows towards orange
- Corrected in November 1949

October 1949 taking characteristics



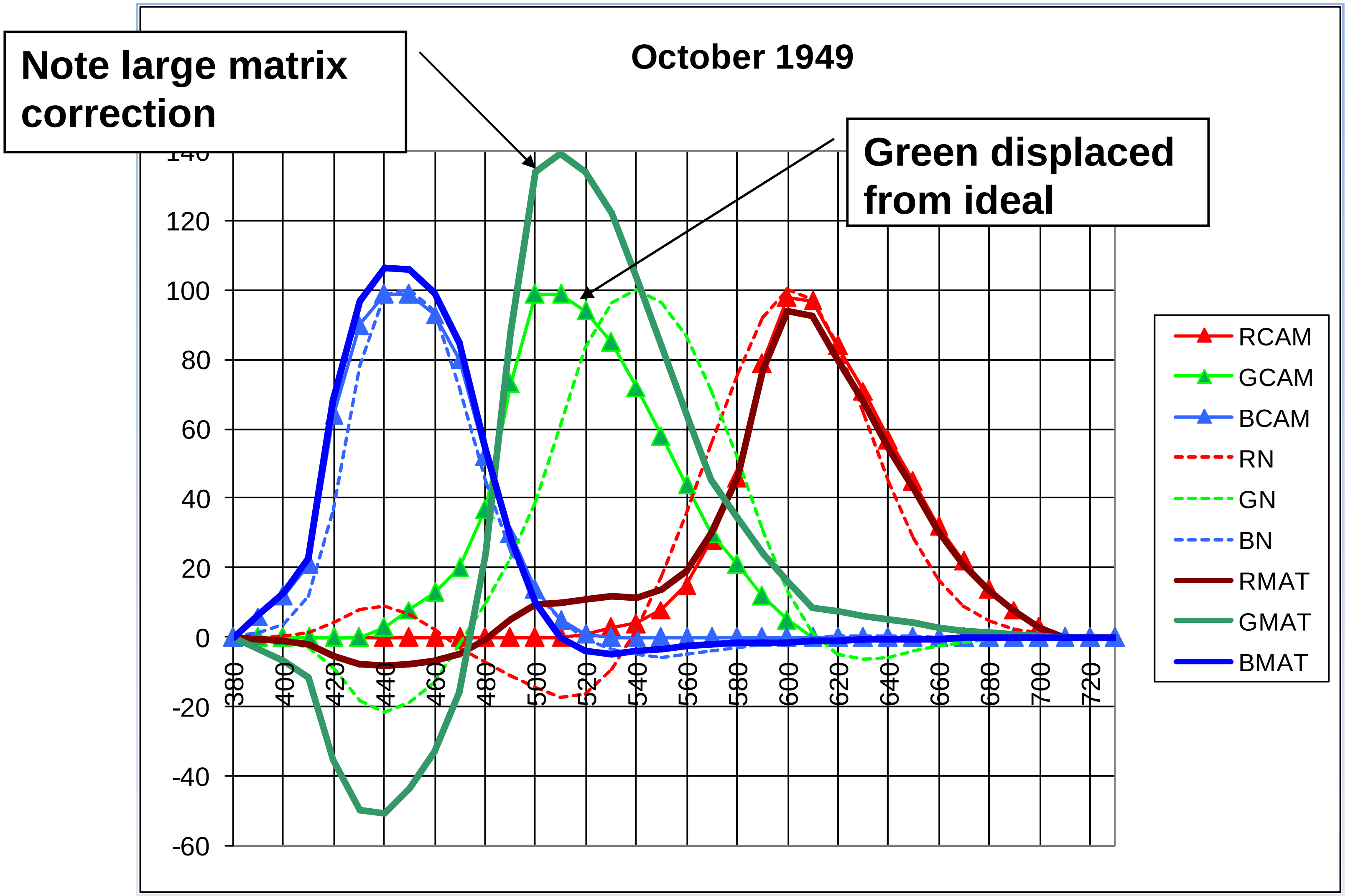
November 1949 taking characteristics



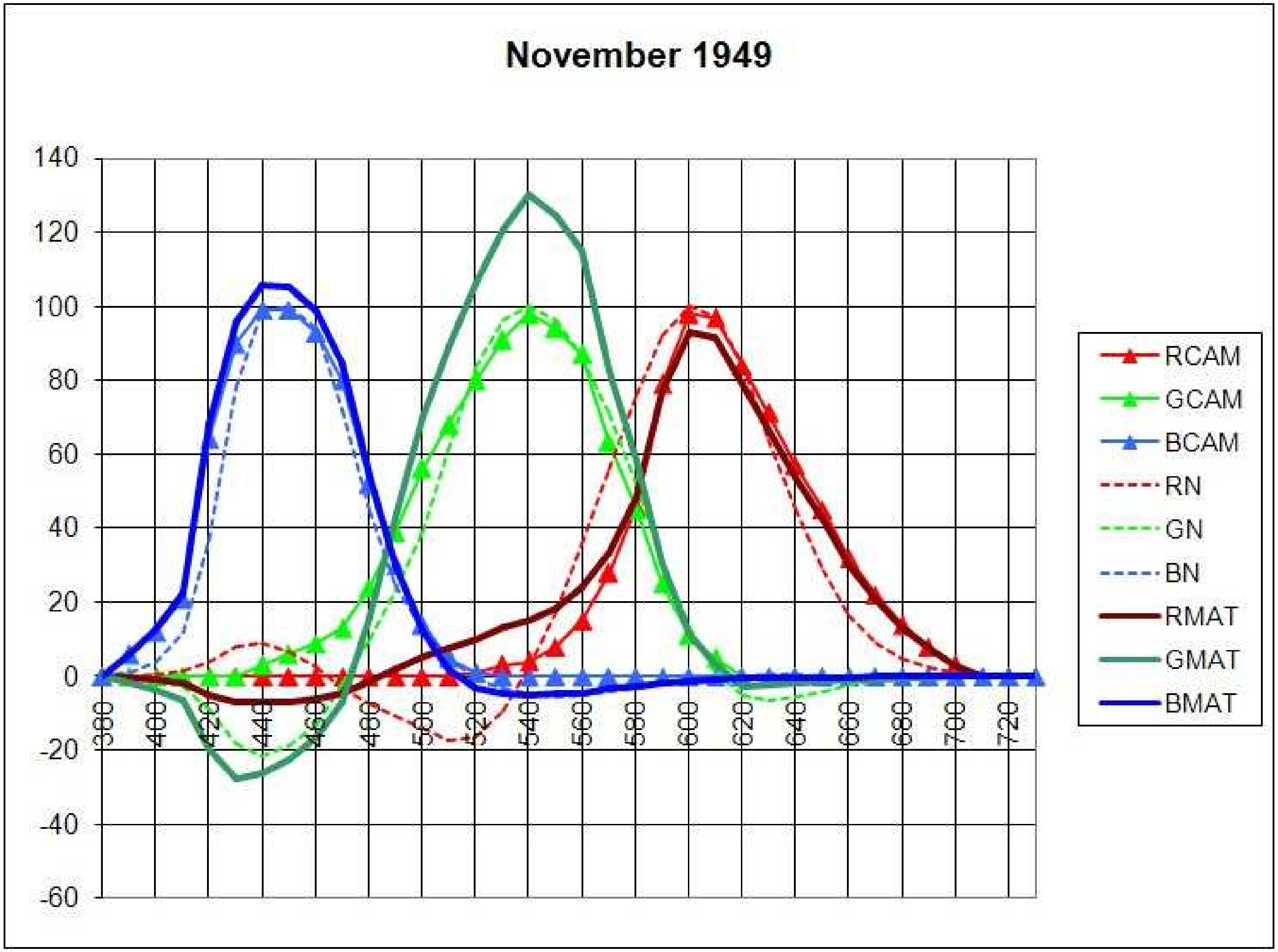
Raw Output vs.Matrixed

- Three sets of curves on each slide
  - Camera output RCAM, GCAM, BCAM (solid lines with point symbols)
  - Matrixed camera output RMAT, GMAT, BMAT (solid lines without symbols)
  - Ideal NTSC characteristics RN, GN, BN (dotted lines)
  - Vertical axis units are arbitrary

October 1949 taking characteristics



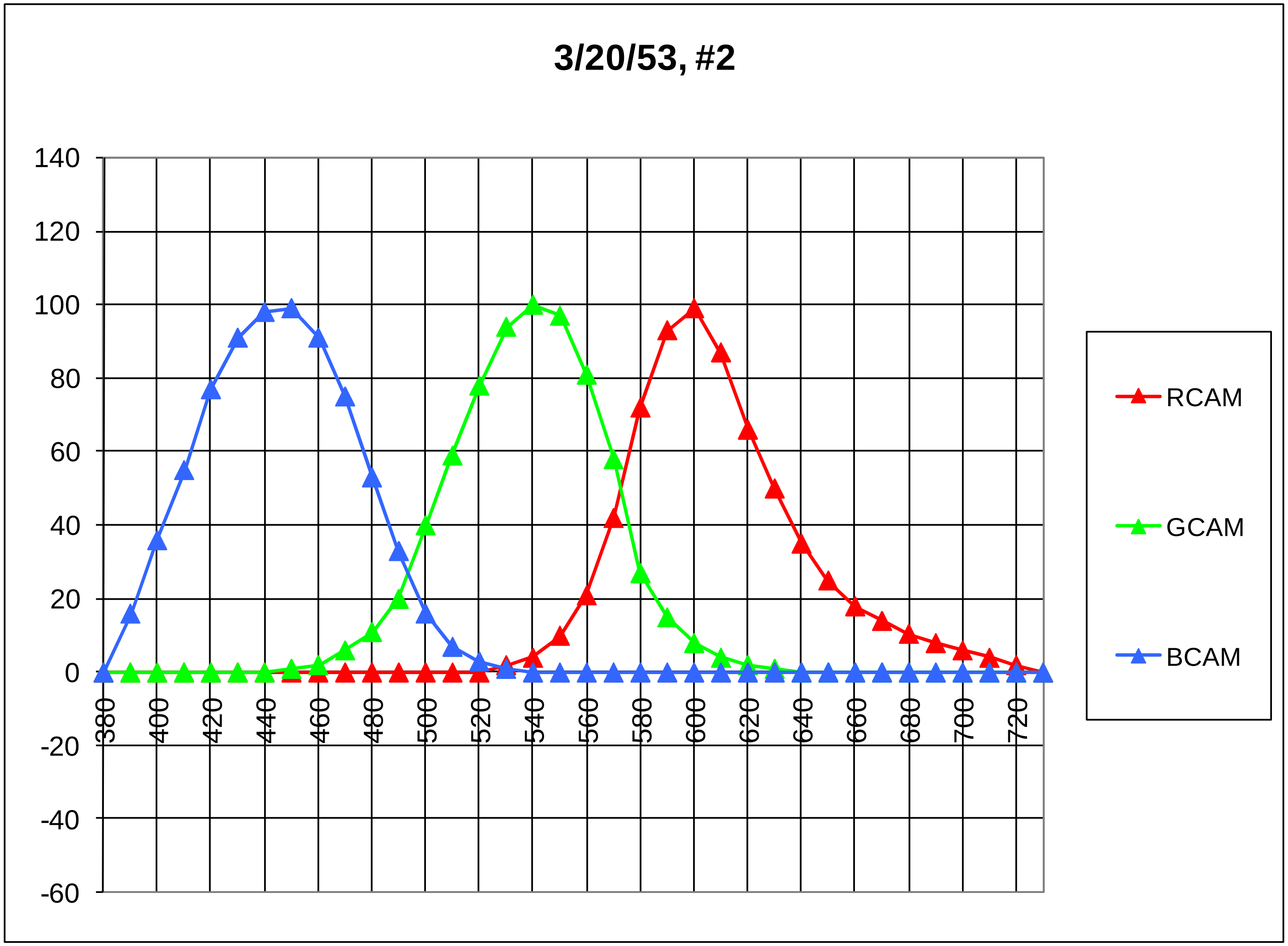
November 1949 taking characteristics



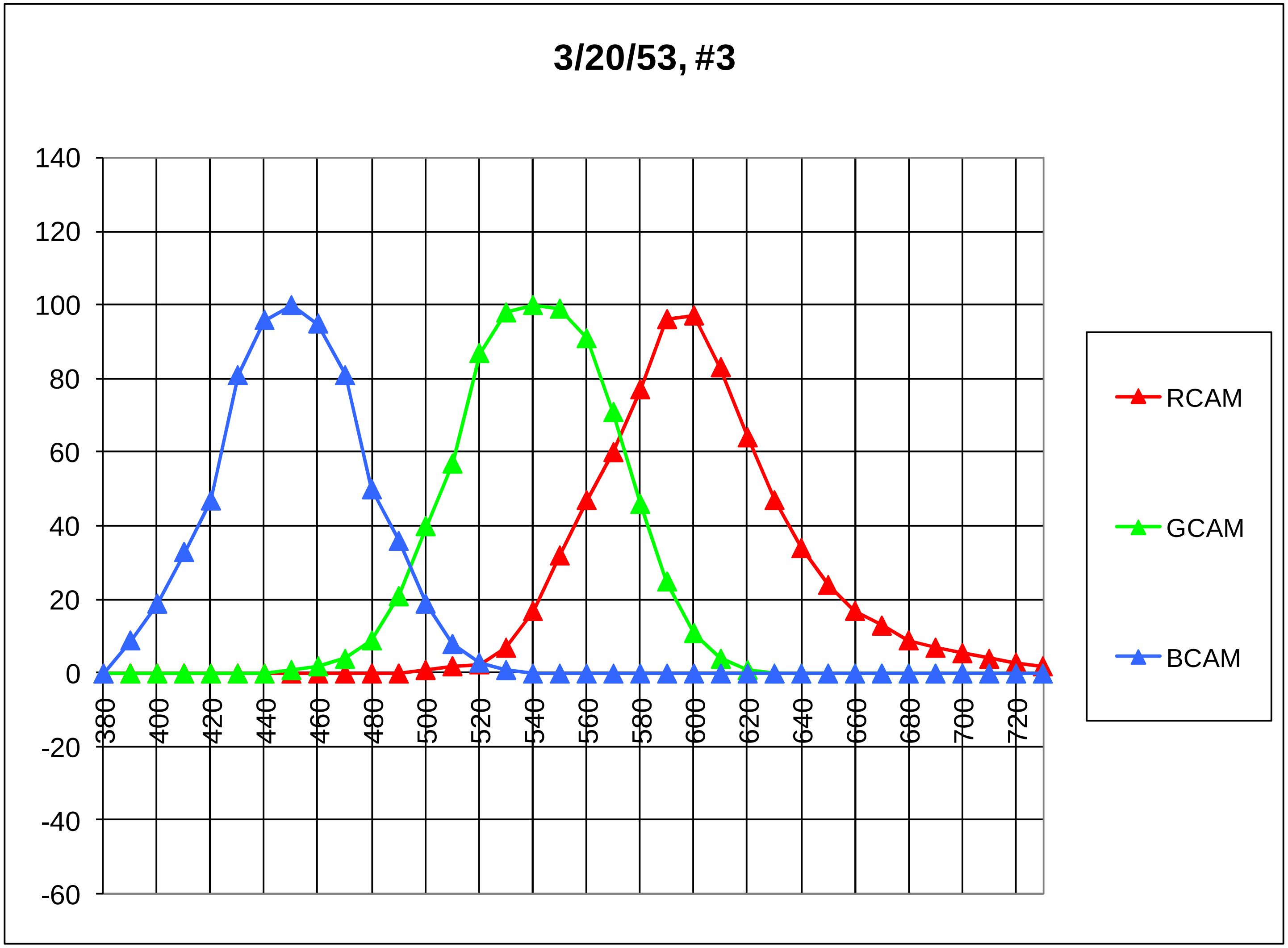
March 1953 Cameras

- Four cameras were documented in March 1953
- For this study, chose #2 and #3, which had the largest difference in R and G curve crossover

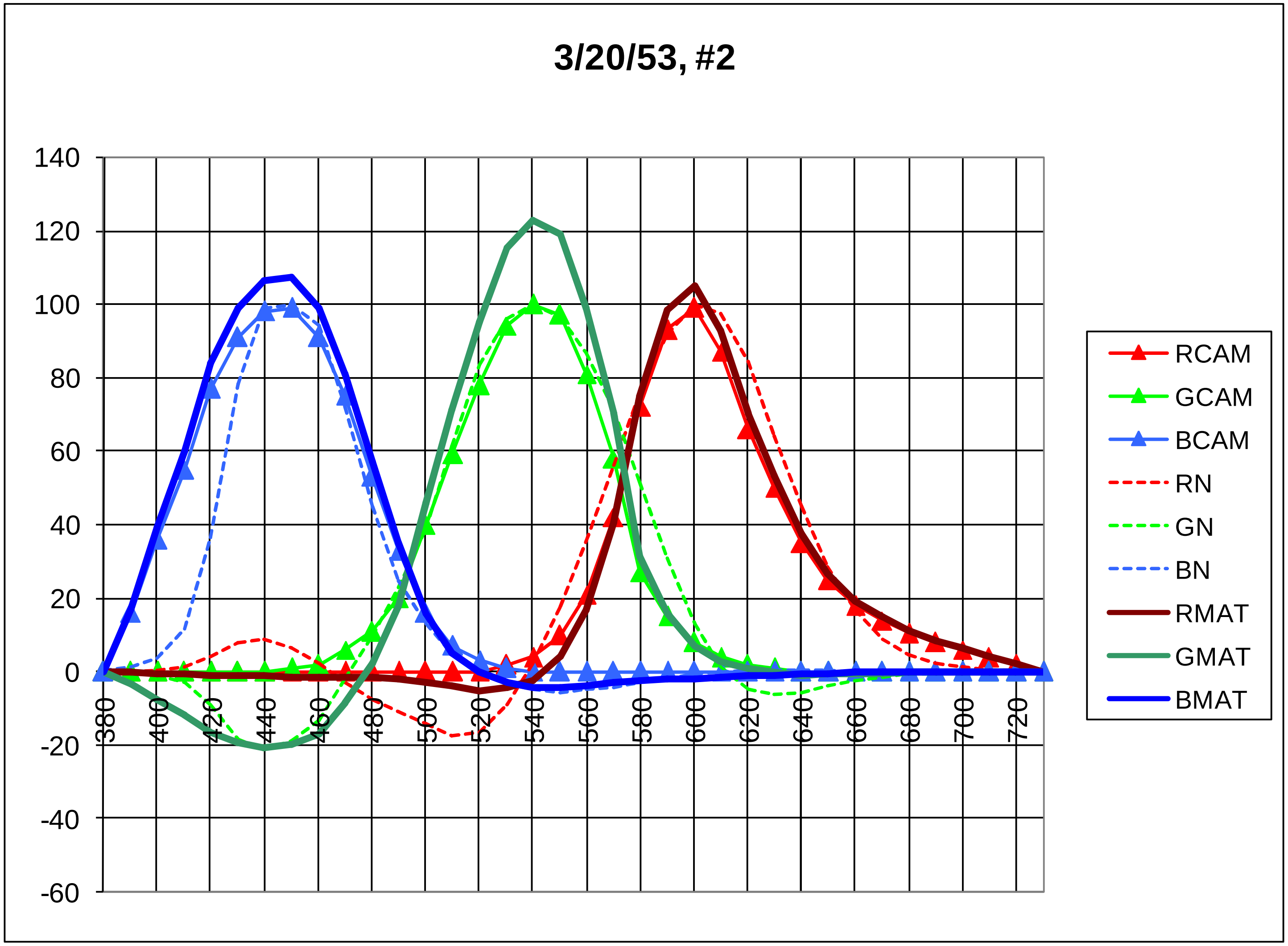
March 1953 Camera No. 2 Taking Characteristics



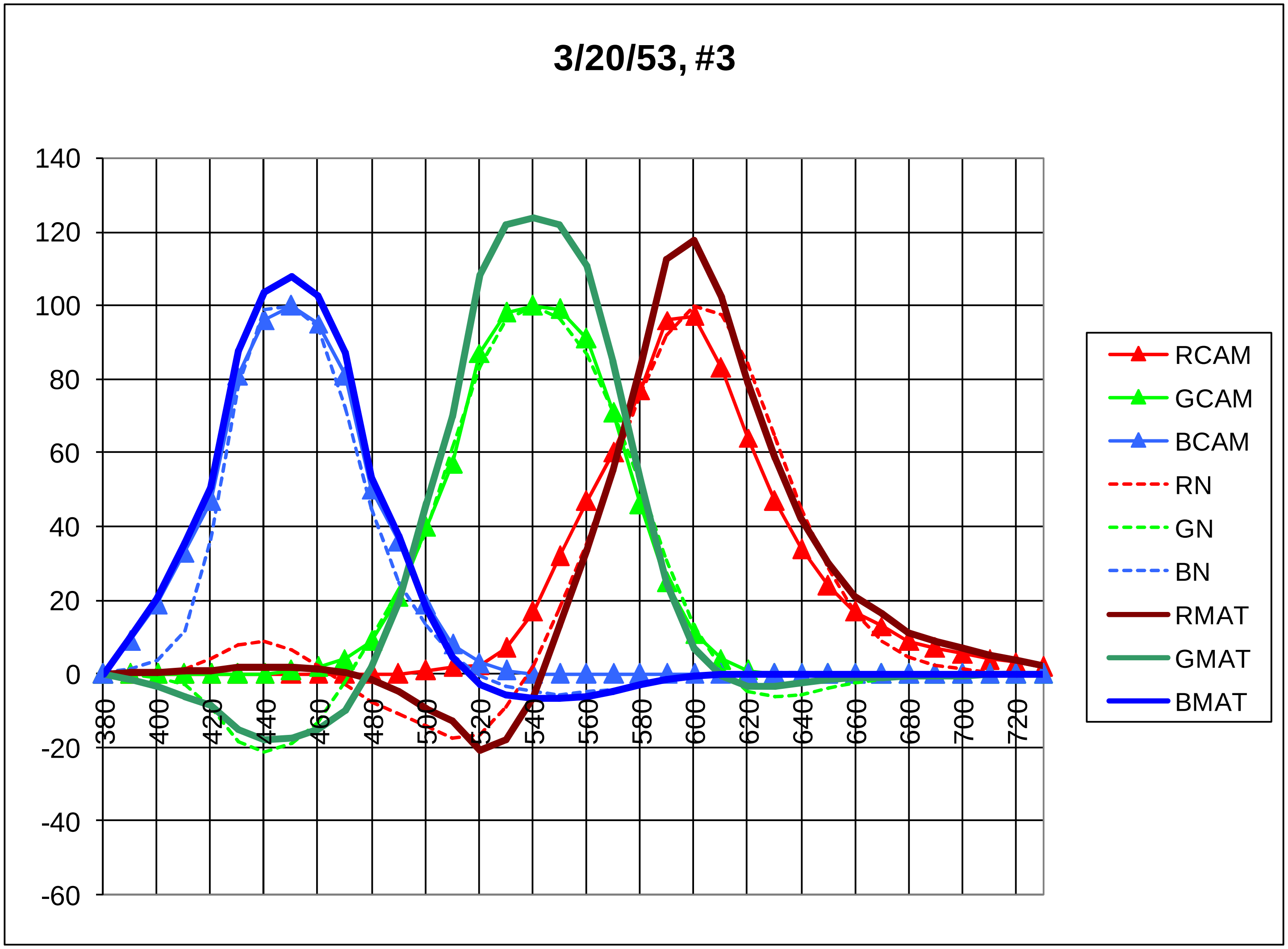
March 1953 Camera No. 3 Taking Characteristics



March 1953 Camera No. 2
Taking Characteristics



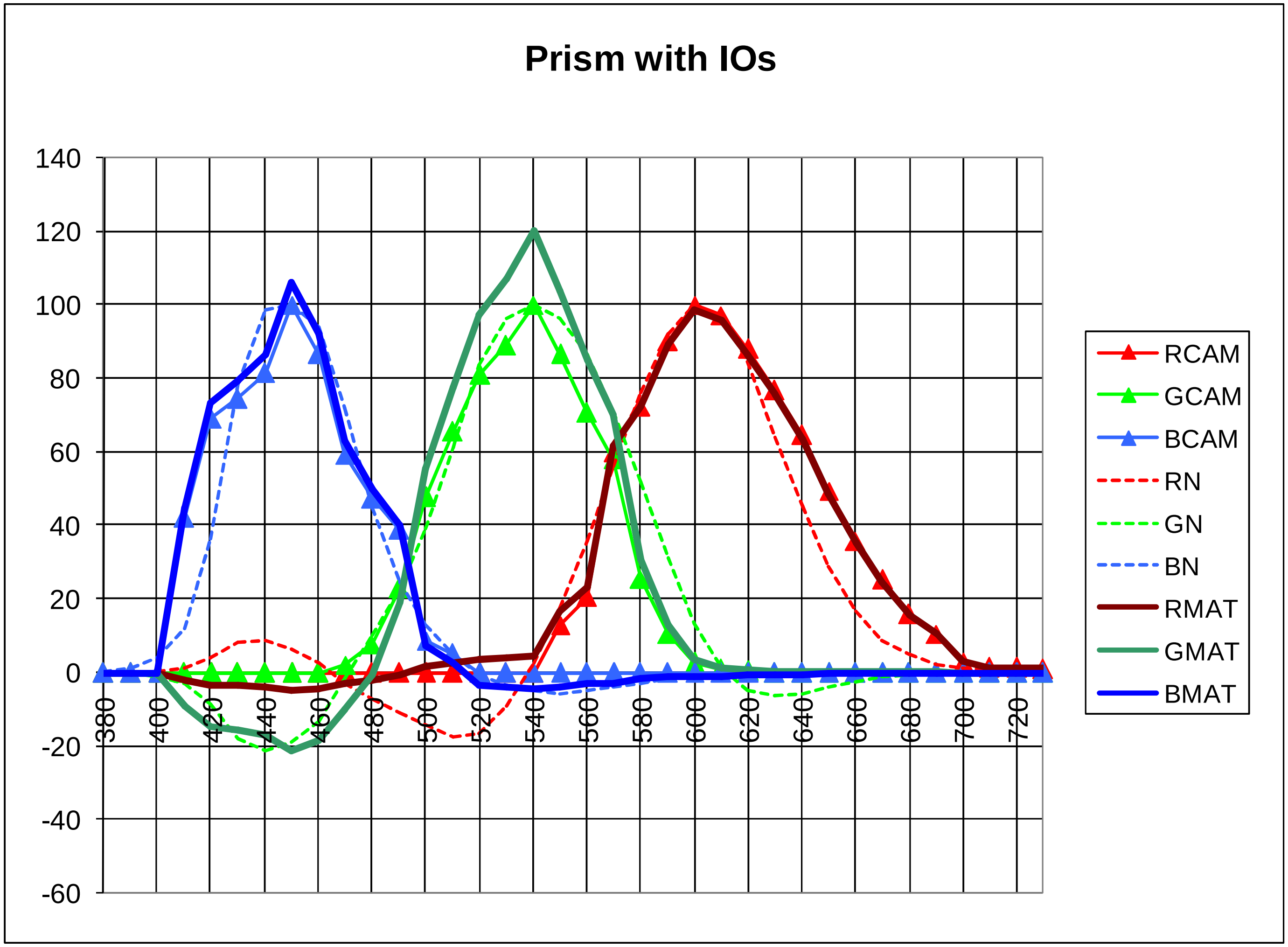
March 1953 Camera No. 3 Taking Characteristics



Prism Camera

- Later versions of TK-41 used prism optics
  - Reduced internal optical reflections
  - Trimming filters (supposedly more stable than separate filters used earlier) cemented in place
- Many earlier cameras were retrofitted

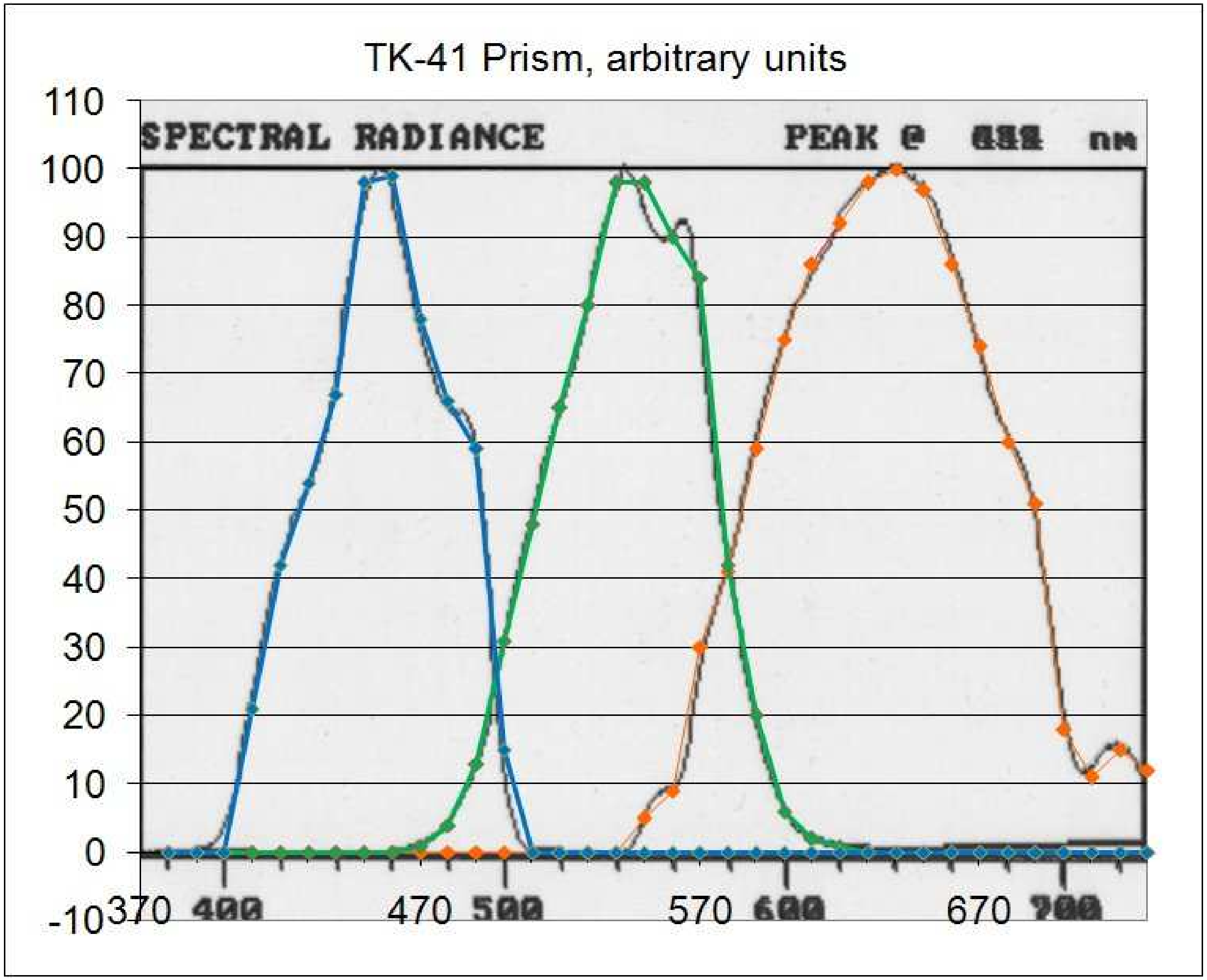
Prism Camera
Taking Characteristics



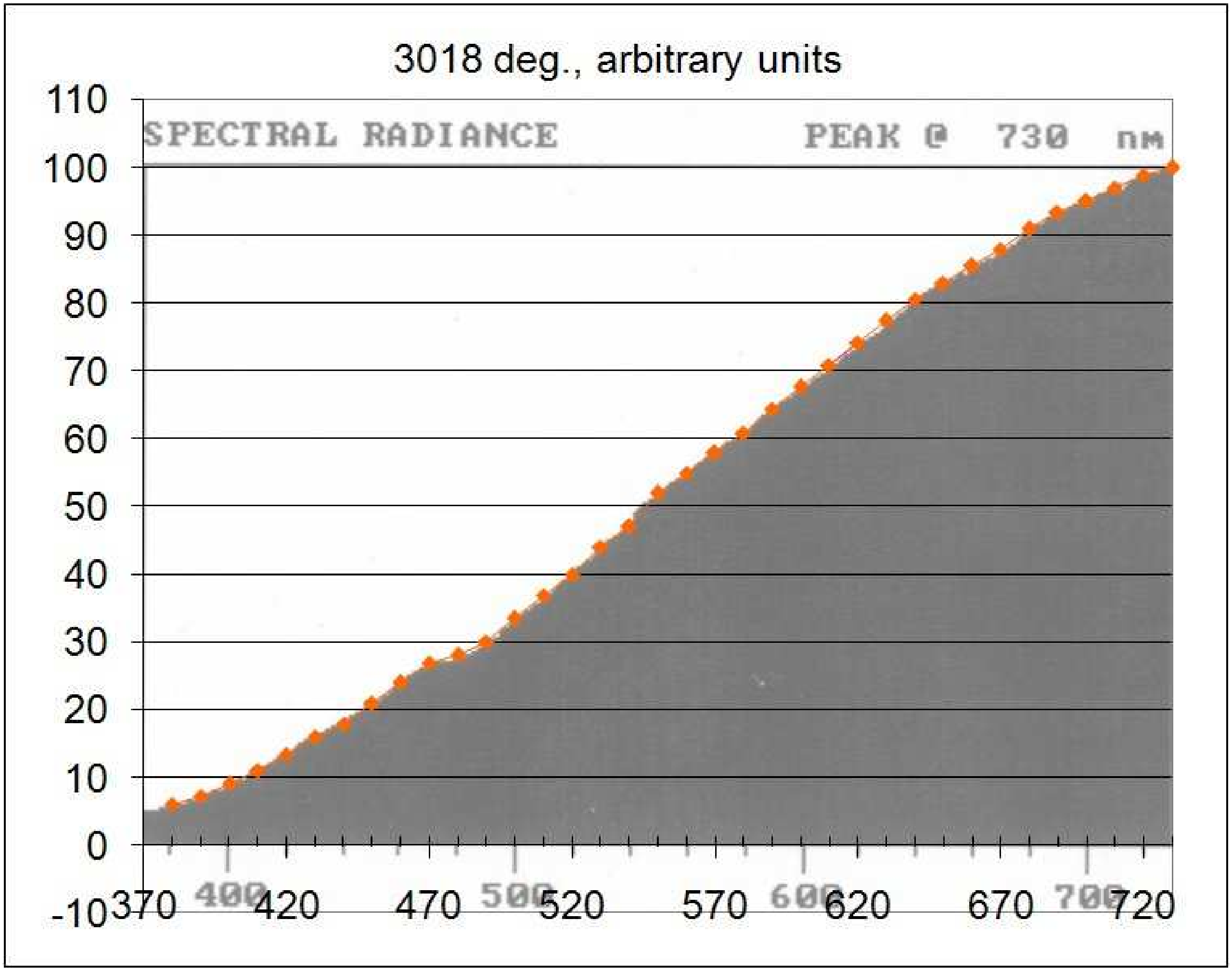
Calculation of Prism Camera Characteristics

- Measurements
  - RGB curves
  - Spectrum of instrument light source
- Divide RGB curves by source
- Multiply by image orthicon response
- Normalize final RGB curves

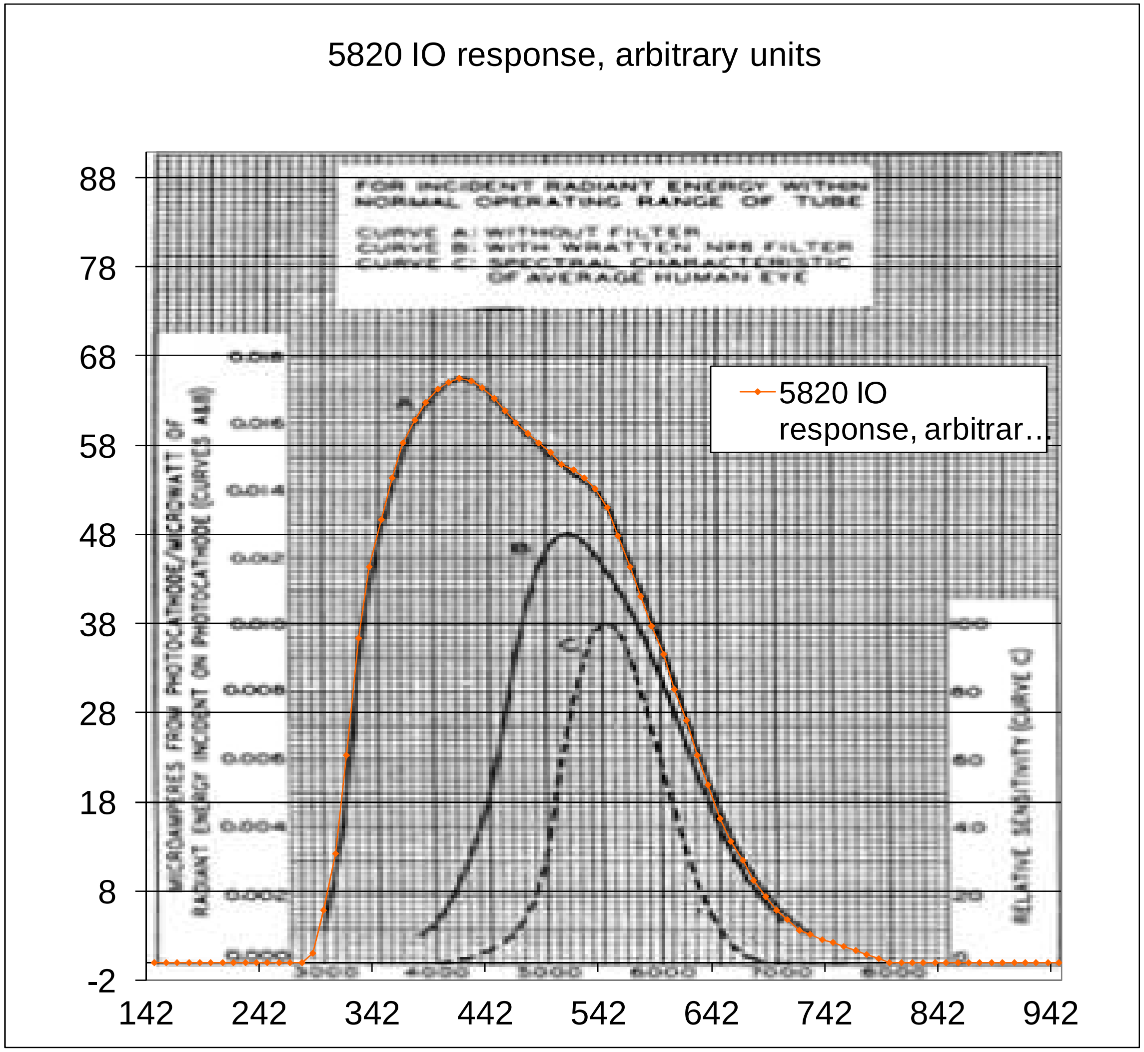
Prism Measurements As Provided, with 10-nm Interval Tracings



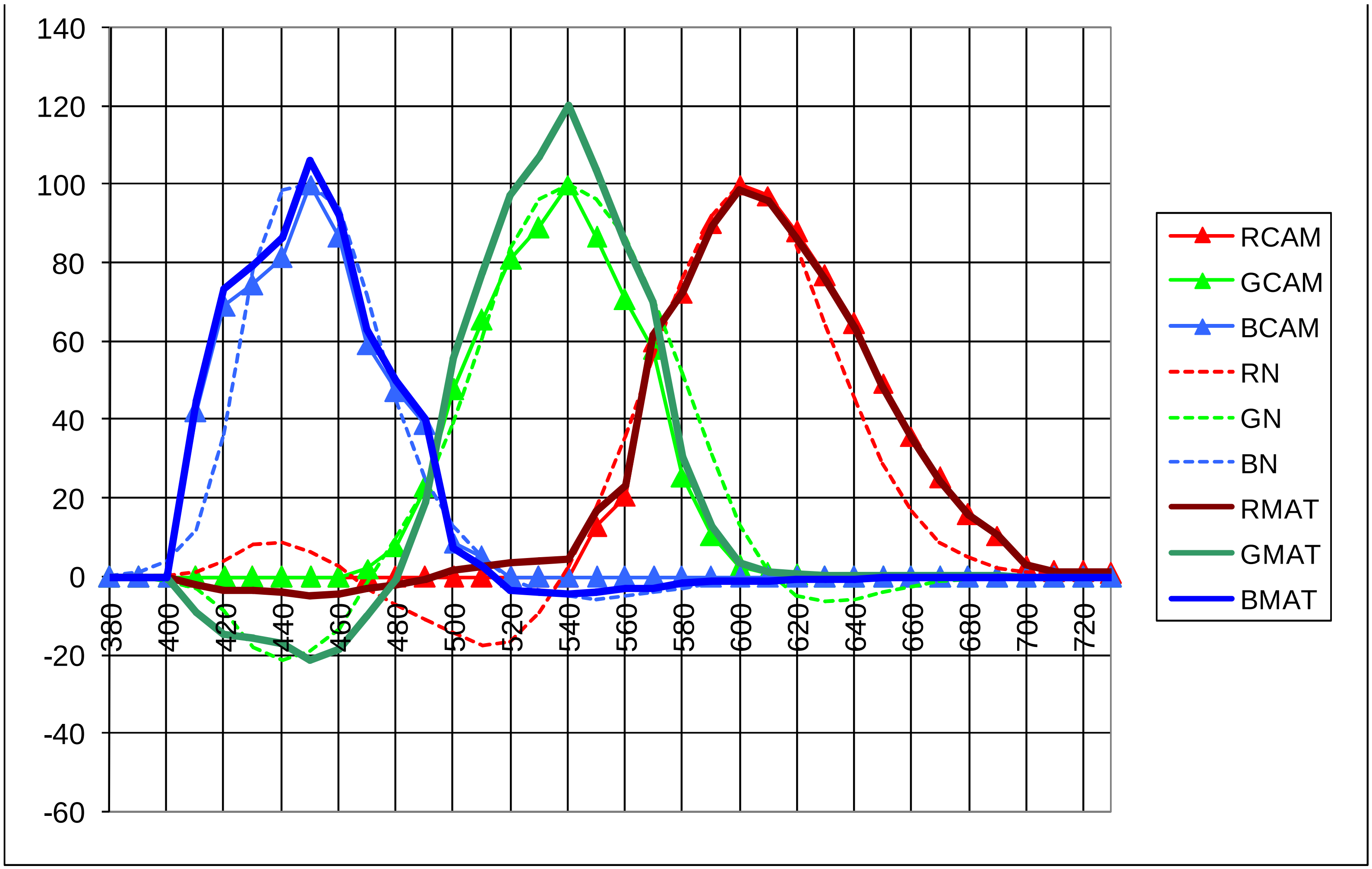
3018 K Illumination Used to Obtain Prism Curves



Tracing of Image Orthicon Spectral Sensitivity Curve

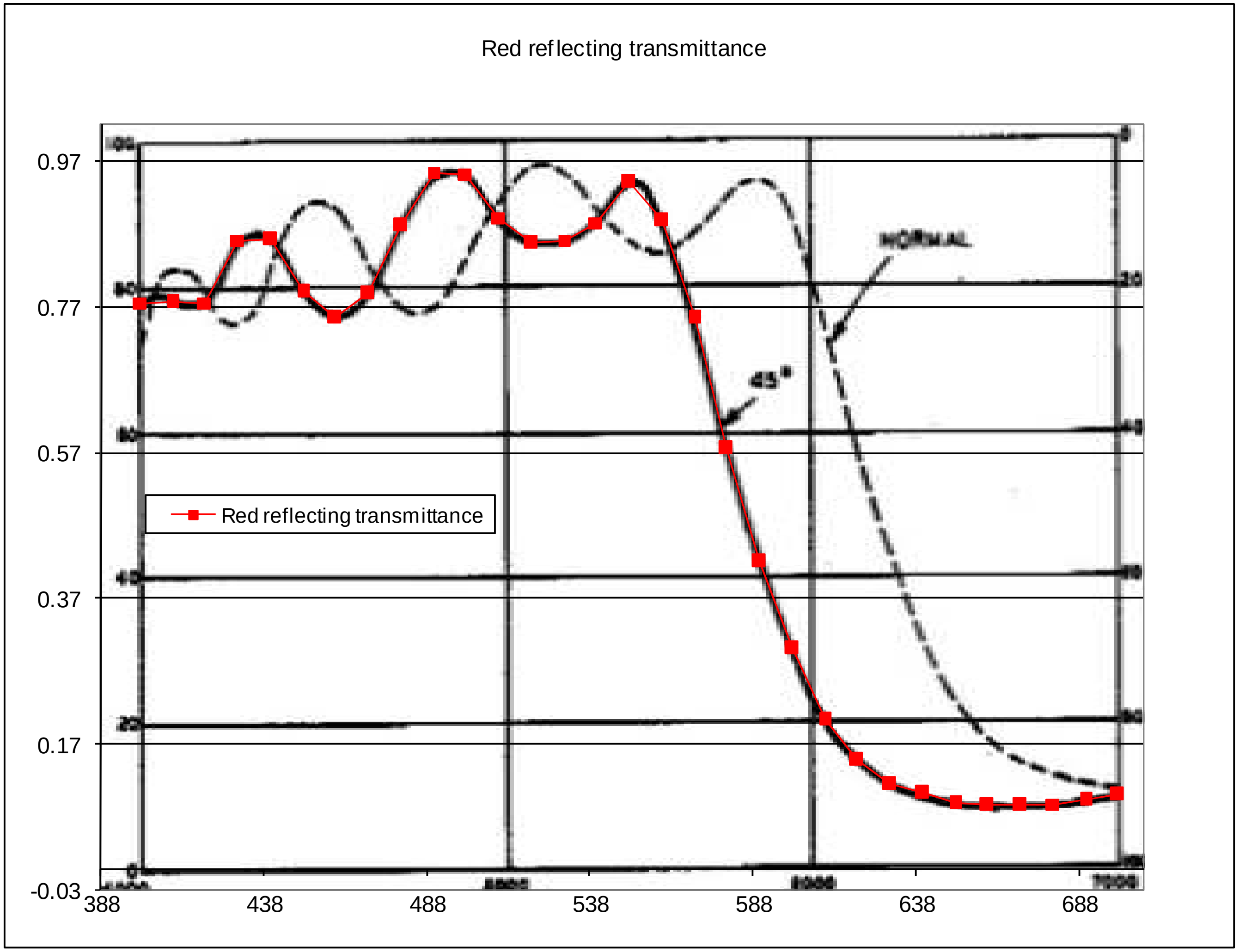


Prism Camera
Taking Characteristics

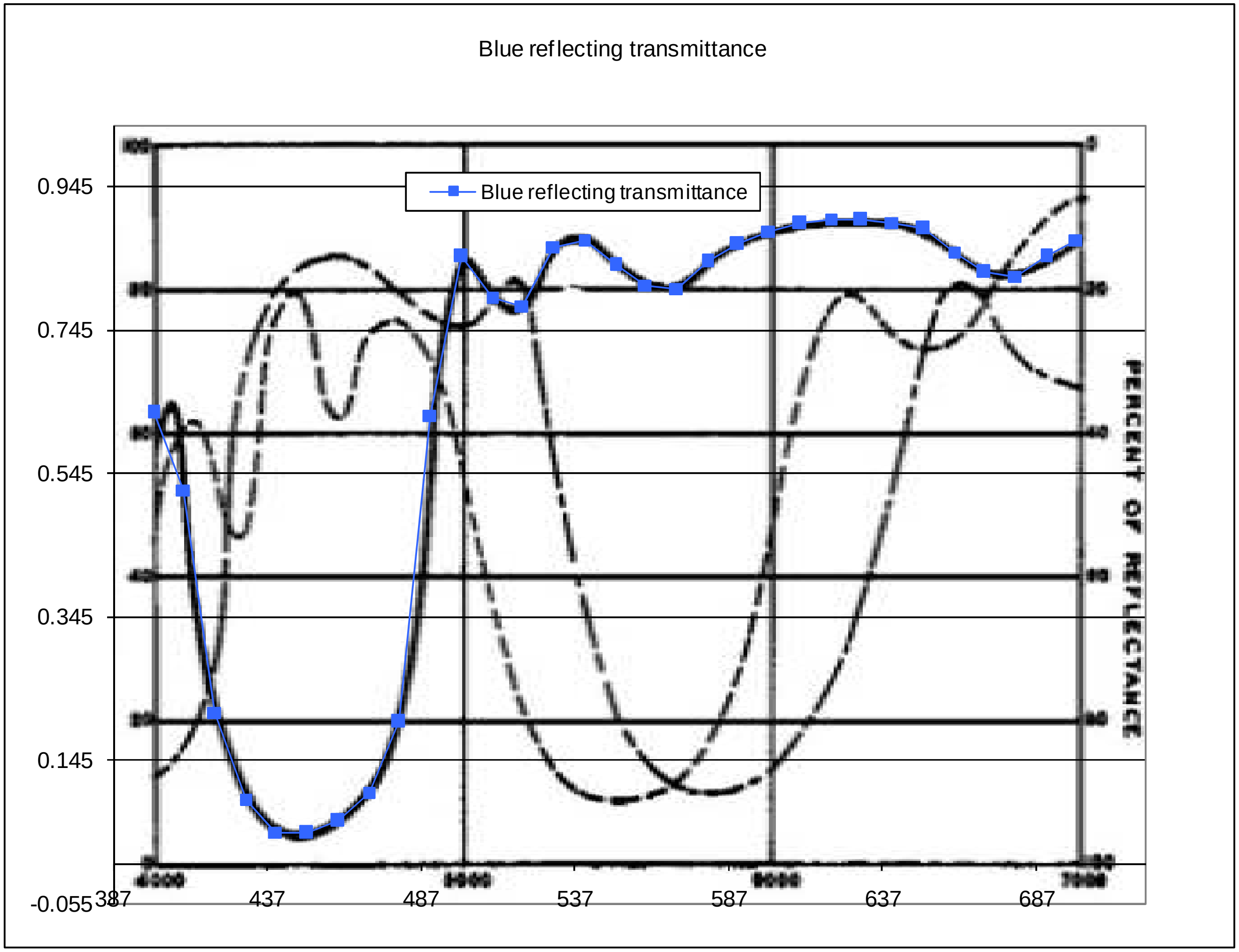


Stage-by-Stage Analysis

Tracing of Widdop's Red Mirror Transmittance



Tracing of Widdop's Blue Mirror Transmittance



Red Channel
Using Widdop's Mirrors

Red Channel

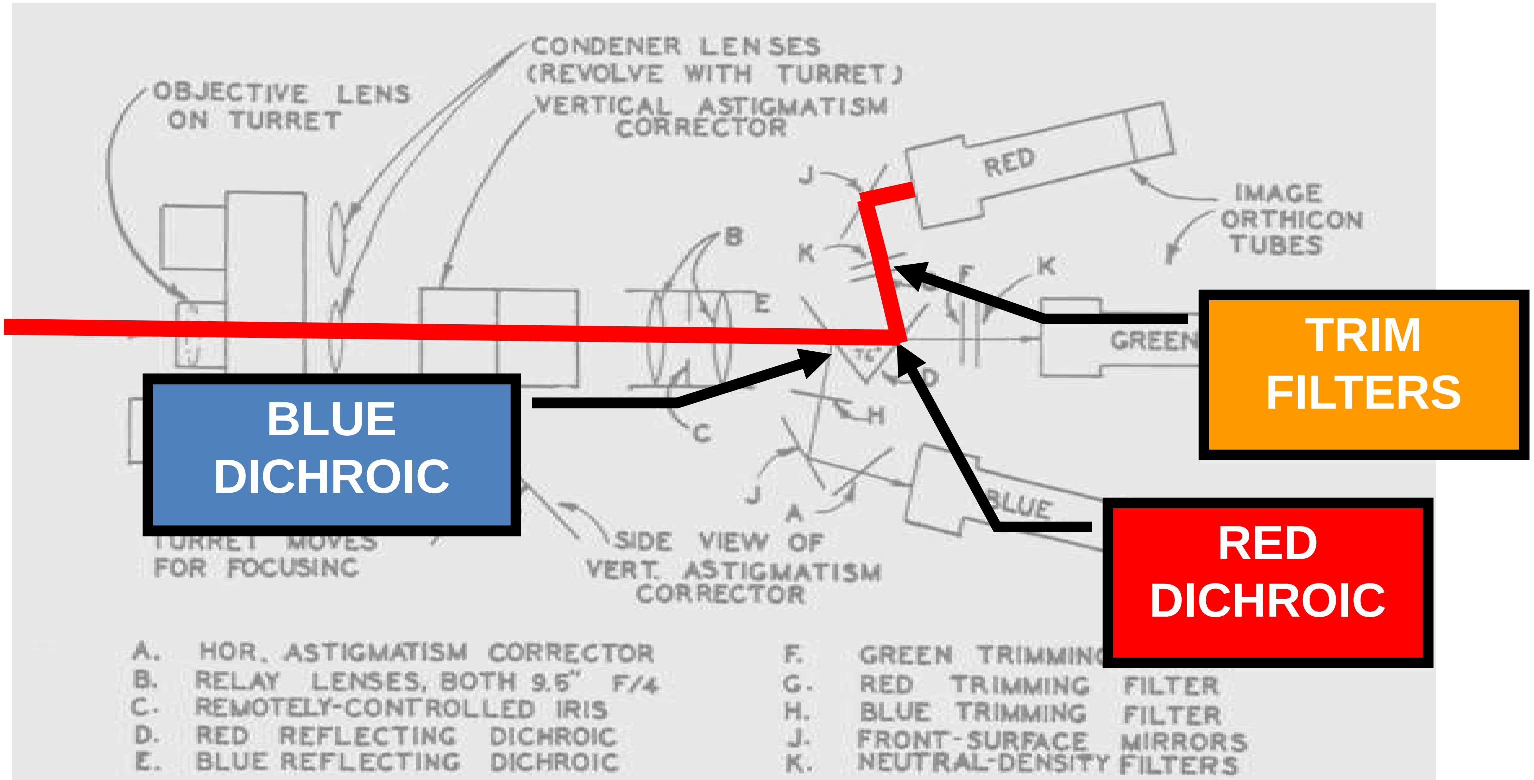
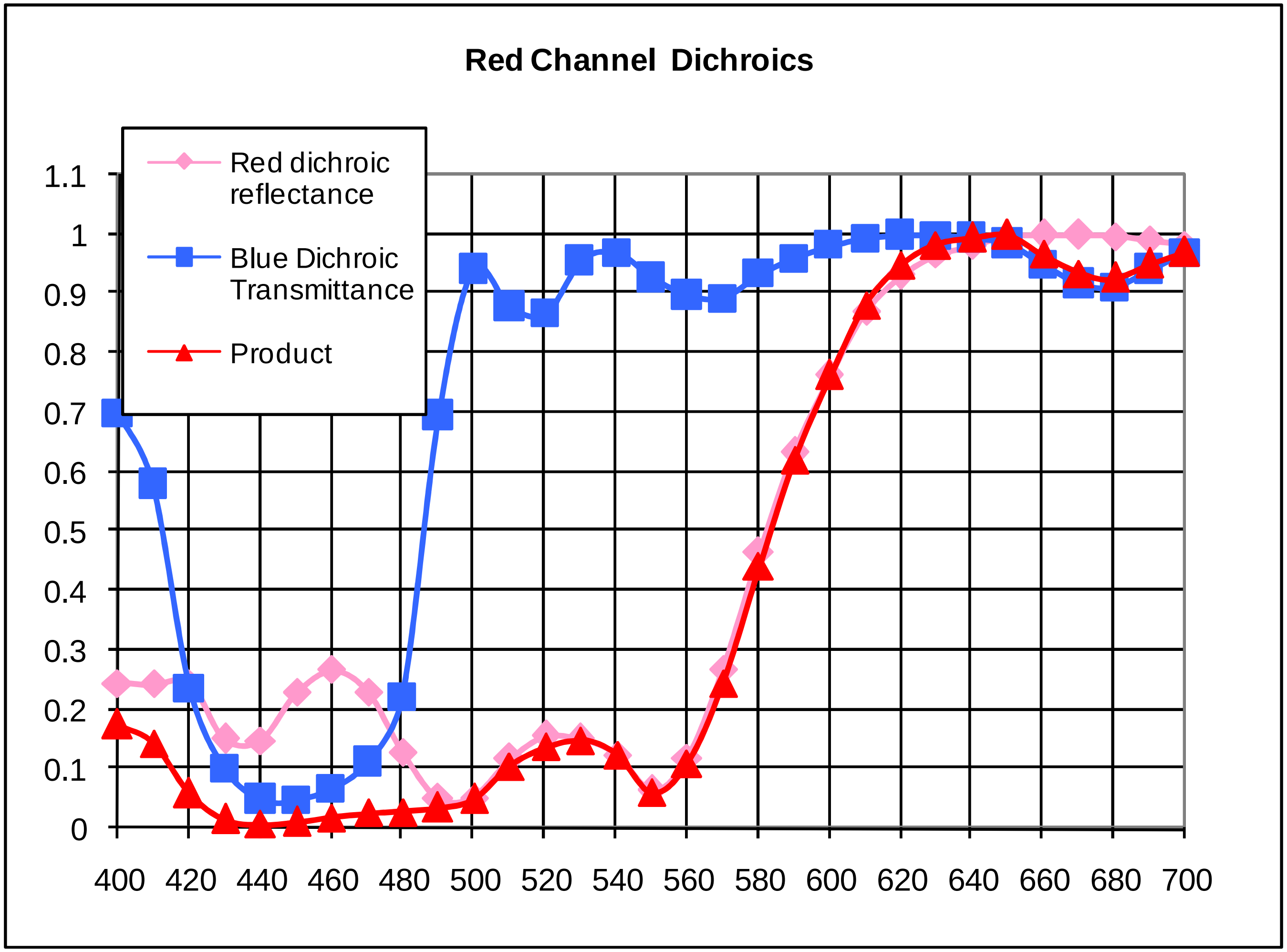


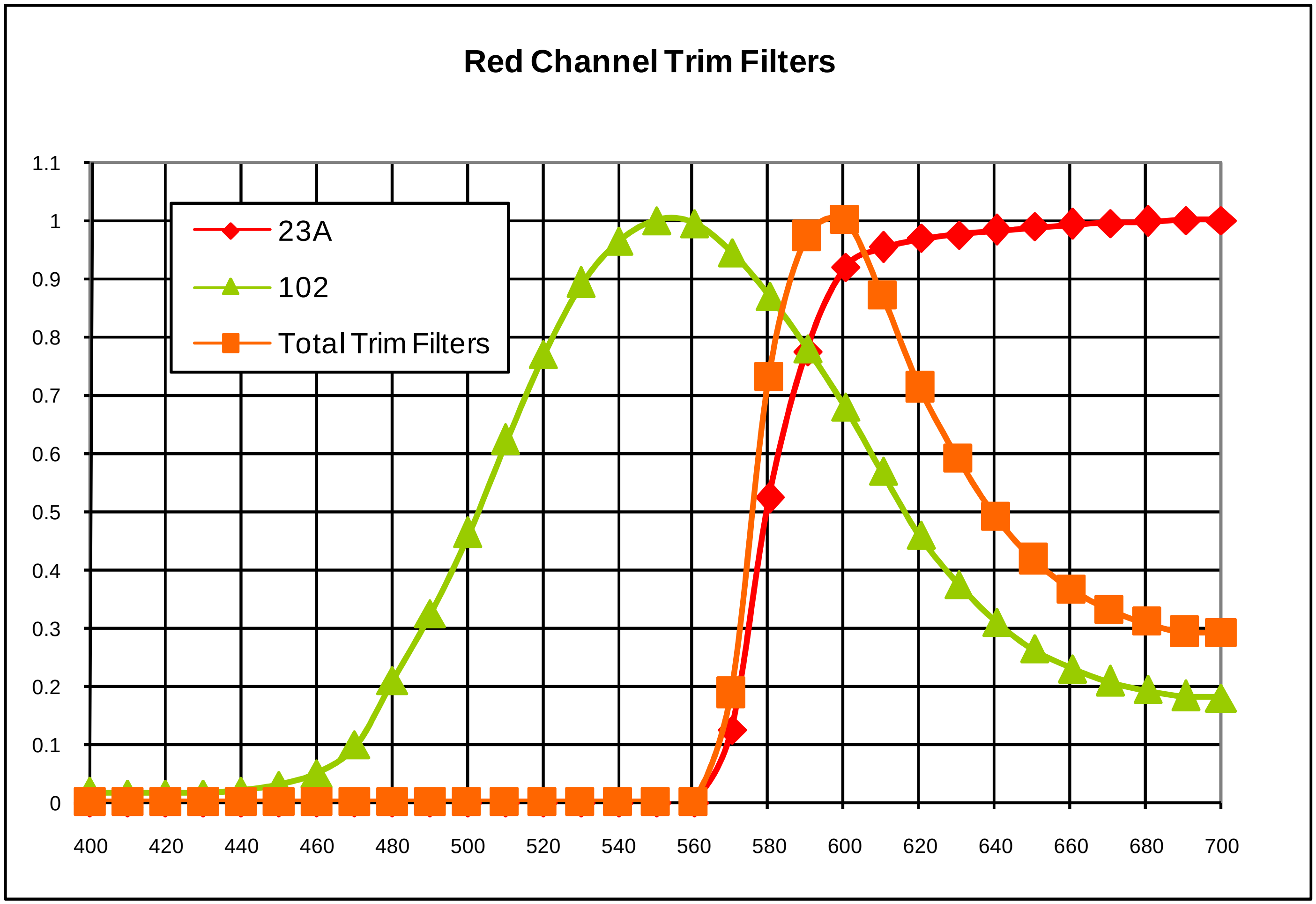
Fig. 9 — Sketch of the optical system used in an RCA three-tube color television camera.

- **Pre-Production, 1949-1953, and Early Production Dichroic Plate Optics**

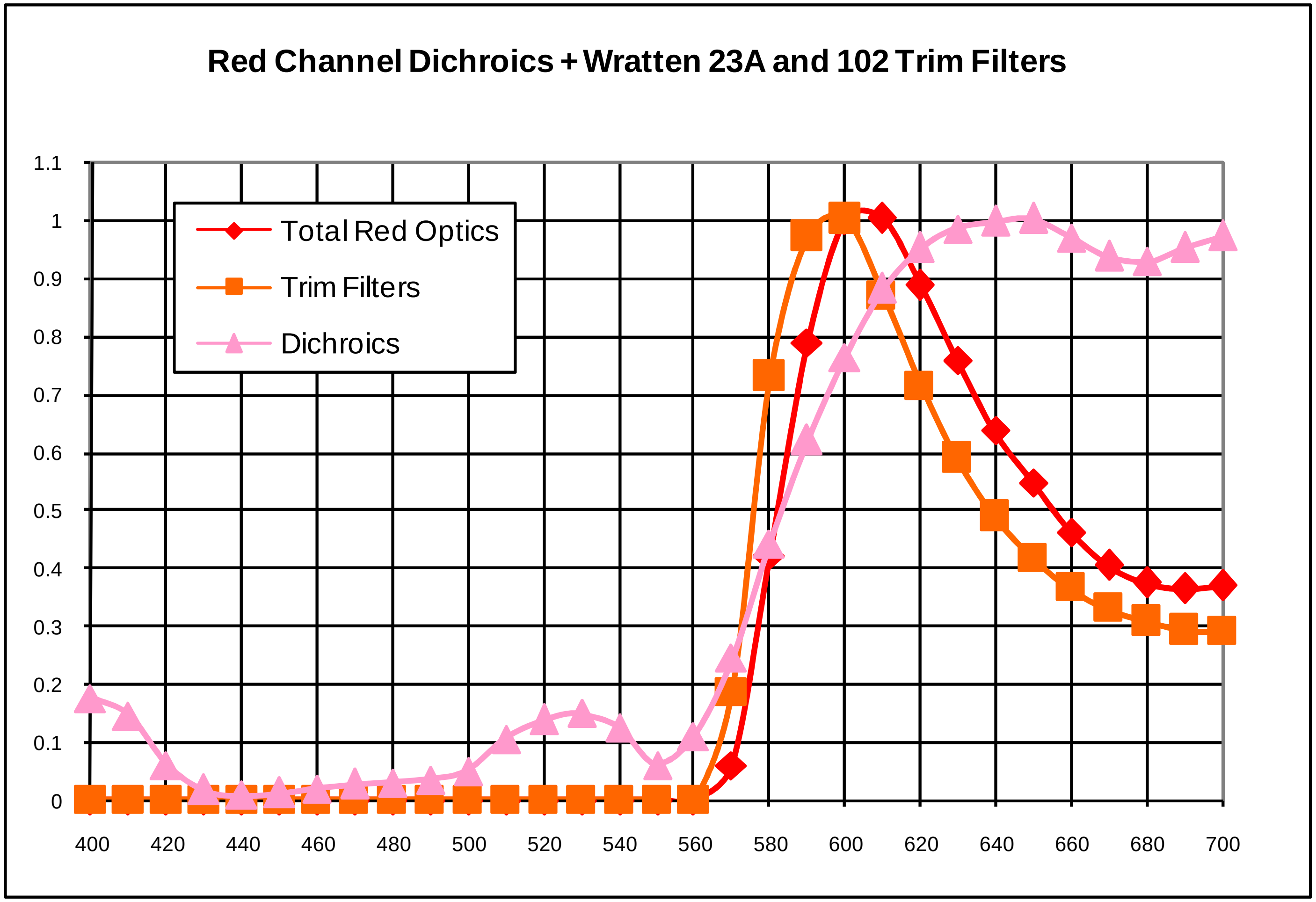
Red channel dichroic mirrors



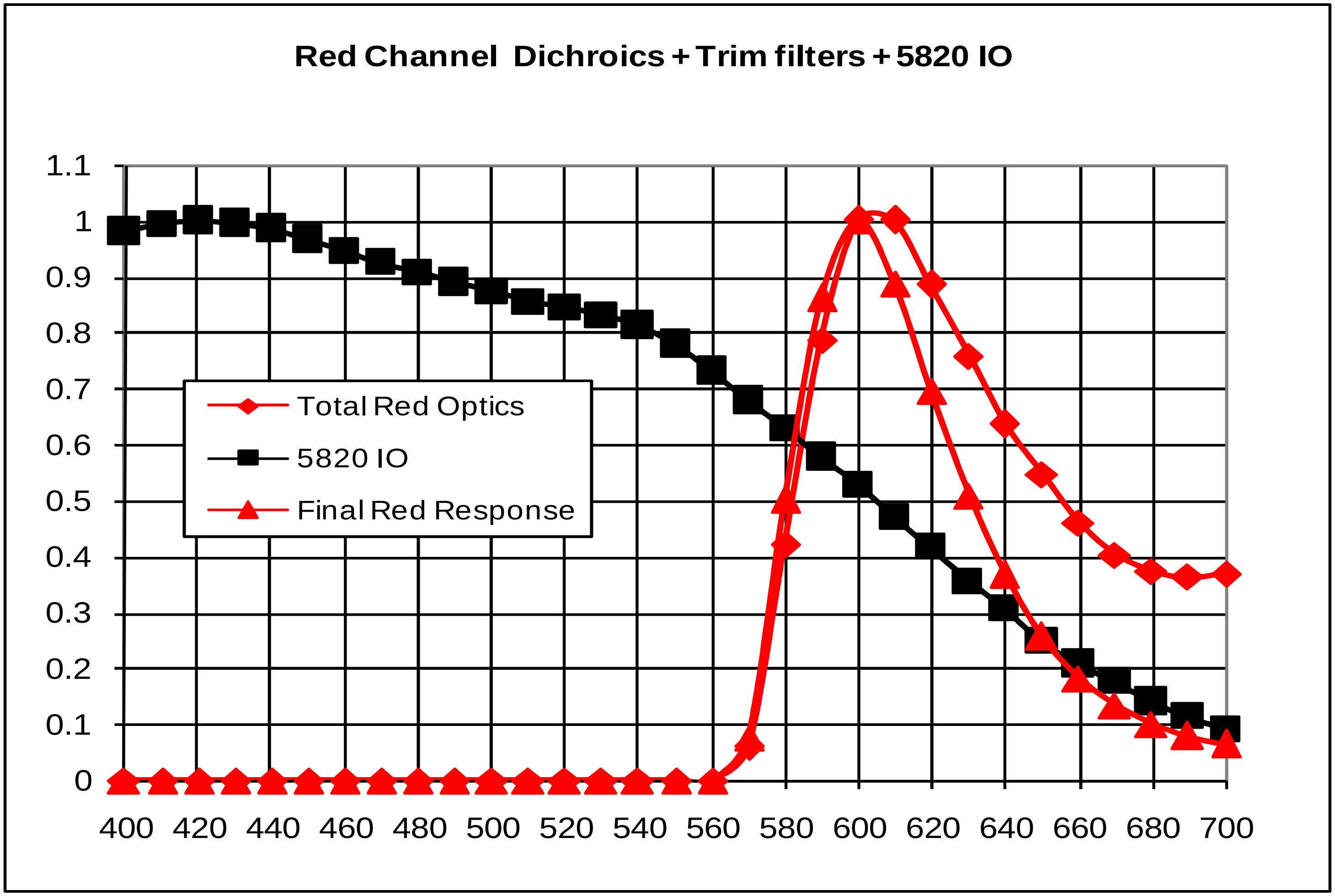
Red Channel Trimming Filters



Red Channel Dichroics Plus Trimming Filters



Red Channel Optics
Plus Image Orthicon



Green Channel
Using Widdop's Mirrors

Green Channel

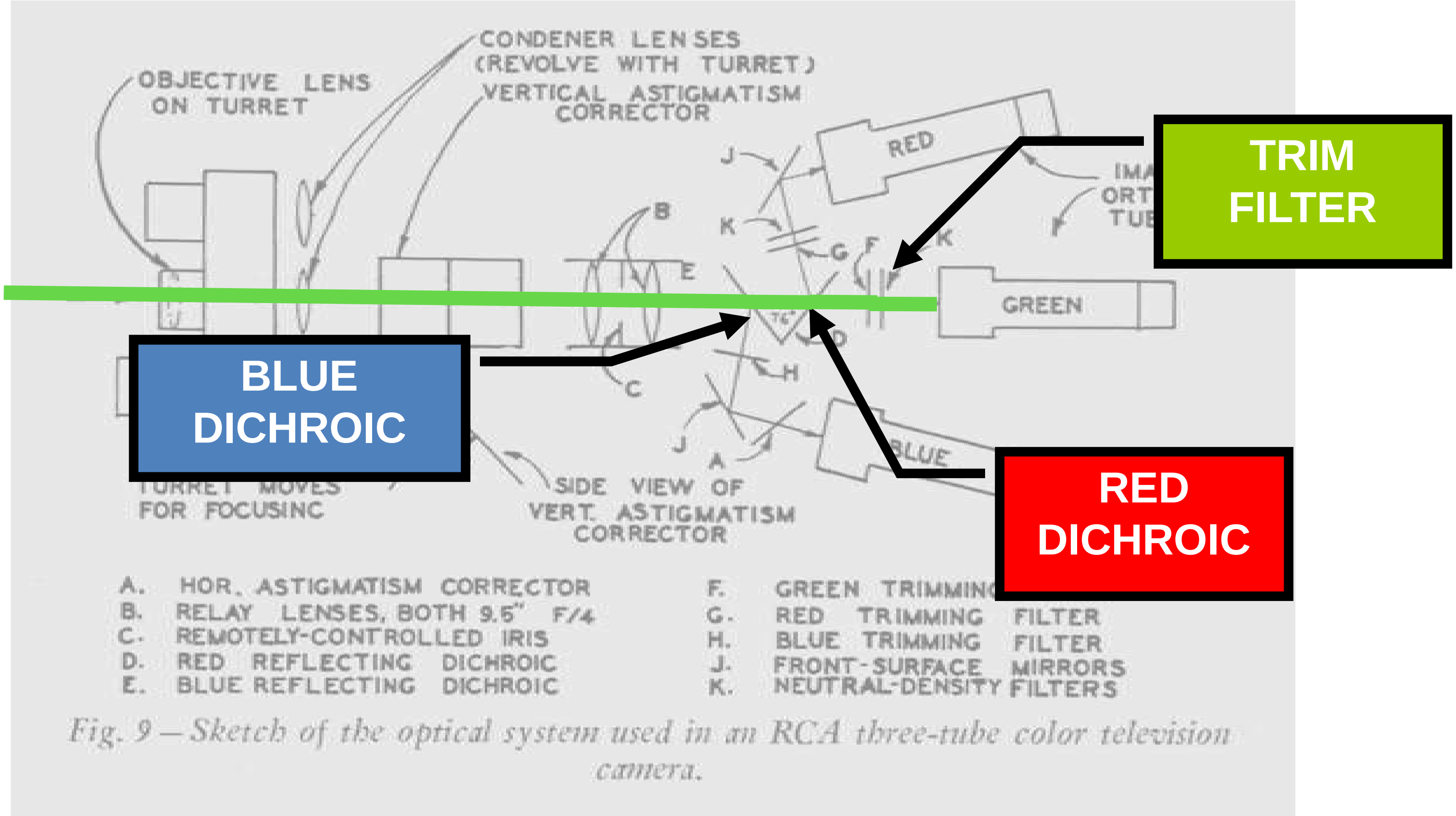
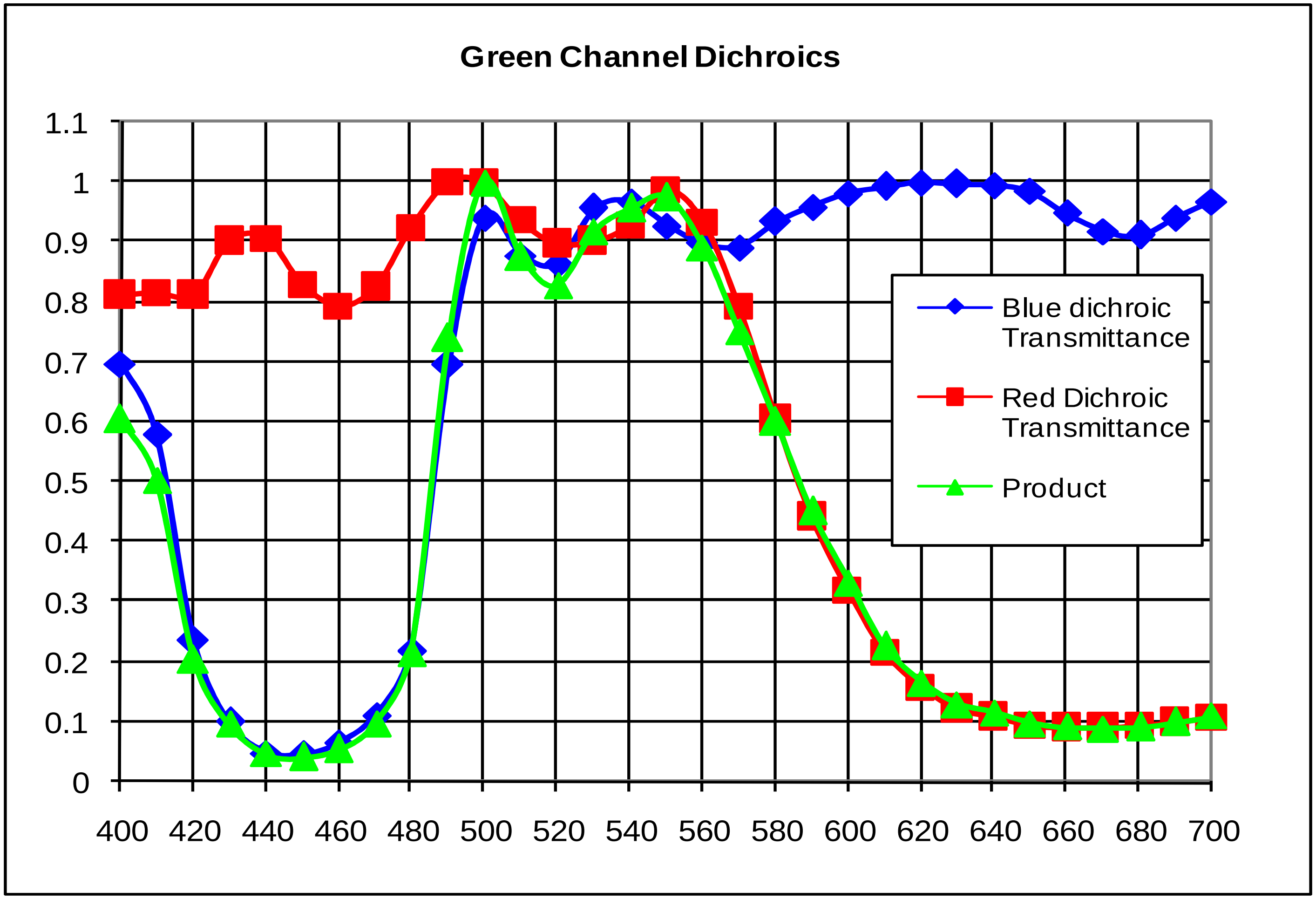


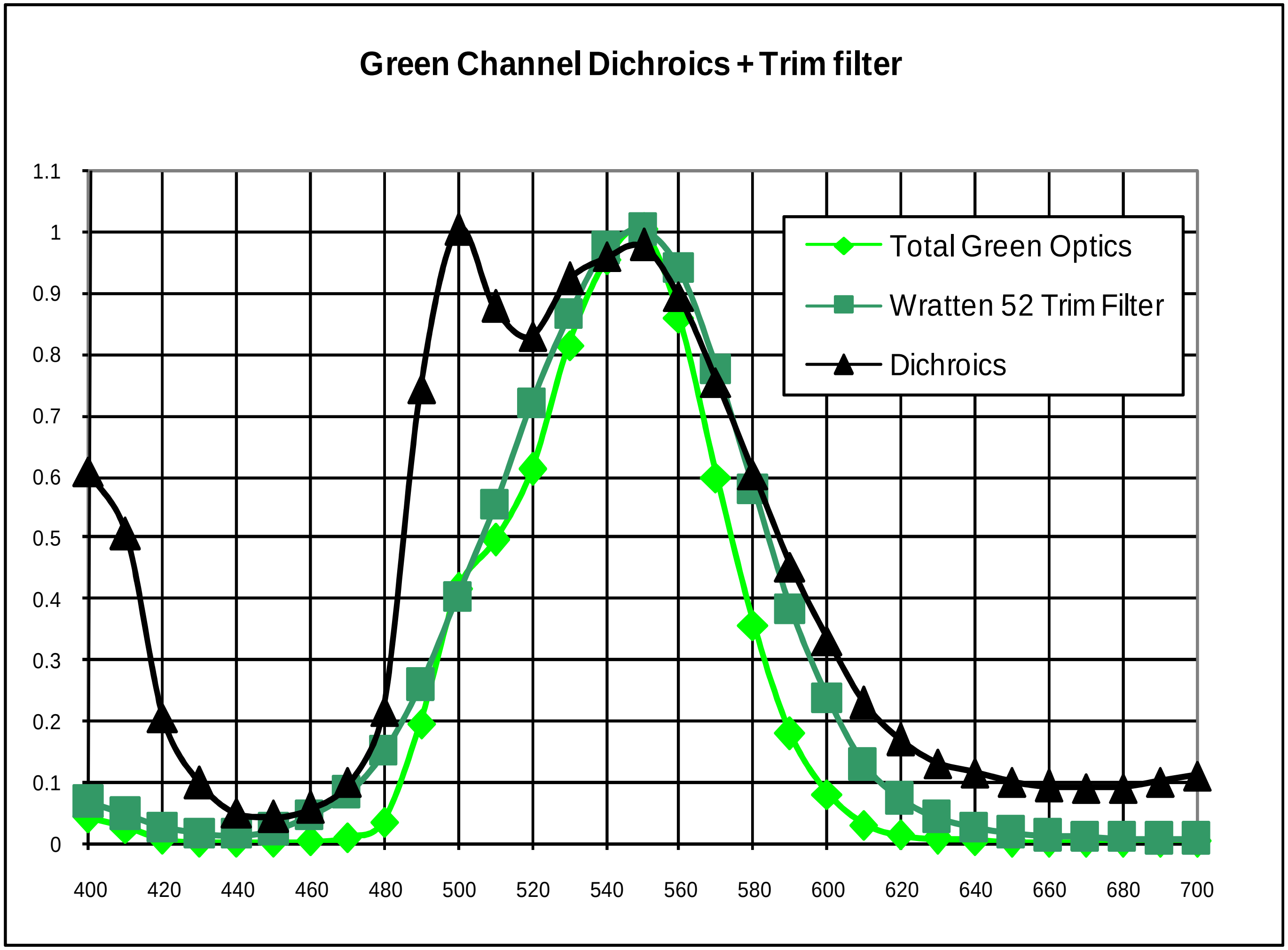
Fig. 9 — Sketch of the optical system used in an RCA three-tube color television camera.

- **Pre-Production, 1949-1953, and Early Production Dichroic Plate Optics**

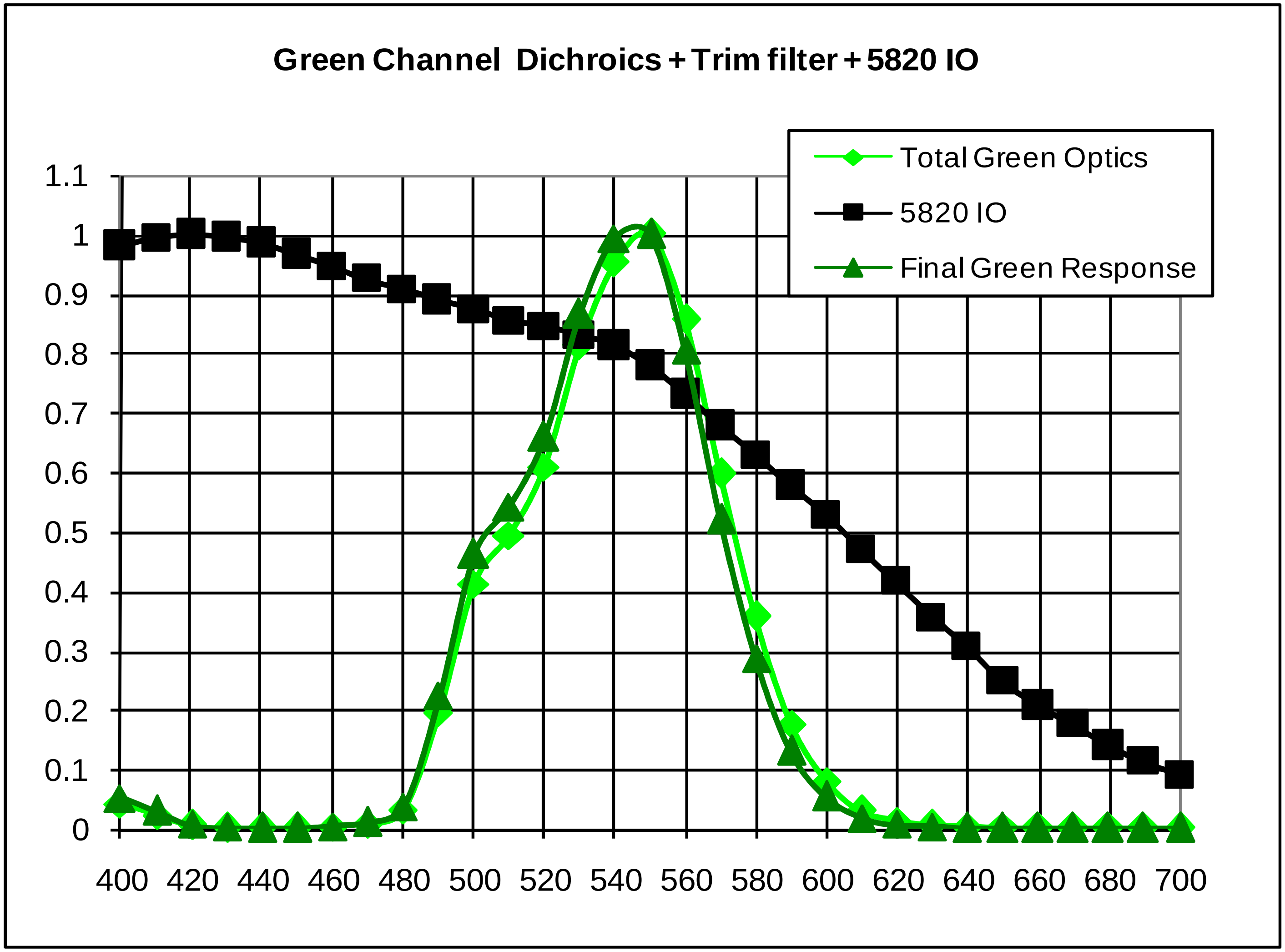
Green Channel Dichroic Mirrors



Green Channel Dichroic Mirrors Plus Trimming Filter



Green Channel Optics
Plus Image Orthicon



Blue Channel
Using Widdop's Mirrors

Blue Channel

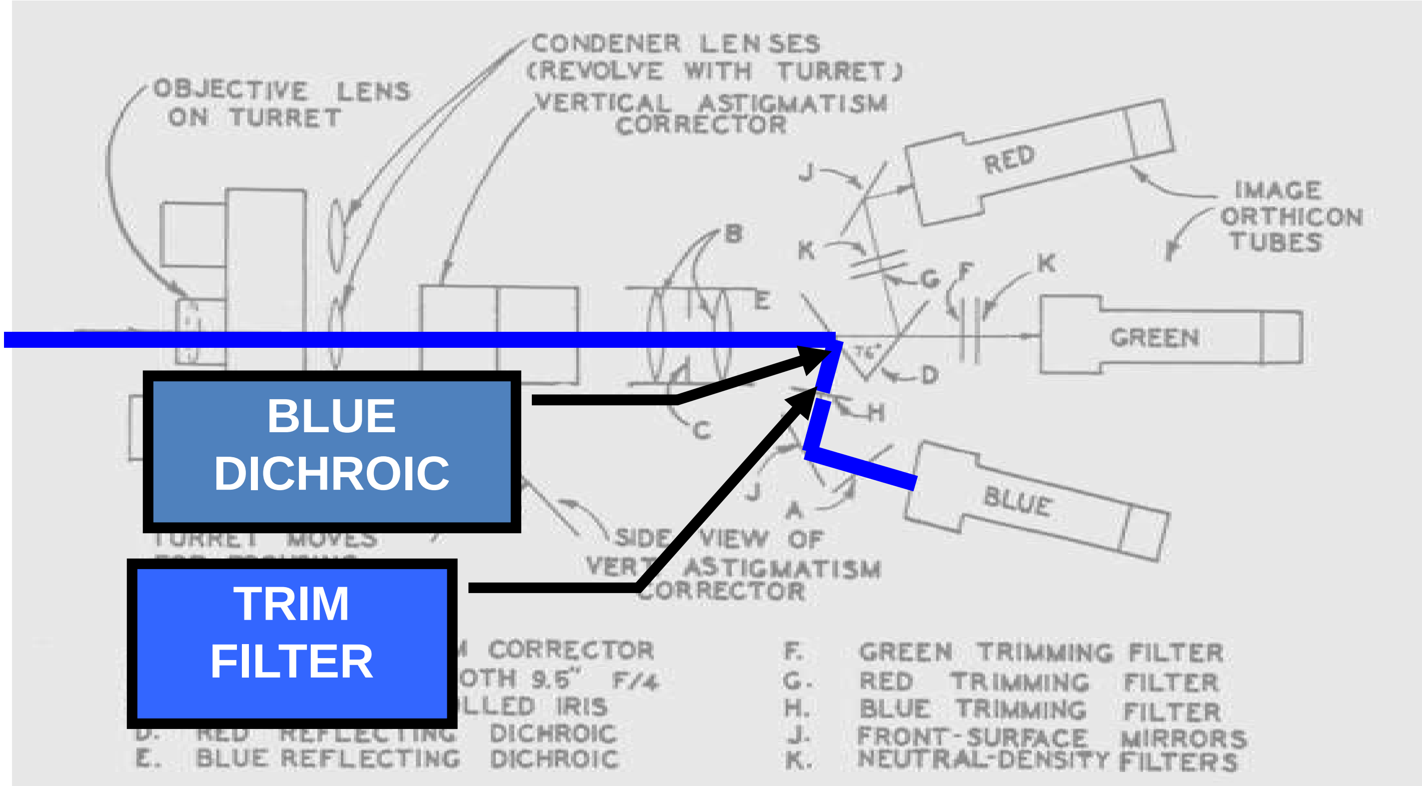
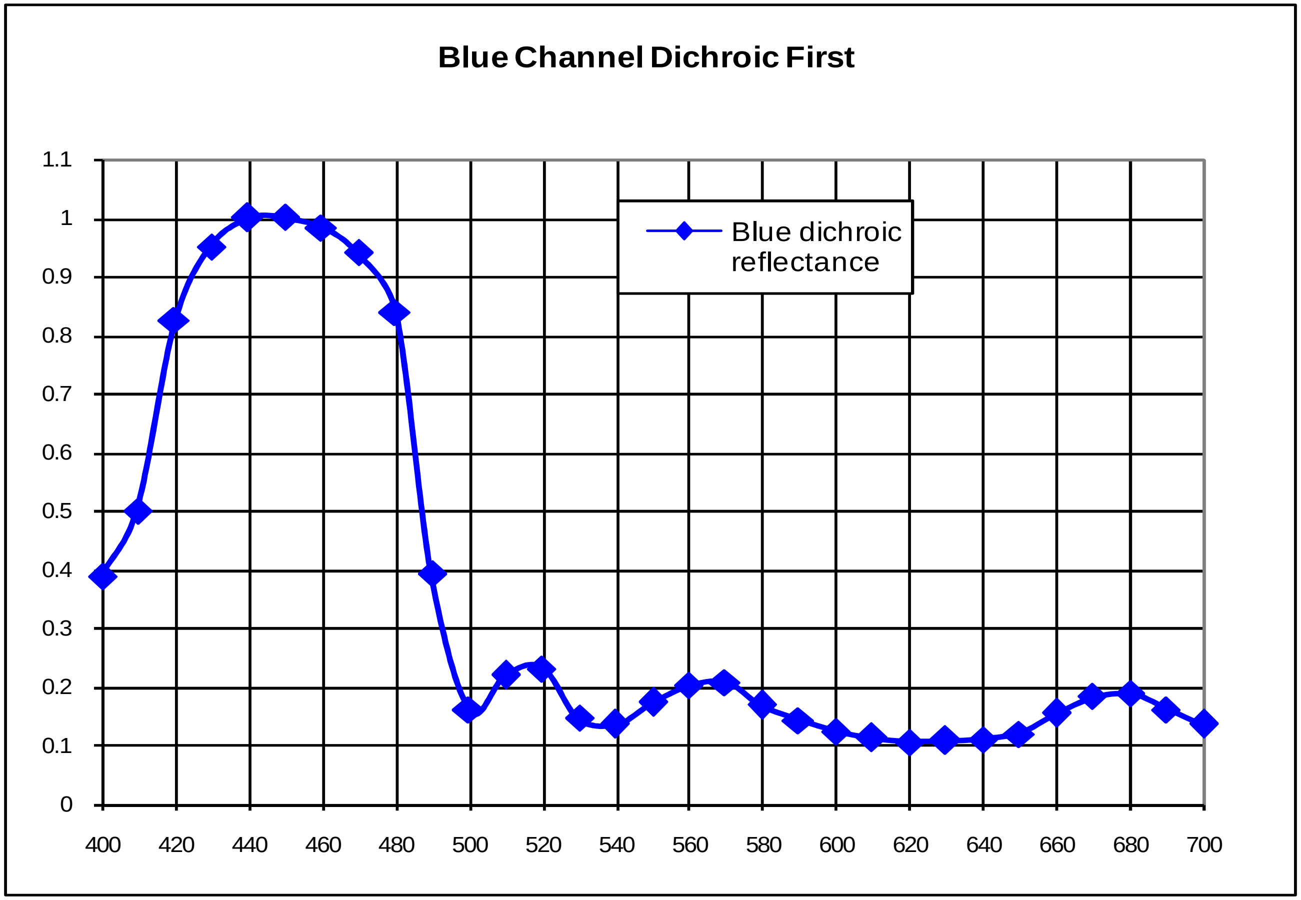


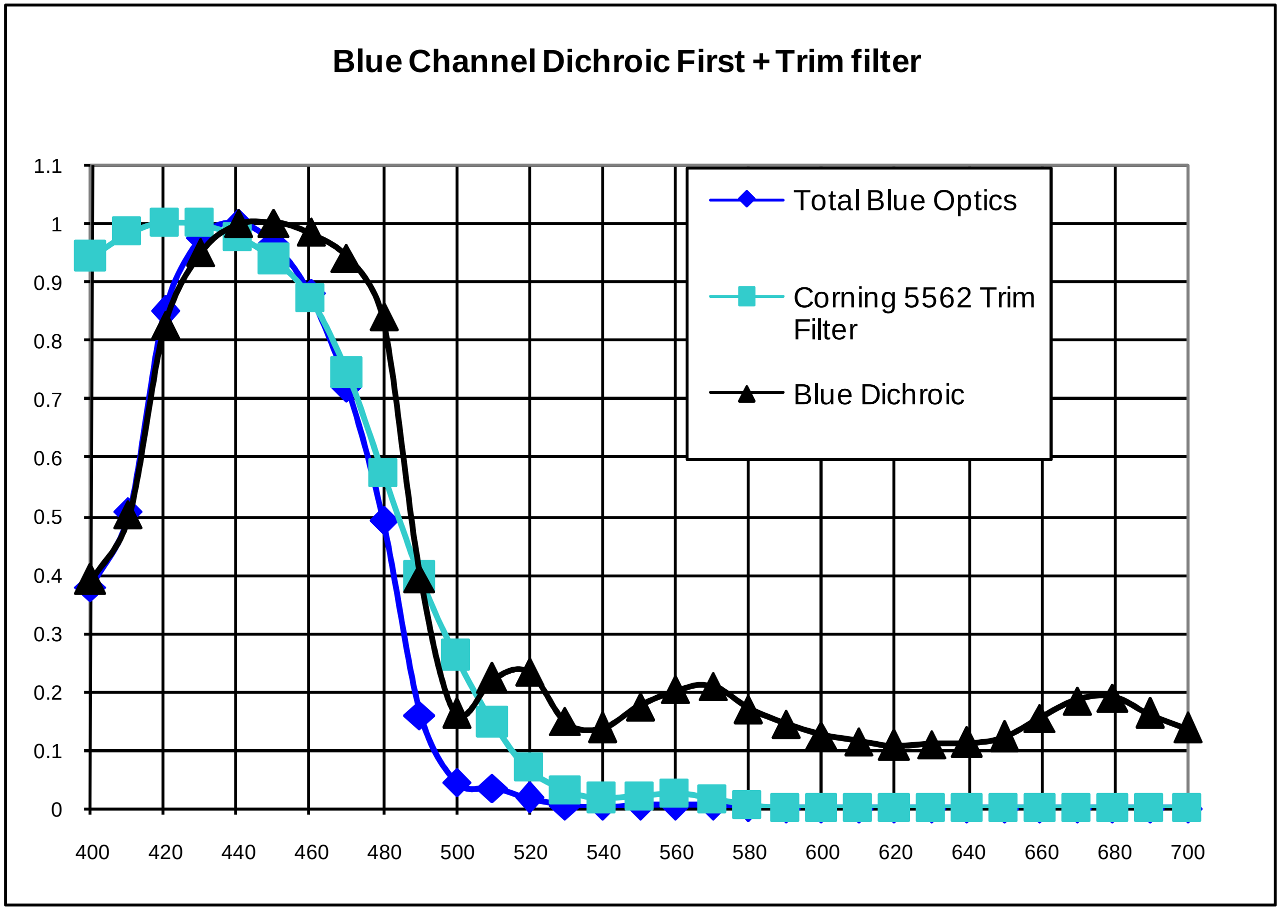
Fig. 9 — Sketch of the optical system used in an RCA three-tube color television camera.

- **Pre-Production, 1949-1953, and Early Production Dichroic Plate Optics**

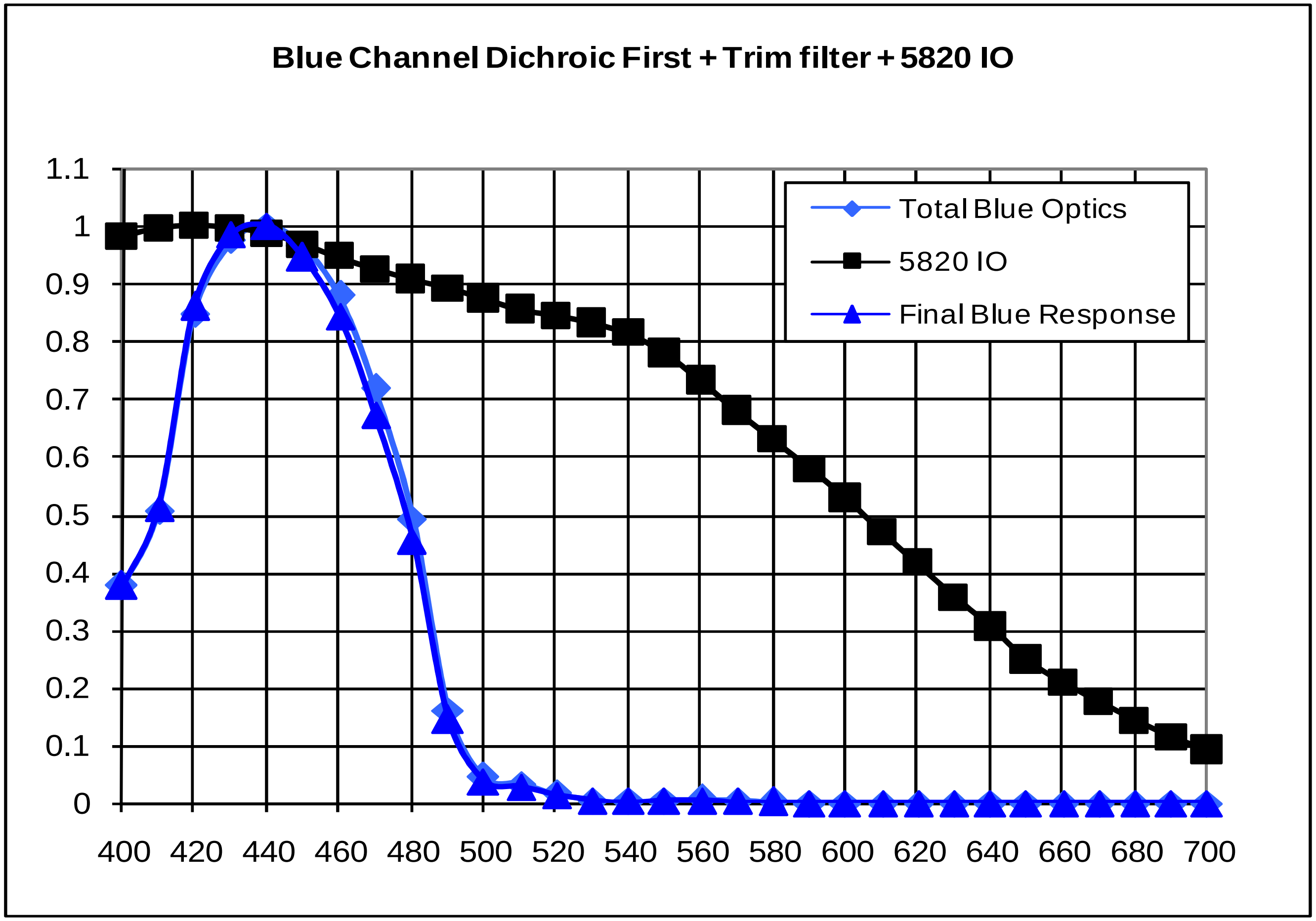
Blue Channel Dichroic Mirror



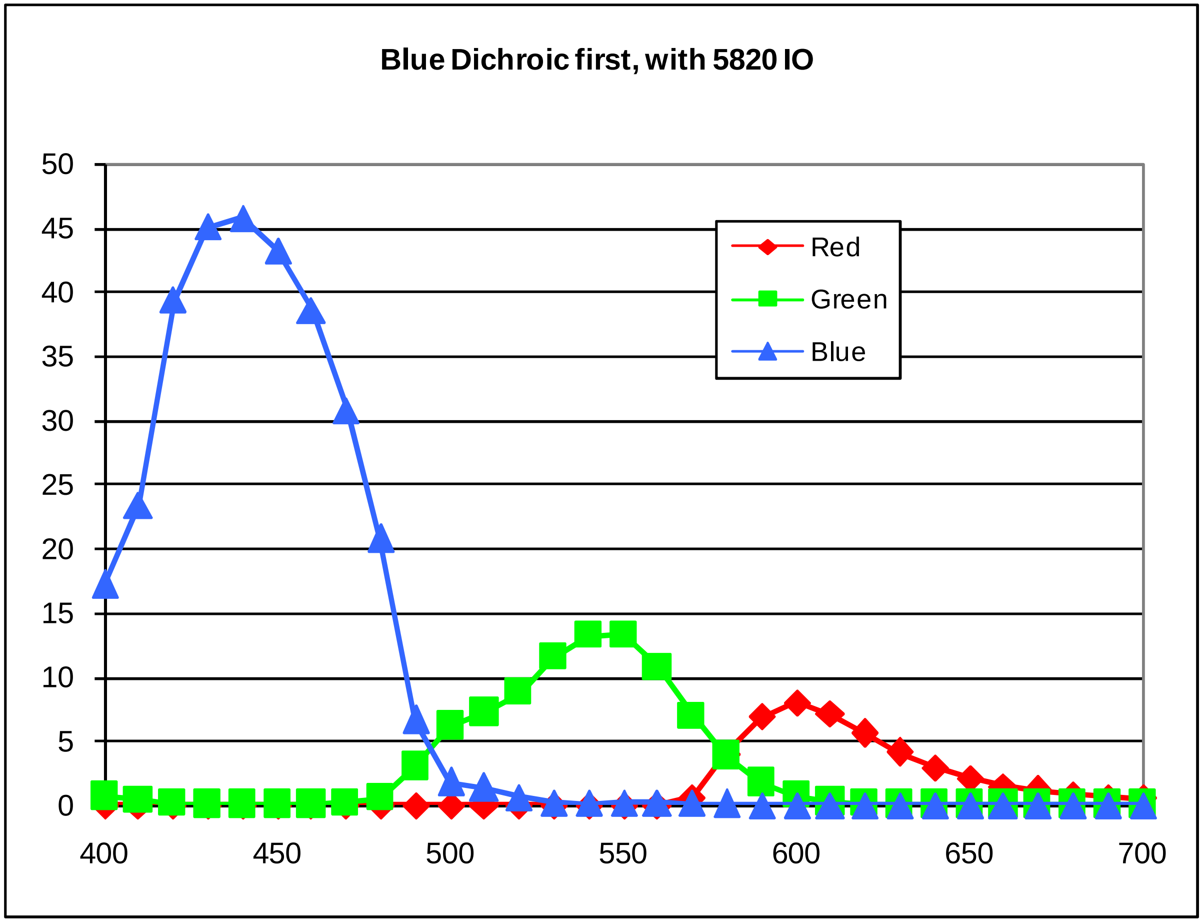
Blue Channel Dichroic Mirror Plus Trimming Filter



Blue Channel Optics Plus Image Orthicon

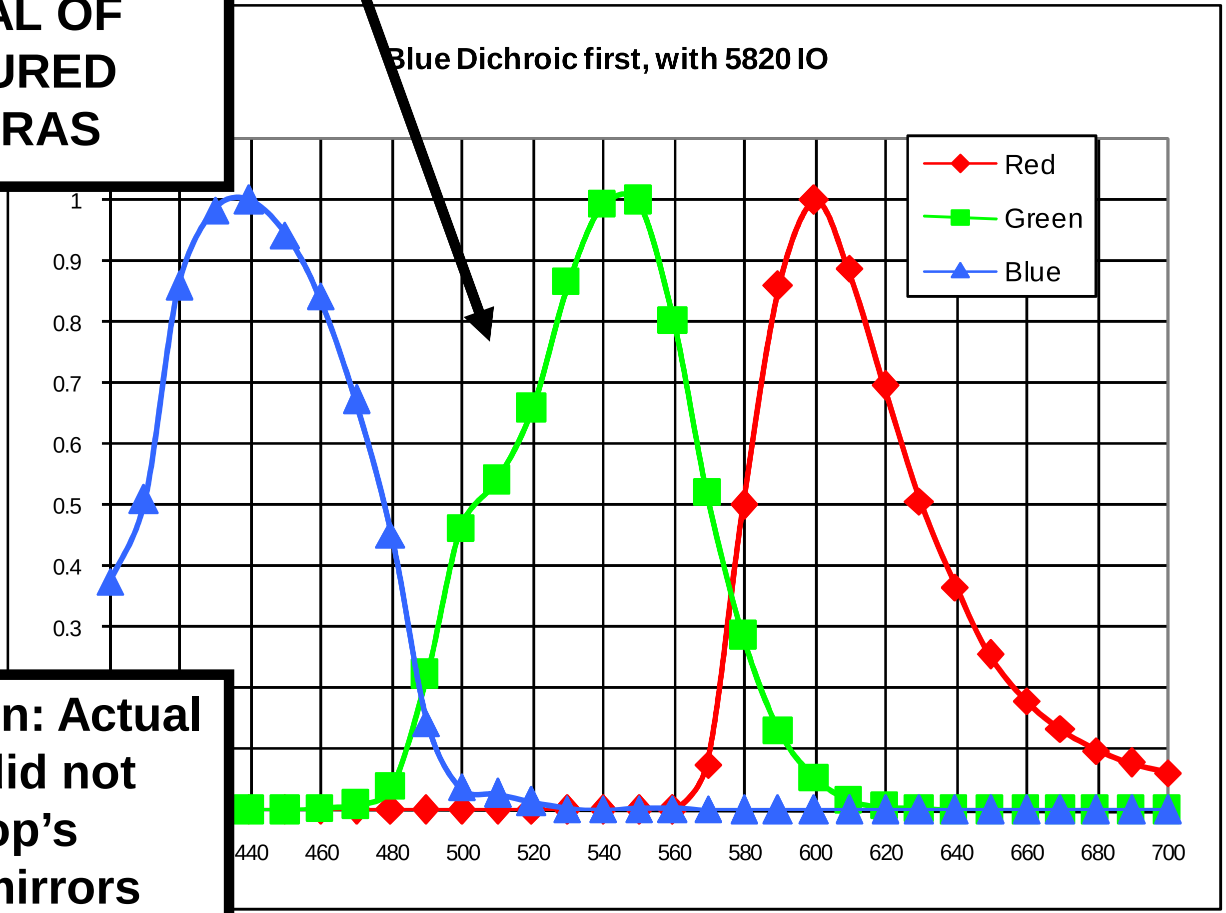


Over-All Results with Widdop's Mirrors



Over-All Results with Widdop's Mirrors Normalized to 1.0

NOTE UNEVEN RESPONSE NOT TYPICAL OF MEASURED CAMERAS

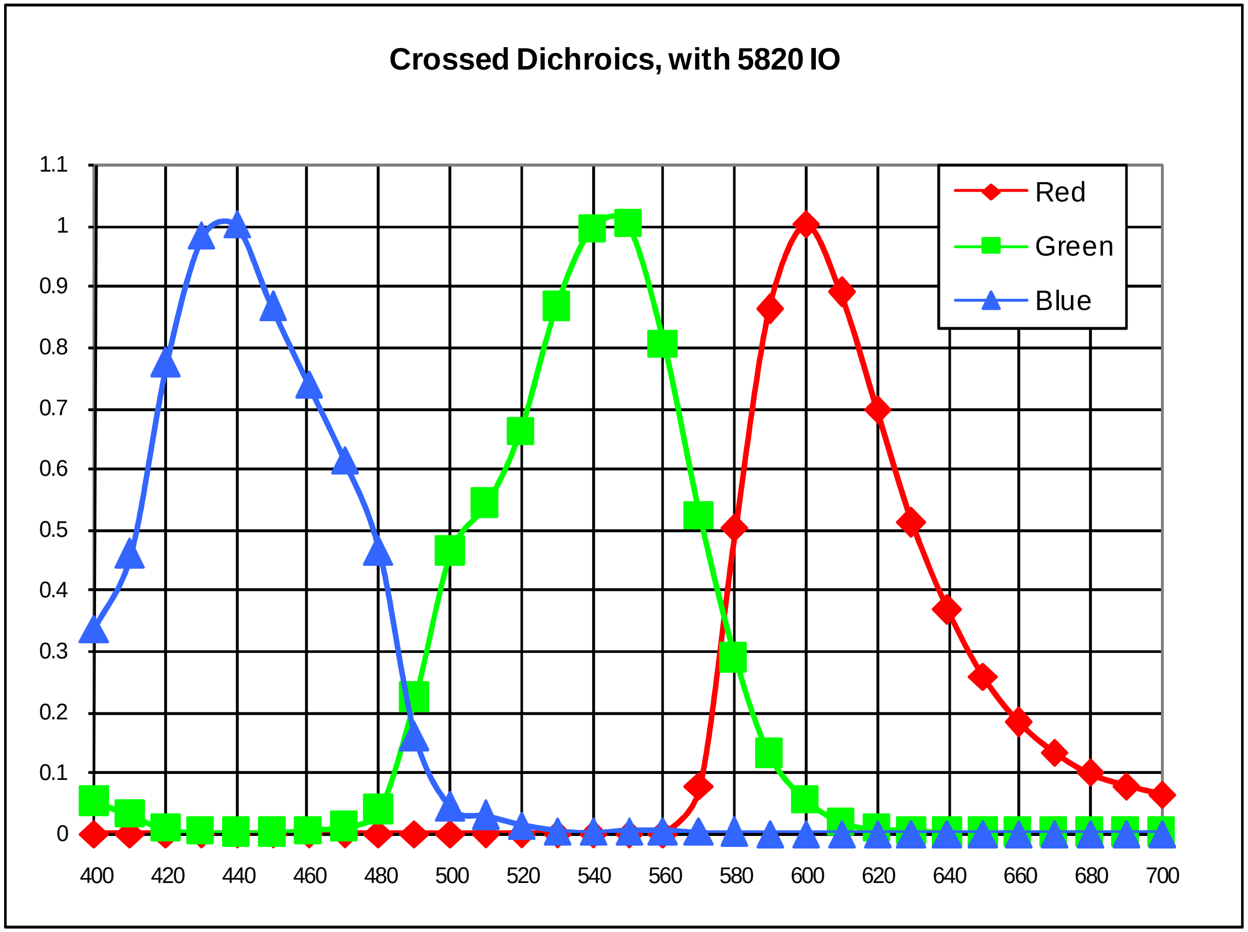


Conclusion: Actual cameras did not use Widdop's example mirrors

Crossed Dichroic Mirrors

- Some early designs proposed using crossed mirrors
- In this case, the blue channel also passes through the red dichroic transmission curve
  - Makes the blue curve more uneven
  - Also not like actual cameras

Over-All Results with Crossed Widdop's Mirrors Normalized to 1.0



Results for NTSC Display

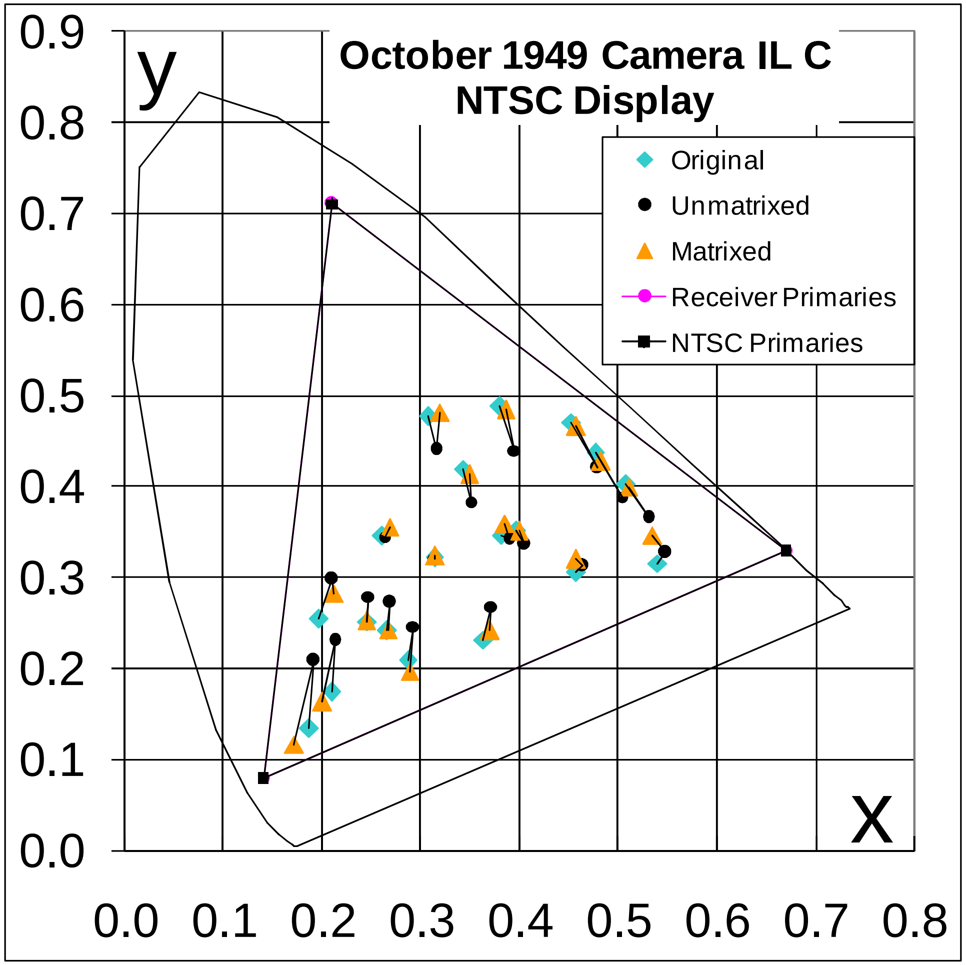
- Color Test Chart – each patch 3 ways
  - As seen by the camera
  - Ideal
  - As seen with least-squares matrix

- Chromaticity Diagrams
  - CIE 1931 [x, y]
  - CIE 1976 UCS [u’, v’]

October 1949 camera

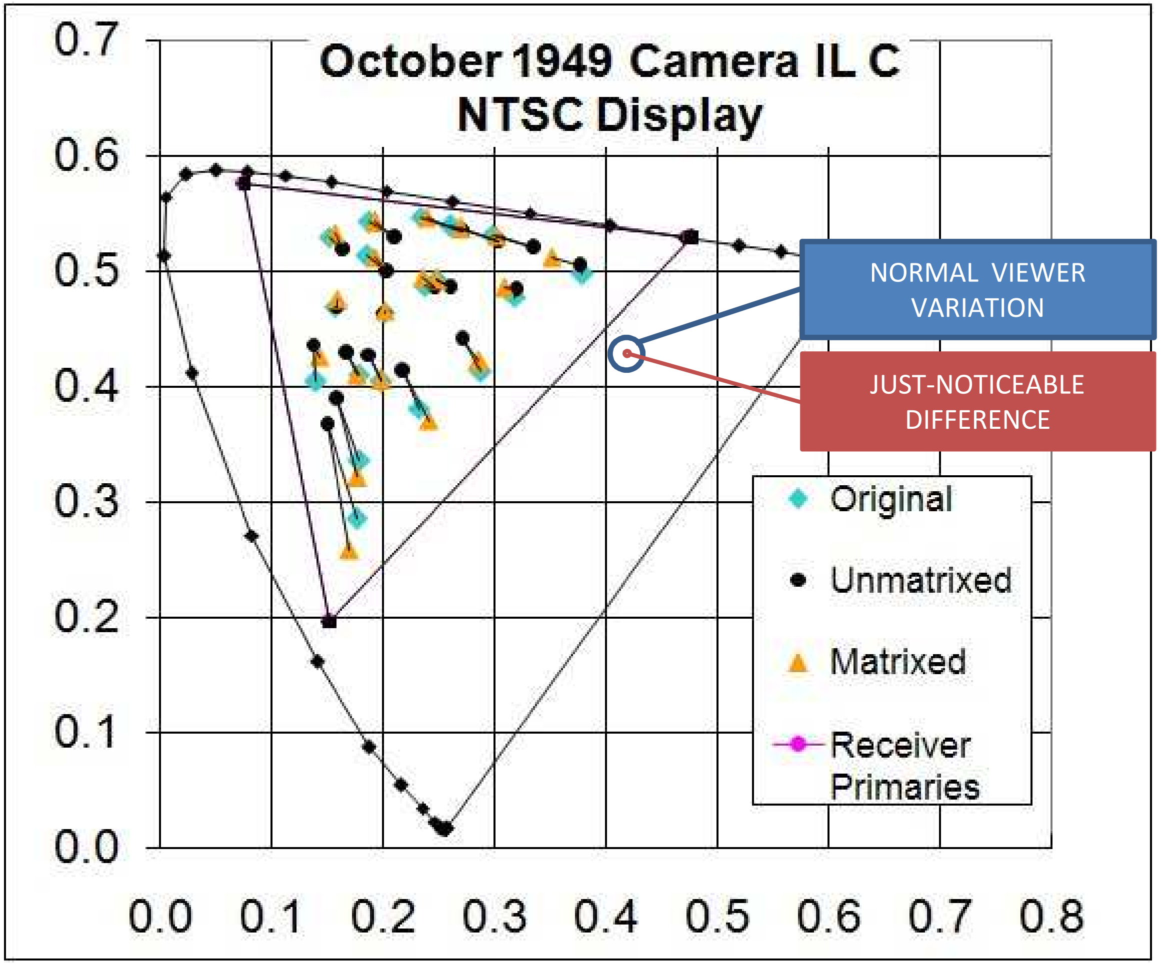
October 1949 camera

CAUTION – Luminance Differences Are Not Shown on this Diagram



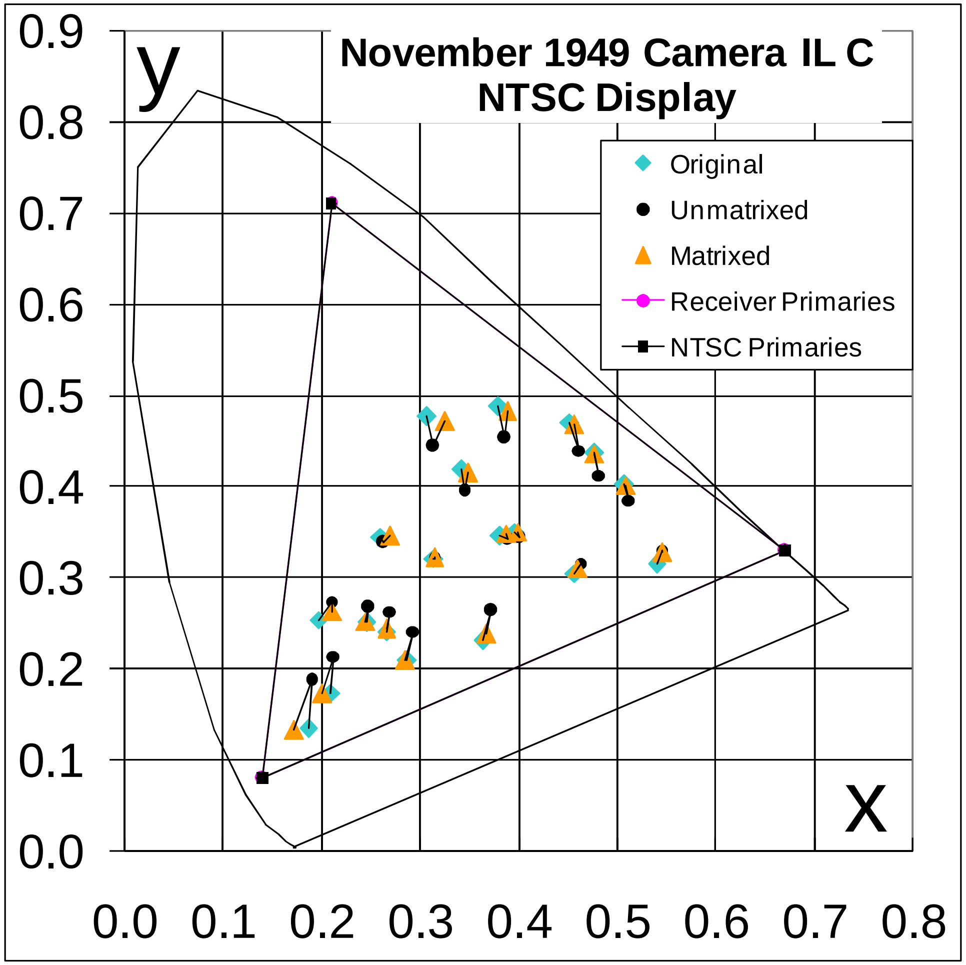
October 1949 camera

CAUTION – Luminance Differences Are Not Shown on this Diagram

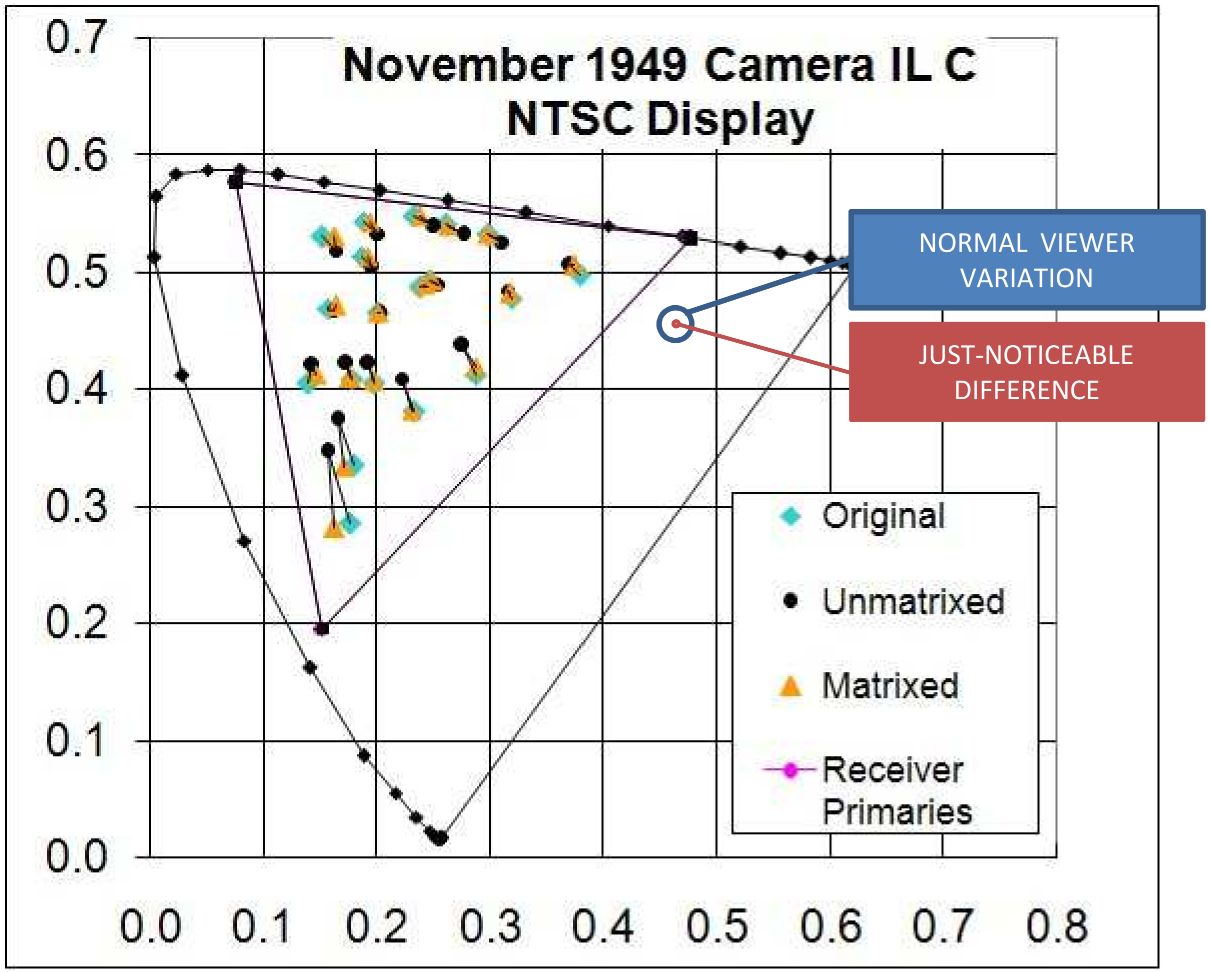


November 1949 camera

November 1949 camera

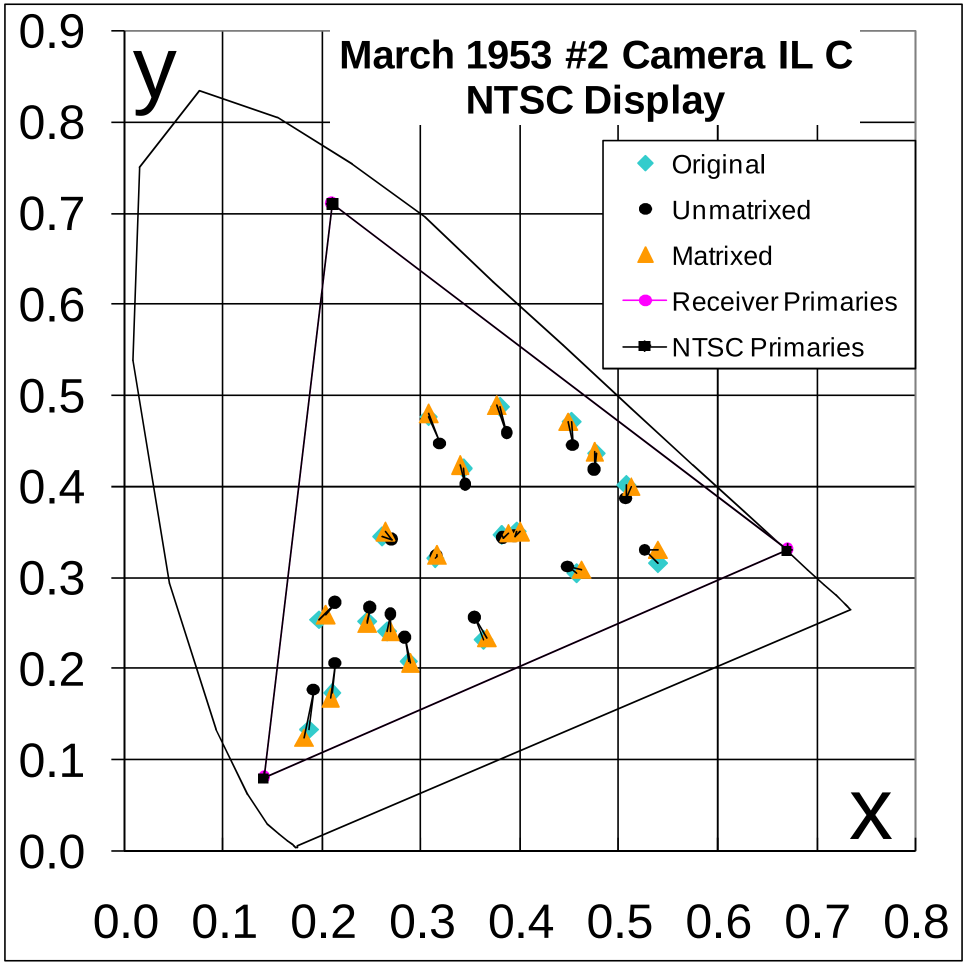


November 1949 camera

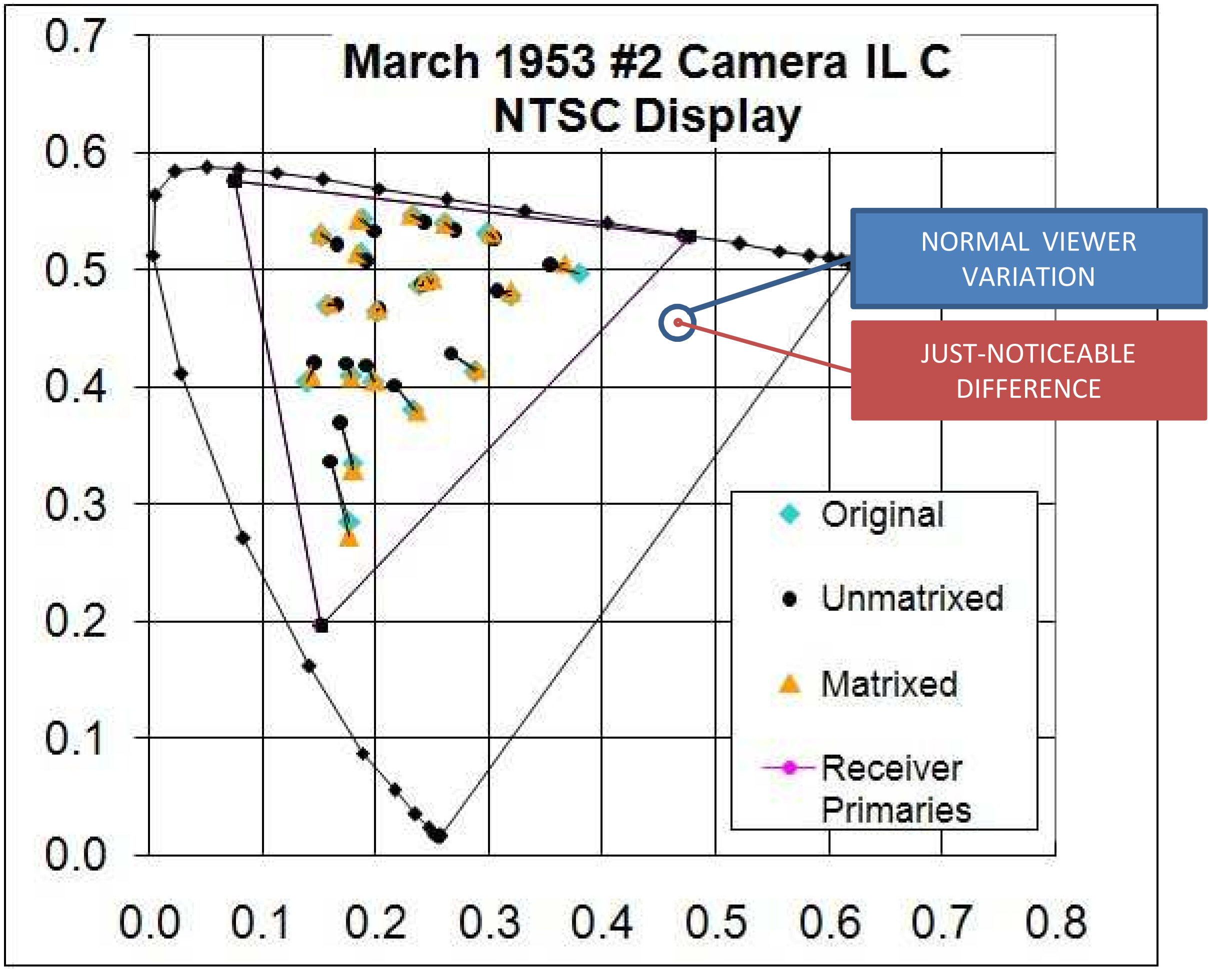


March 1953 no.2 camera

March 1953 no.2 camera

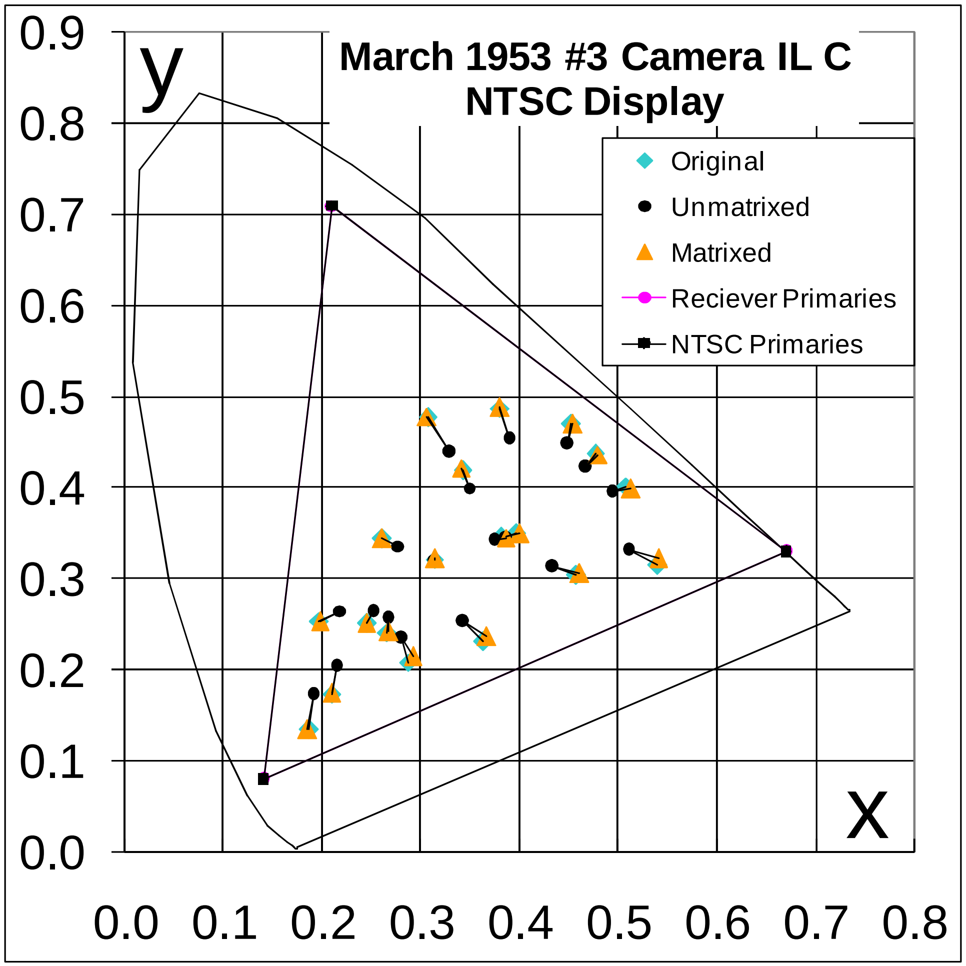


March 1953 no.2 camera

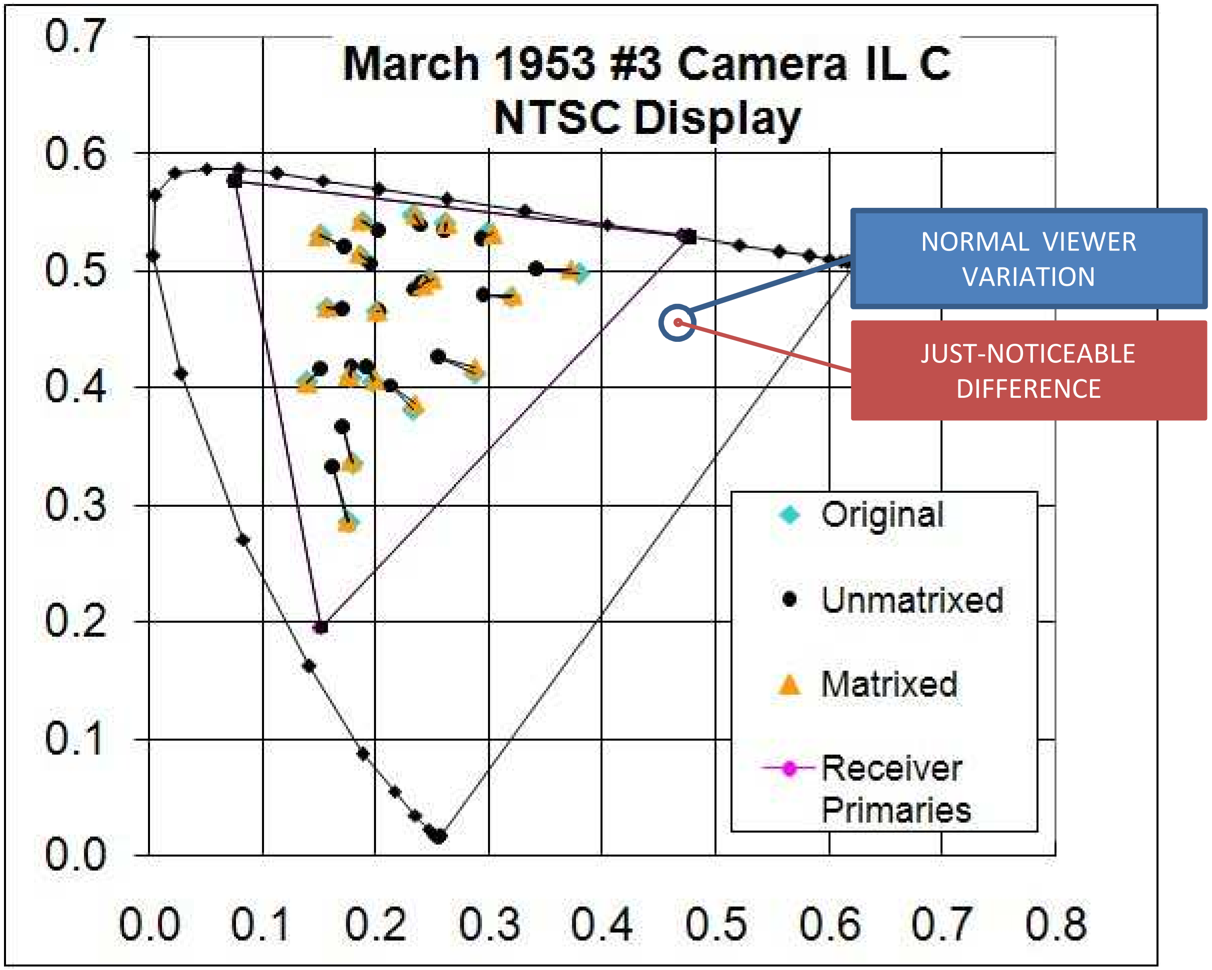


March 1953 no.3 camera

March 1953 no.3 camera

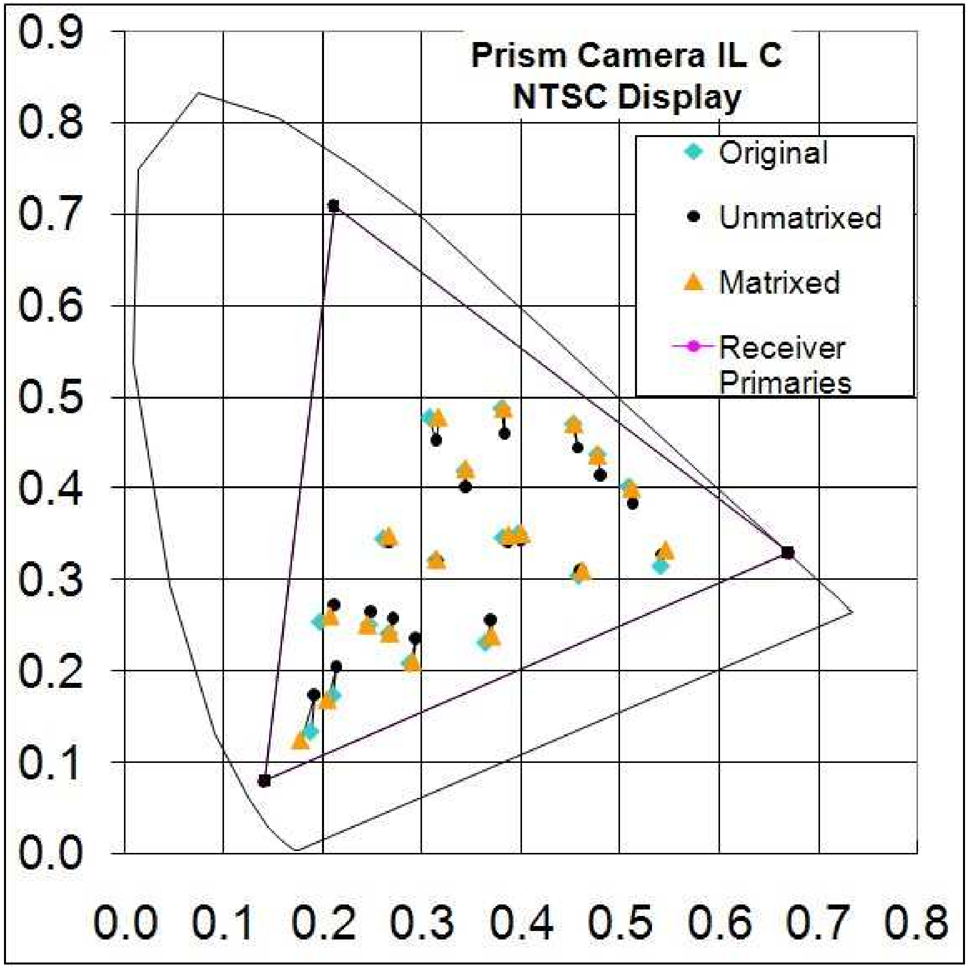


March 1953 no.3 camera

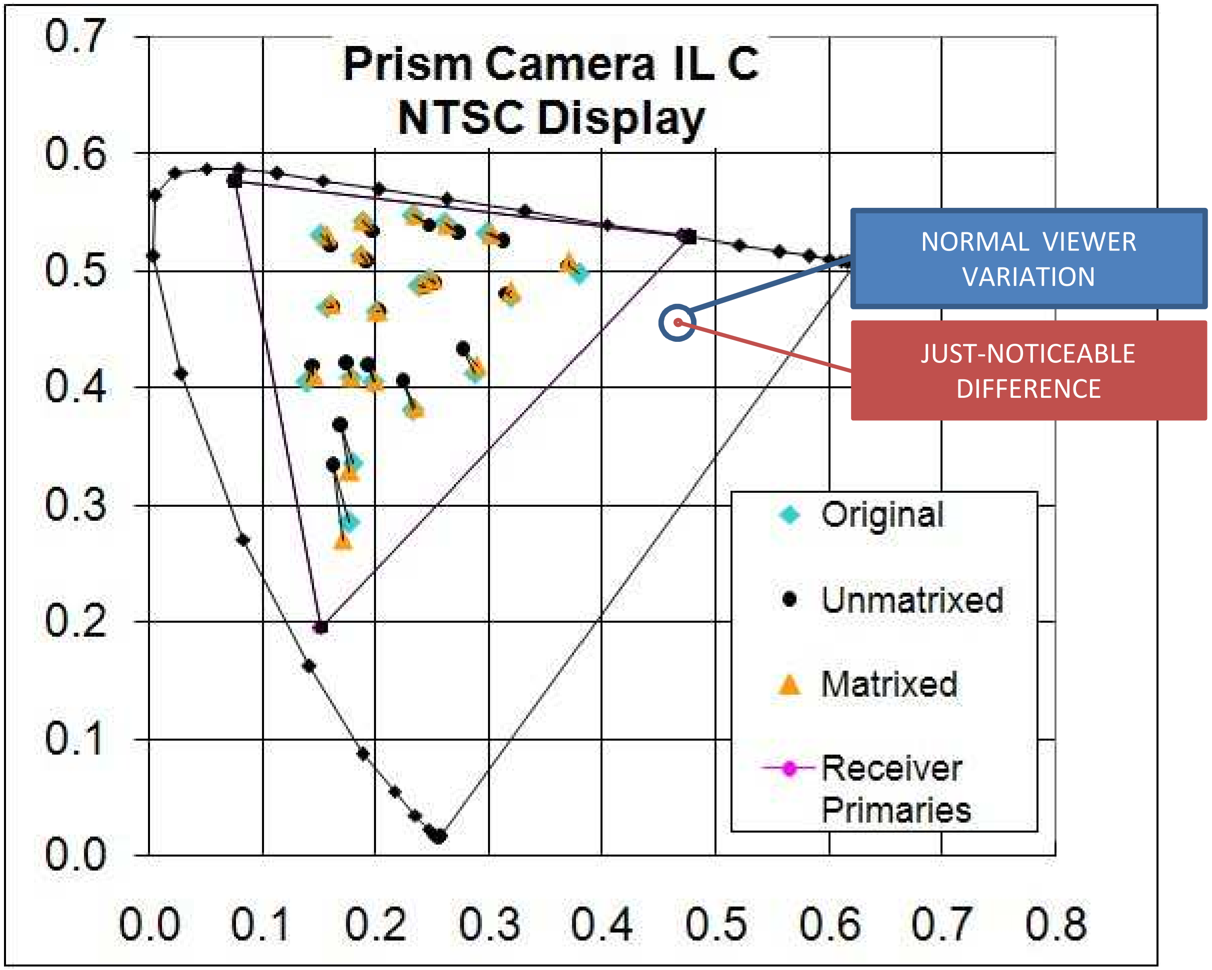


Prism camera

Prism camera



Prism camera



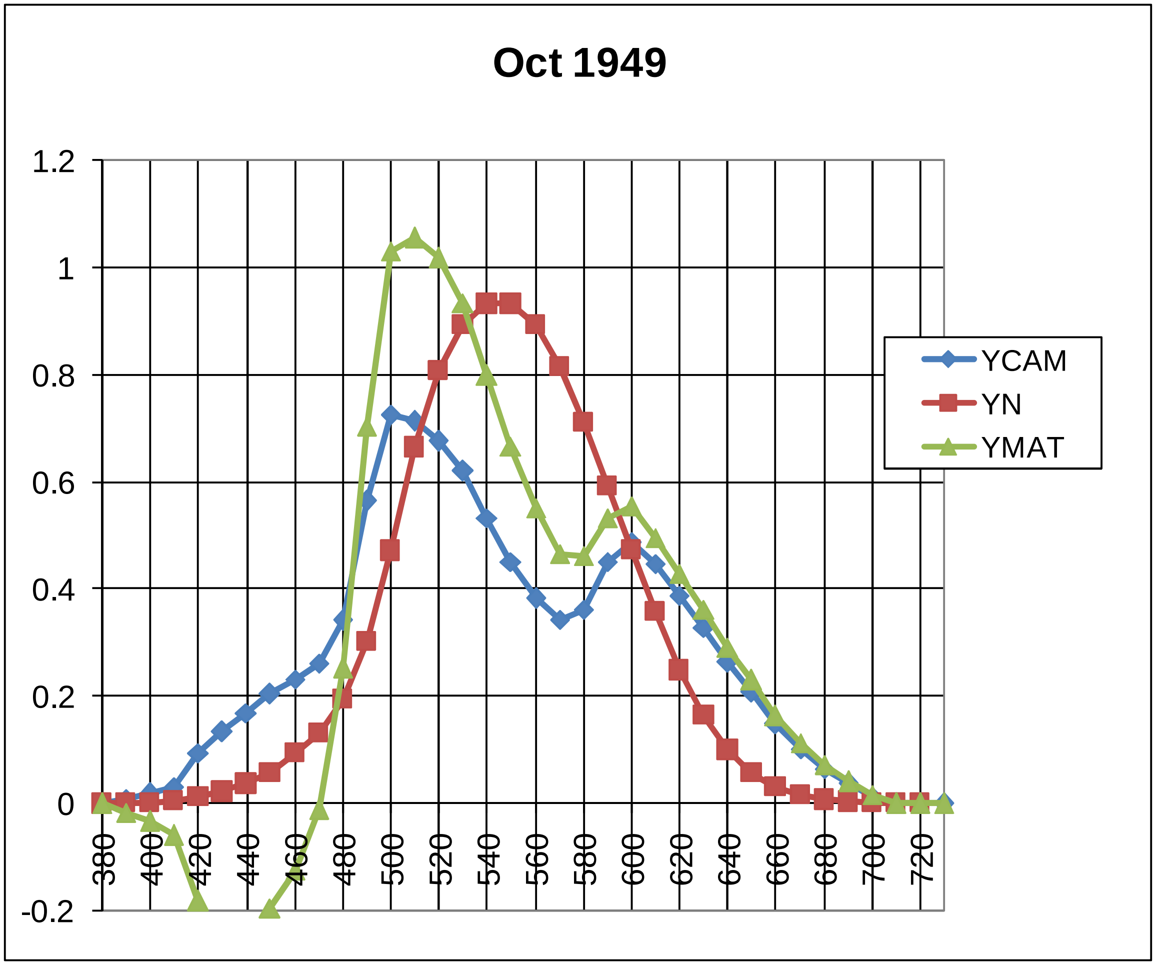
Linear Luminance Curves

- The luminance response for spectral colors can be calculated
- Fictional for actual spectral colors, since there will be clipping somewhere in the system for colors beyond the NTSC gamut
- However, indicates correctness of luminance value for colors within the system gamut
- Can be calculated for unmatrixed and matrixed cases

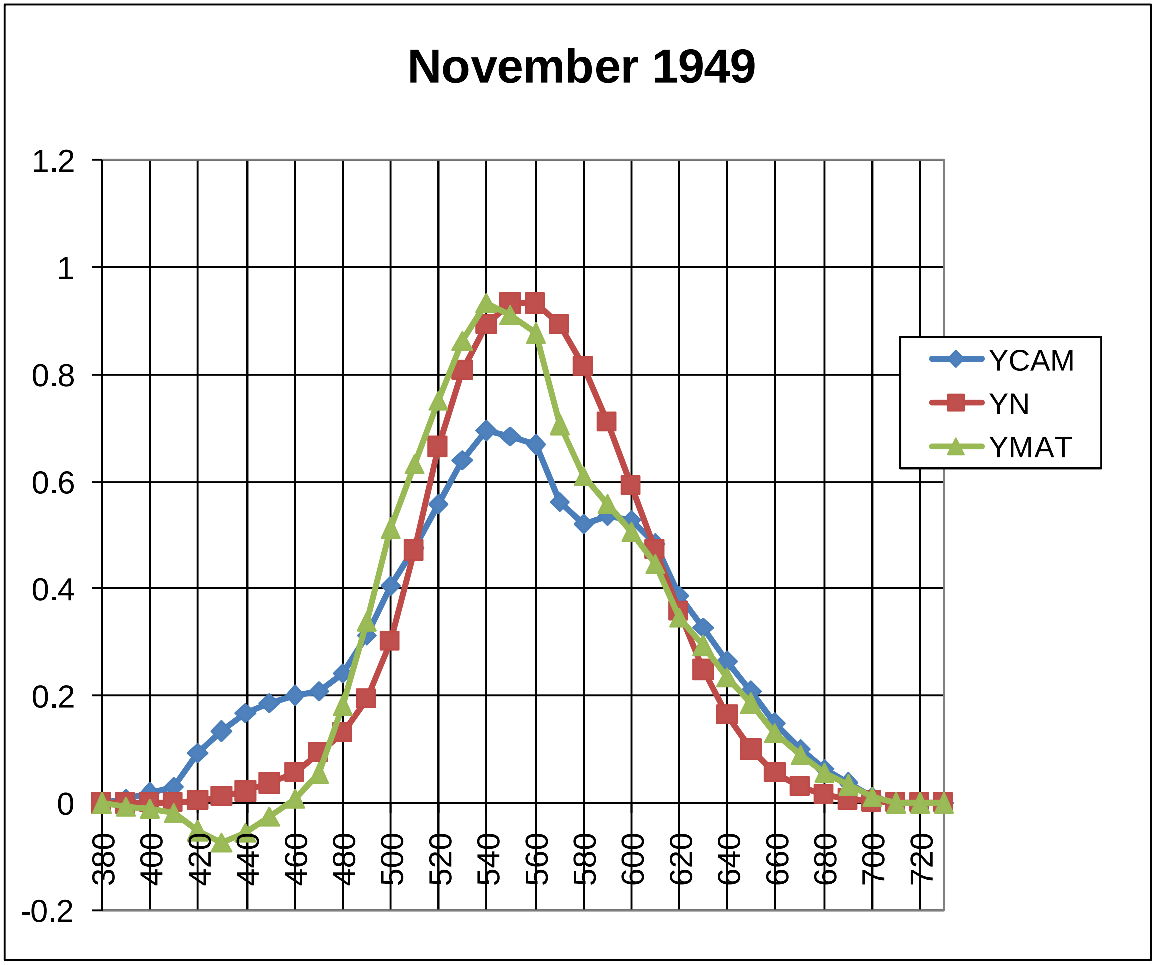
Linear Luminance Curves

- Each slide has three curves
  - YCAM – as the unmatrixed camera sees it
  - YN – the ideal NTSC and eyeball Y_λ curve
  - YMAT – as the matrixed camera sees it

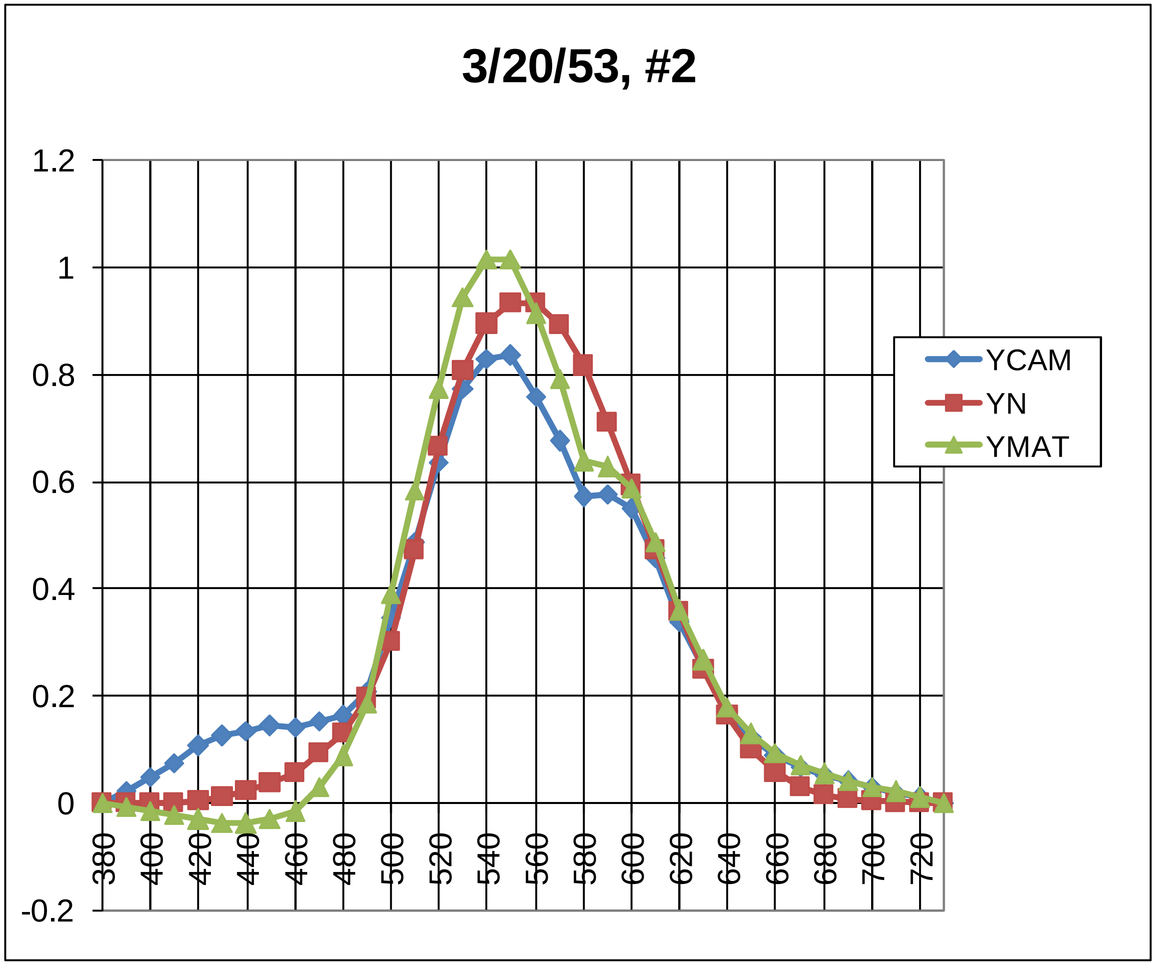
October 1949 linear luma



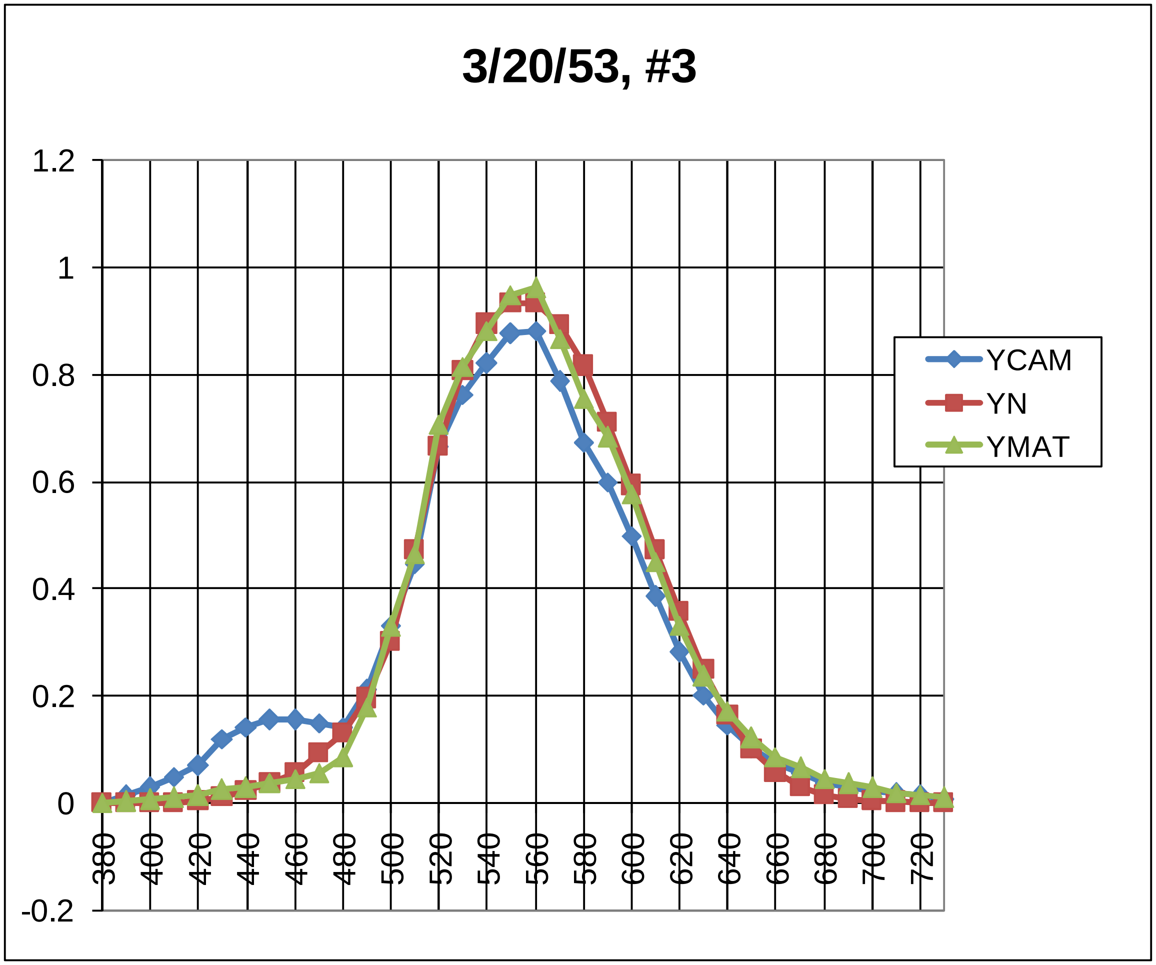
November 1949 linear luma



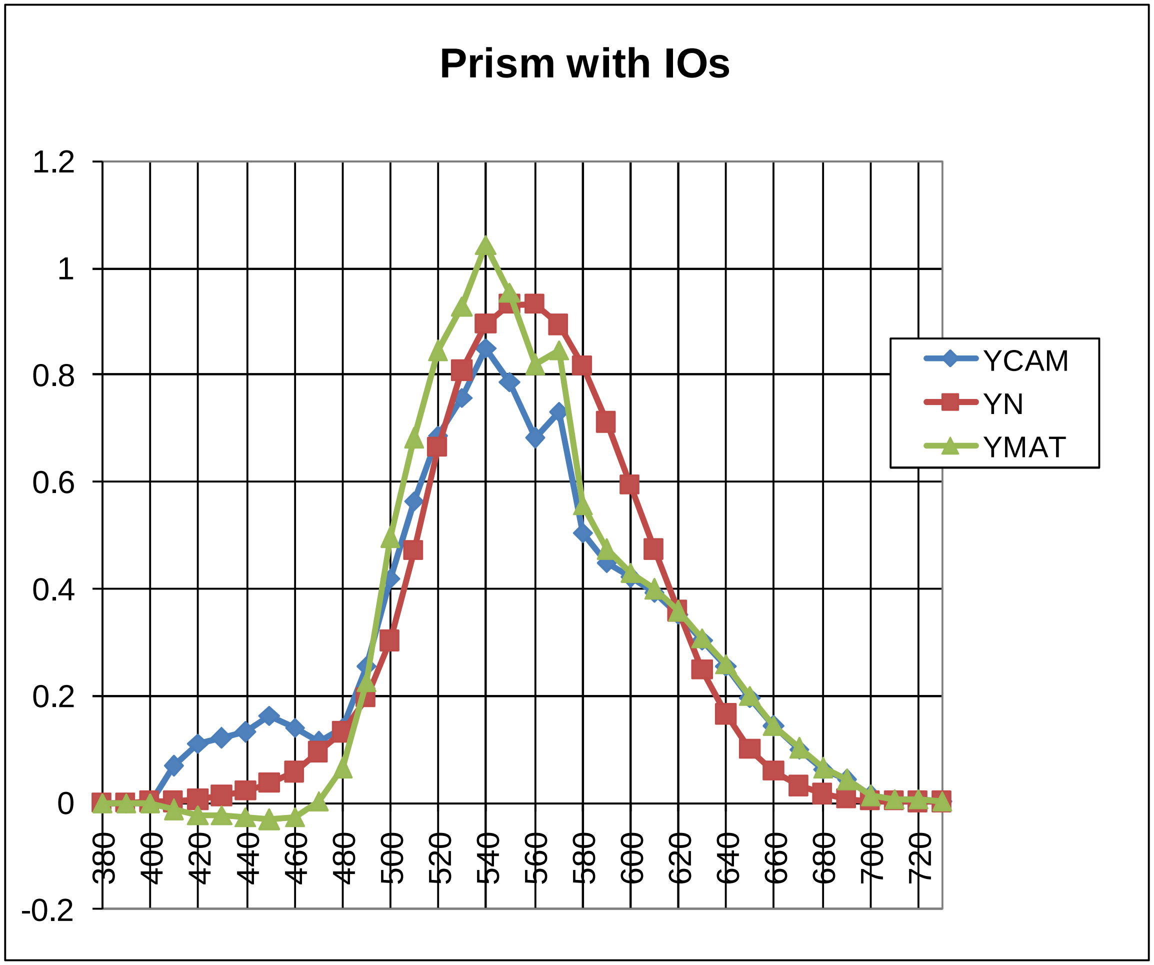
March 1953 no.2 linear luma



March 1953 no.3 linear luma



Prism linear luma

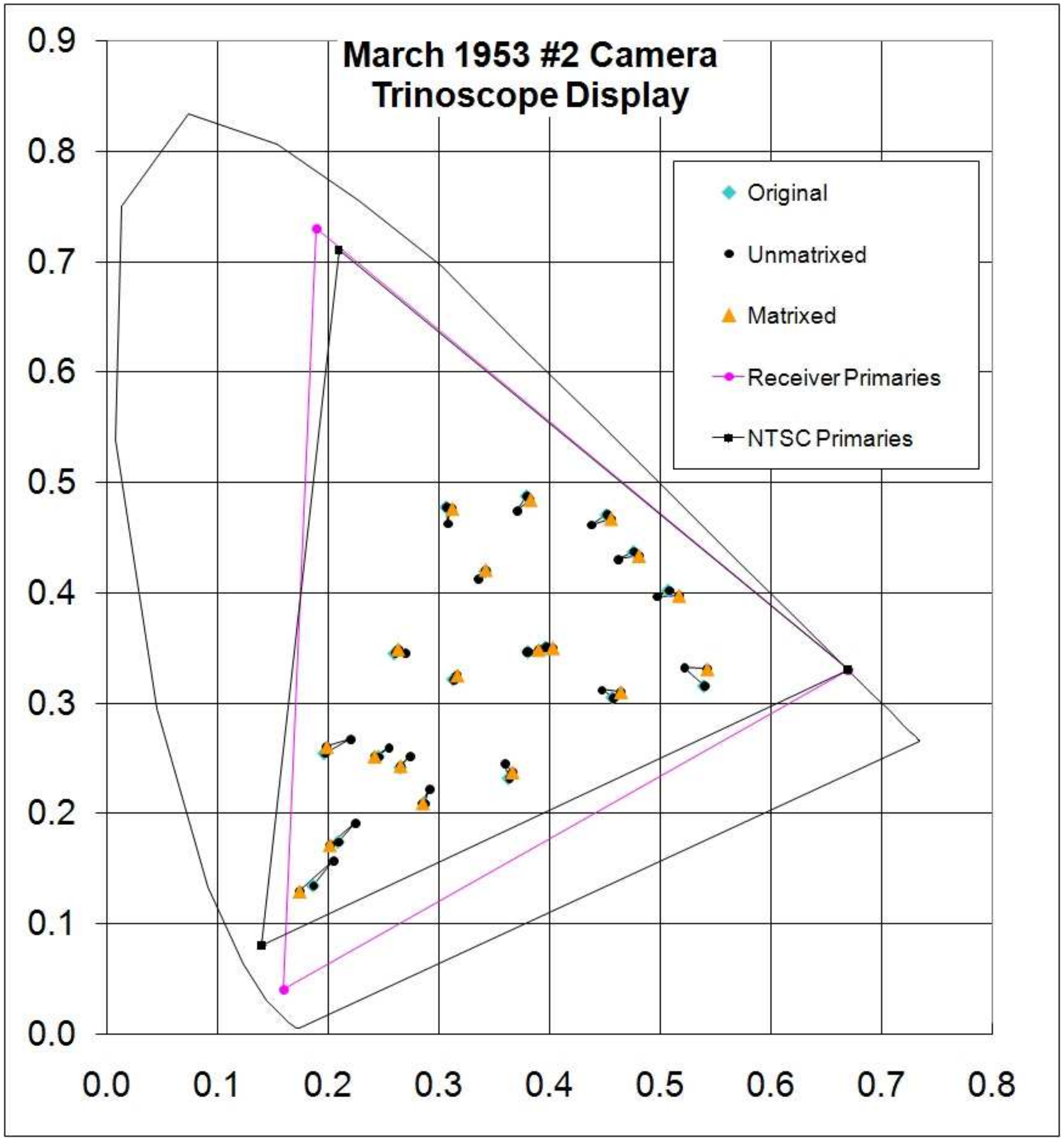


Results for Experimental and Hypothetical Displays

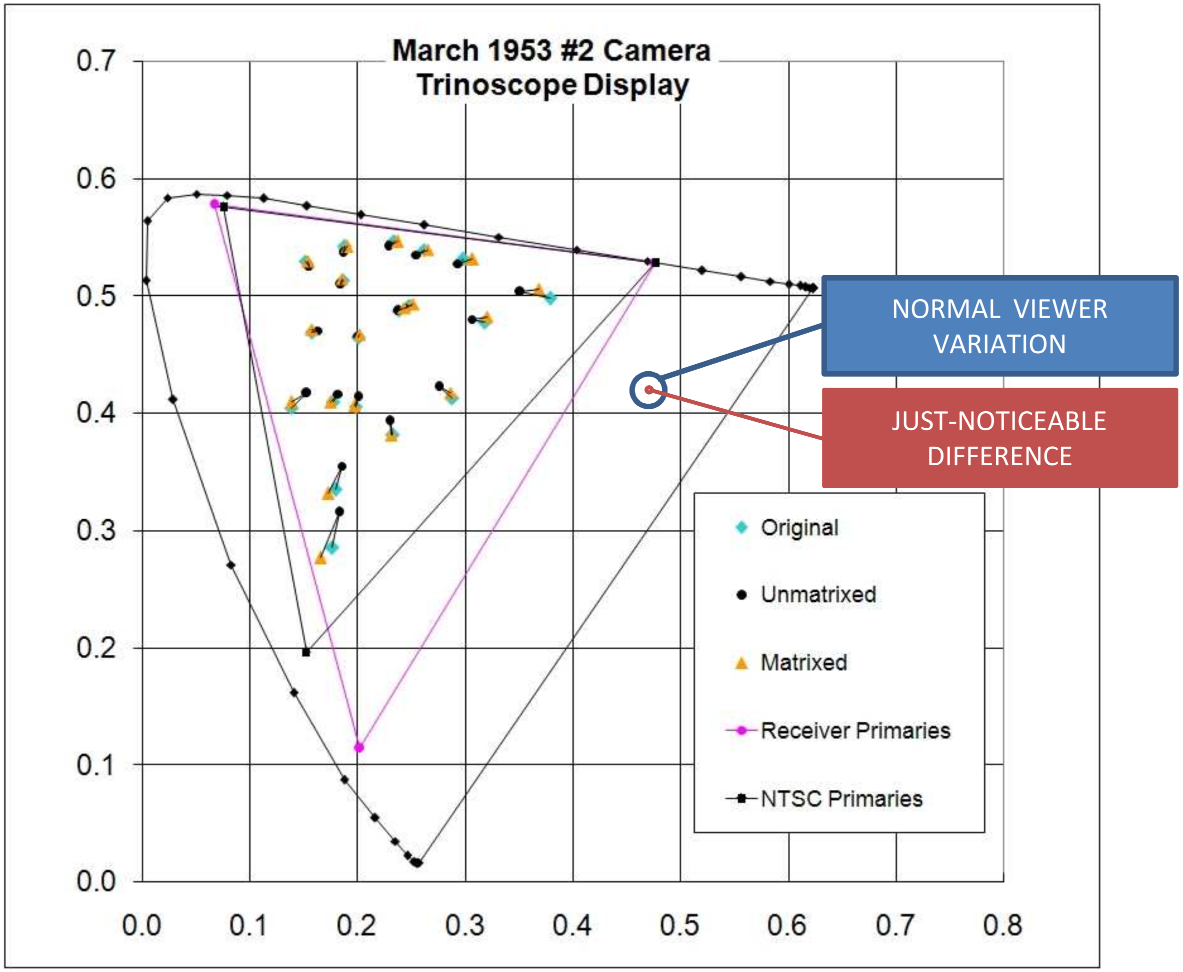
- **March 1953 Camera No. 2 with Trinoscope**
- **March 1953 Camera No. 2 with Reduced-Gamut Display**
- **Camera matrix calculated for best fit to each display**

March 1953 Camera No. 2 with Trinoscope Display

March 1953 Camera No. 2 with Trinoscope Display

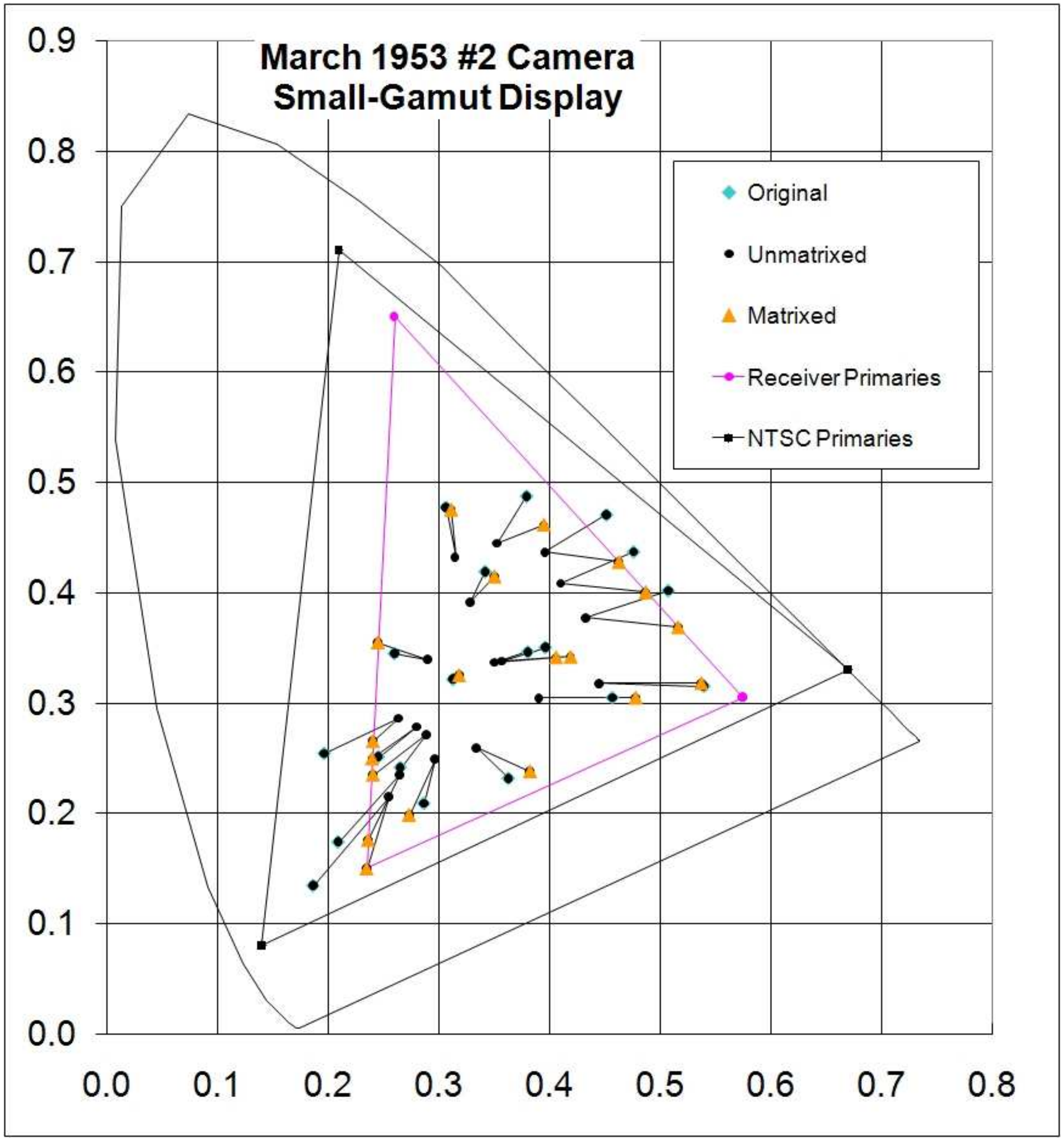


March 1953 Camera No. 2 with Trinoscope Display

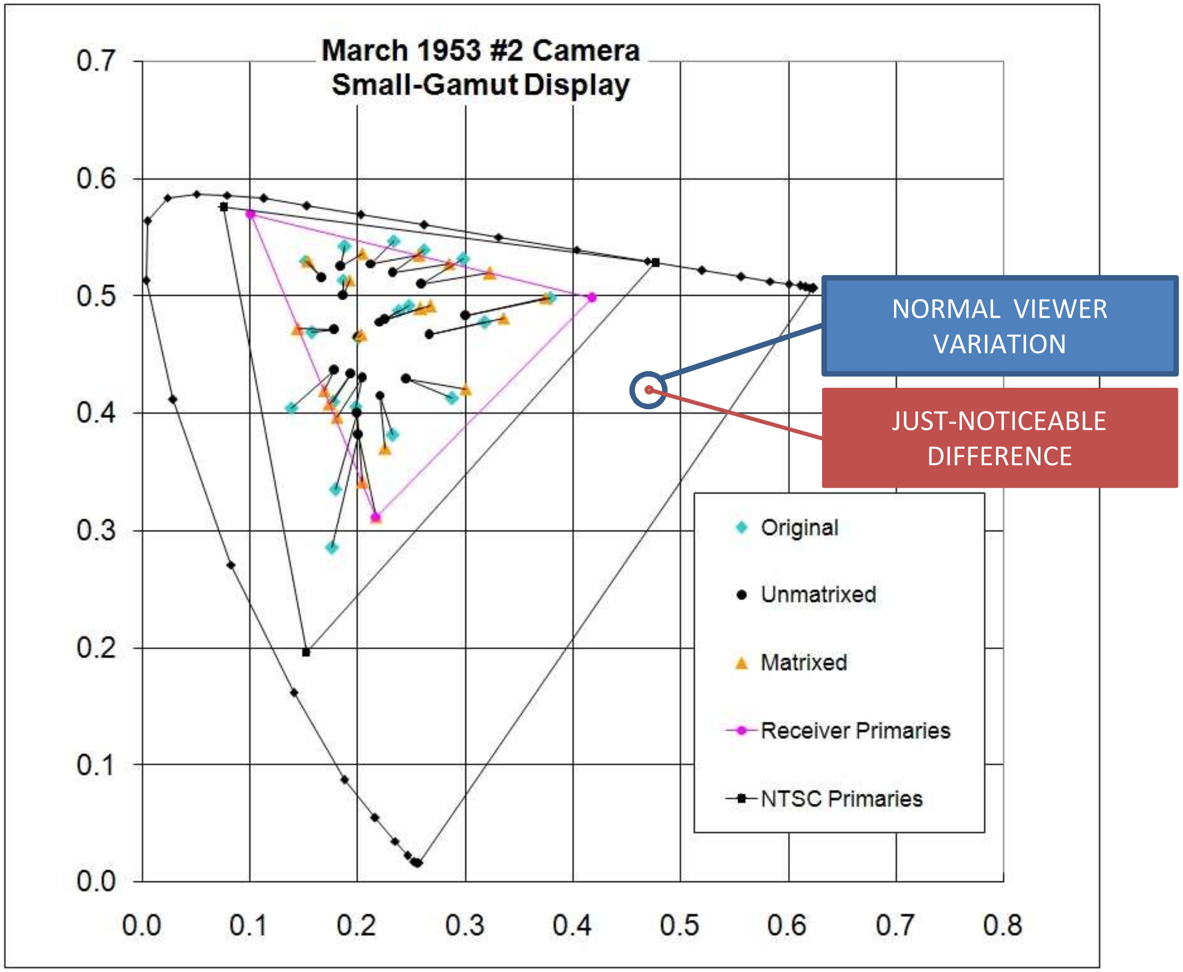


March 1953 Camera No. 2 with Reduced-Gamut Display

March 1953 Camera No. 2 with Reduced-Gamut Display



March 1953 Camera No. 2 with Reduced-Gamut Display



Comments on Reduced-Gamut Display

- Least-squares fit linear matrix gives poor results because it attempts to drive the reproduction of colors outside the receiver gamut
- More sophisticated techniques of color management involving a rendering intent (e.g., maintain hue and lightness at the expense of saturation) would be needed to get even somewhat reasonable results
- **Fortunately, this display was only hypothetical at the time, and no such display was ever used for the home**

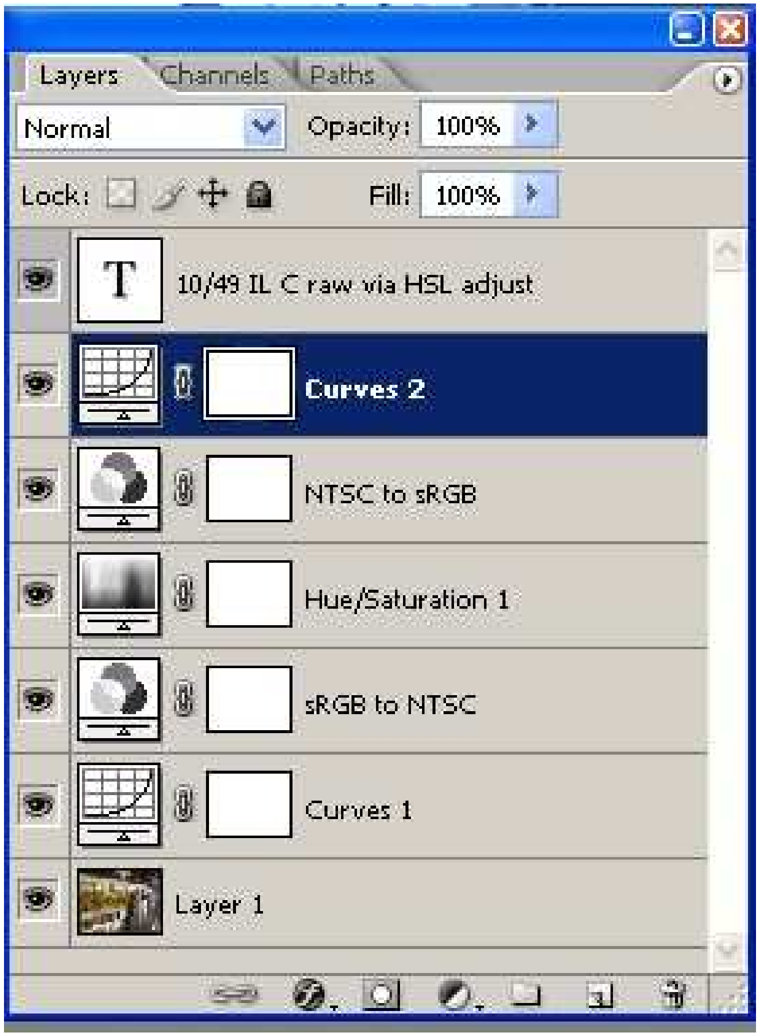
Comments on Reduced-Gamut Display

- Some aspects of rendering in television were studied at the time and in subsequent decades, but full 3-dimensional color-space mapping had to wait for computers, where it not only became possible, but was necessary for satisfactory home color printing of natural scenes.
- Aspects of television color that have been studied in the past include:
  - Viewer tolerances for hue and saturation errors
  - effects of gamma correction exponent, stray light, black level setting
  - relative gamuts of film and television displays at various brightness levels
  - “masking” (matrixing in the logarithmic domain, so as to work with dye densities)
  - Use of approximate matrices in receivers, working on the gamma–corrected signals, to compensate for non-NTSC receiver phosphors

Approximate Results for Images

- **Processing Steps (in Photoshop):**
  - Input photo in sRGB color space
  - Linearize by applying a gamma adjustment
  - Matrix from sRGB primaries to the NTSC color space,
  - Adjust hue , saturation and lightness to match a particular camera's color chart result (separate adjustments for each primary and secondary color range)
  - Matrix to sRGB color space
  - Apply gamma correction
  - Apply a text label

Photoshop Adjustments to Approximate Color Camera Response

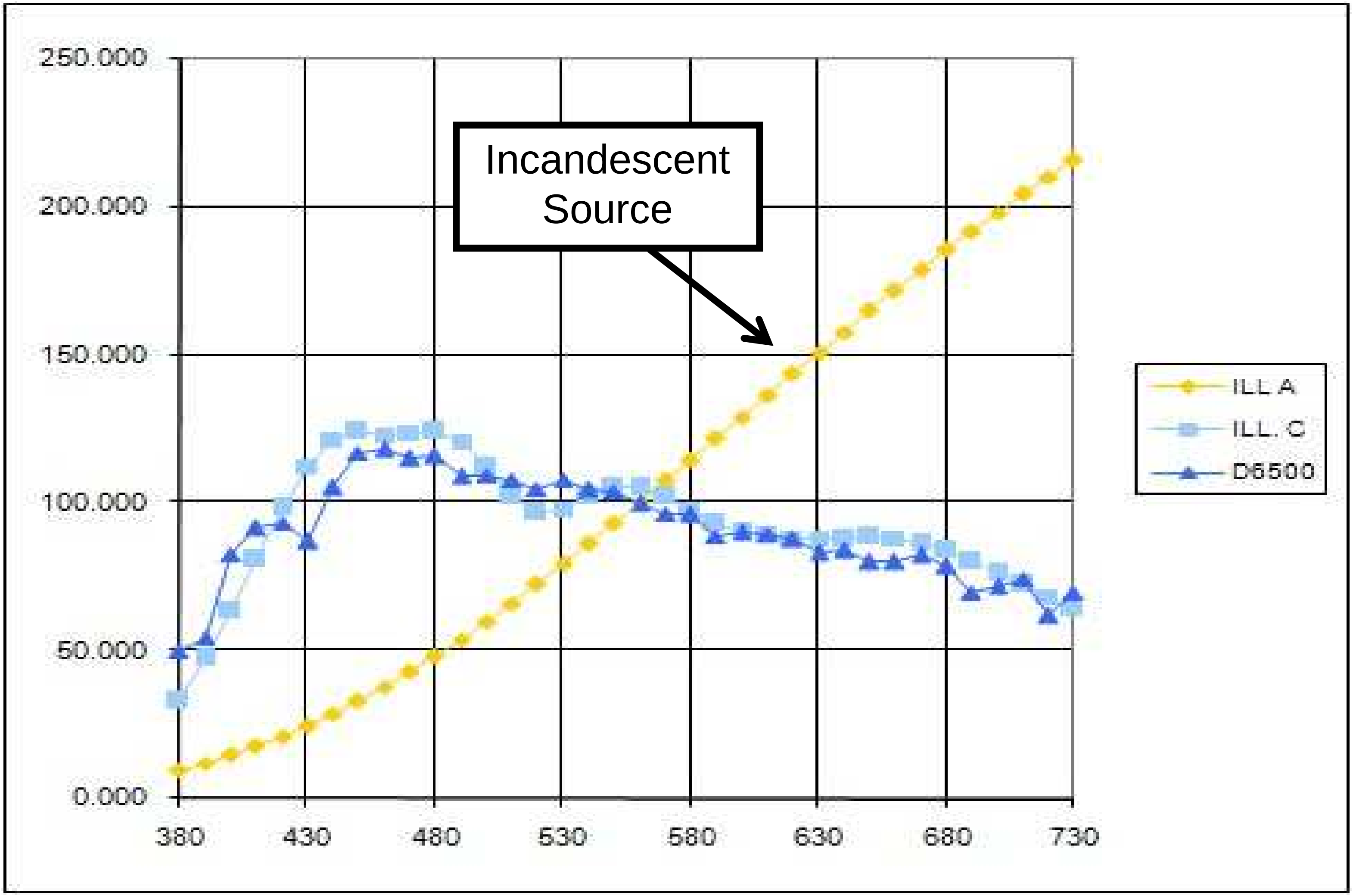


Veggie Market Original

Veggie Market As Seen by 10/49 Camera

Effect of Incandescent Lighting

Effect of Incandescent Lighting



Effect of Incandescent Lighting

- The effect of the tilt in the incandescent lighting spectrum is to change the effective taking characteristics of the camera
- This can be corrected by inserting a color correcting filter with the opposite tilt
  - Image Orthicon cameras had no place for such filters
  - Adjustment was by means of neutral-density filters in two of the R, G, B paths

Analysis of Illuminant Effects

- To calculate camera output, need product (for each wavelength) of three quantities:
  1. Illuminant, $I(\lambda)$
  2. Object reflectance, $O(\lambda)$
  3. Taking characteristics $Rbar(\lambda)$, $Gbar(\lambda)$, $Bbar(\lambda)$

  $I(\lambda) \times O(\lambda) \times Rbar(\lambda) = R(\lambda)$

  $I(\lambda) \times O(\lambda) \times Gbar(\lambda) = G(\lambda)$

  $I(\lambda) \times O(\lambda) \times Bbar(\lambda) = B(\lambda)$

Analysis of Illuminant Effects

- Integrals (sums) over wavelength give camera output

Σ [R(λ)] = Σ [I(λ) x O(λ) x Rbar(λ)] = R

Σ [G(λ)] = Σ [I(λ) x O(λ) x Gbar(λ)] = G

Σ [B(λ)] = Σ [I(λ) x O(λ) x Bbar(λ)] = B

- However, these quantities are not correct unless the camera has been white balanced, i.e., R,G, B gains adjusted so that, for a perfect white object, R = G = B =1.0

Analysis of Illuminant Effects

- To find white-balanced taking characteristics, integrate the product of the taking characteristics and the illuminant

Σ R(λ) = Σ [I(λ) x 1.0 x Rbar(λ)] = R_{IL}

Σ G(λ) = Σ [I(λ) x 1.0 x Gbar(λ)] = G_{IL}

Σ B(λ) = Σ [I(λ) x 1.0 x Bbar(λ)] = B_{IL}

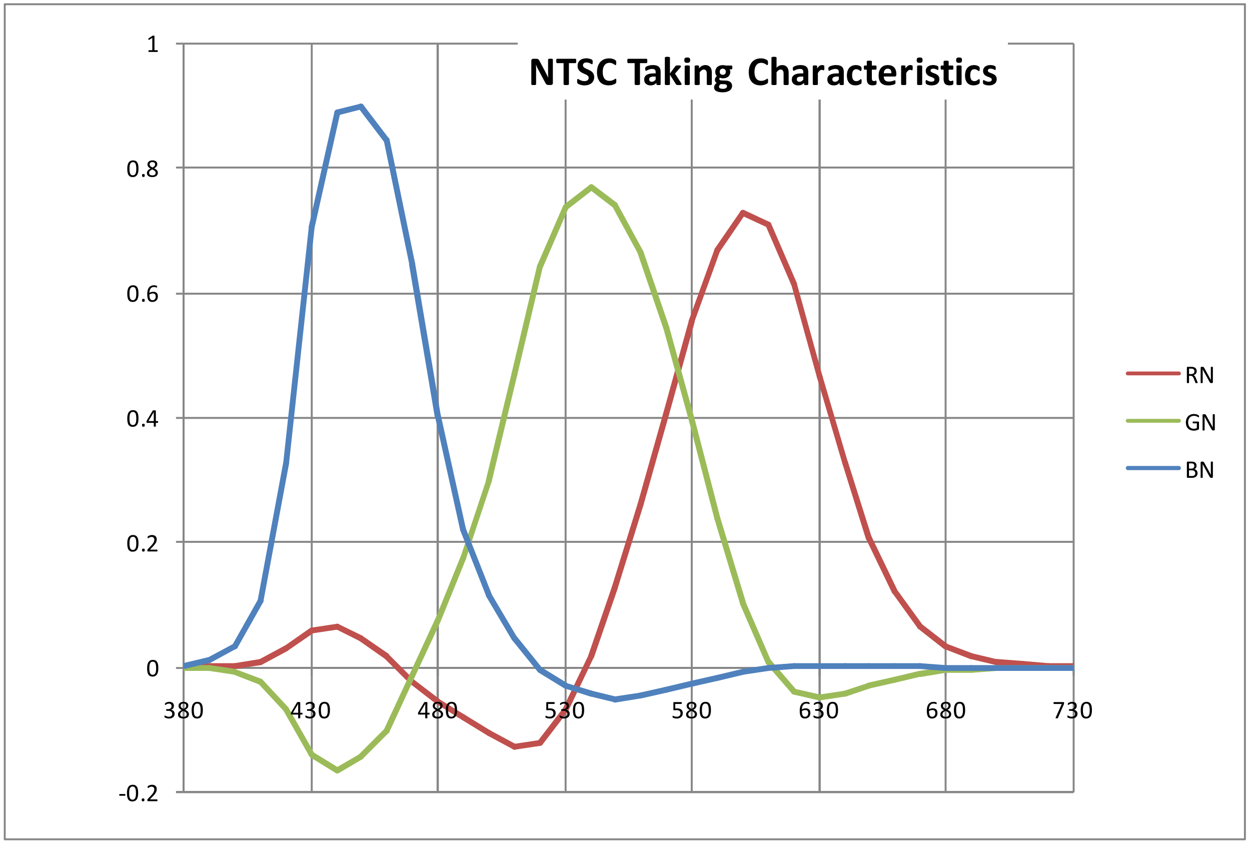
- Next, normalize the taking characteristics by dividing to get the white-balanced product of taking characteristics and illuminant

Rbal(λ) = I(λ) x Rbar(λ) / R_{IL}

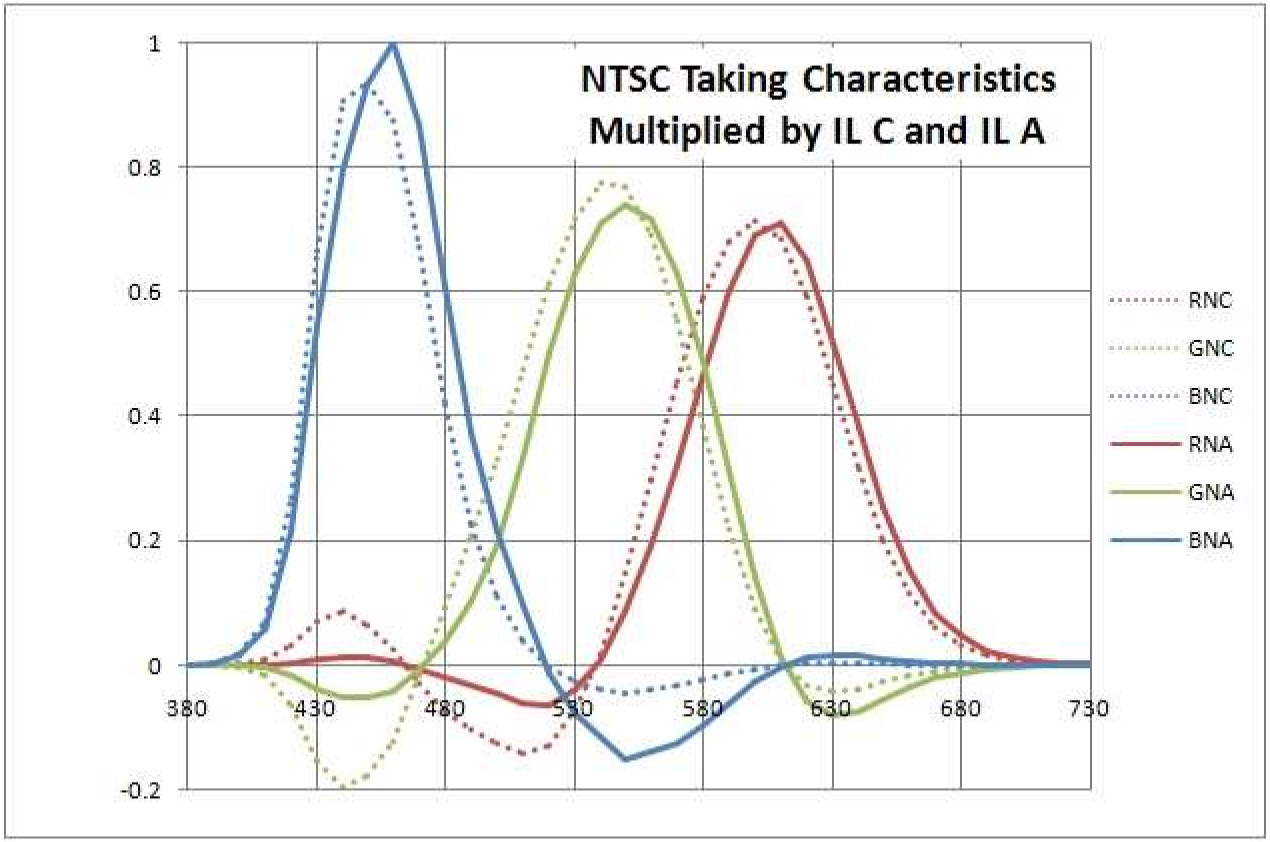
Gbal(λ) = I(λ) x Gbar(λ) / G_{IL}

Bbal(λ) = I(λ) x Bbar(λ) / B_{IL}

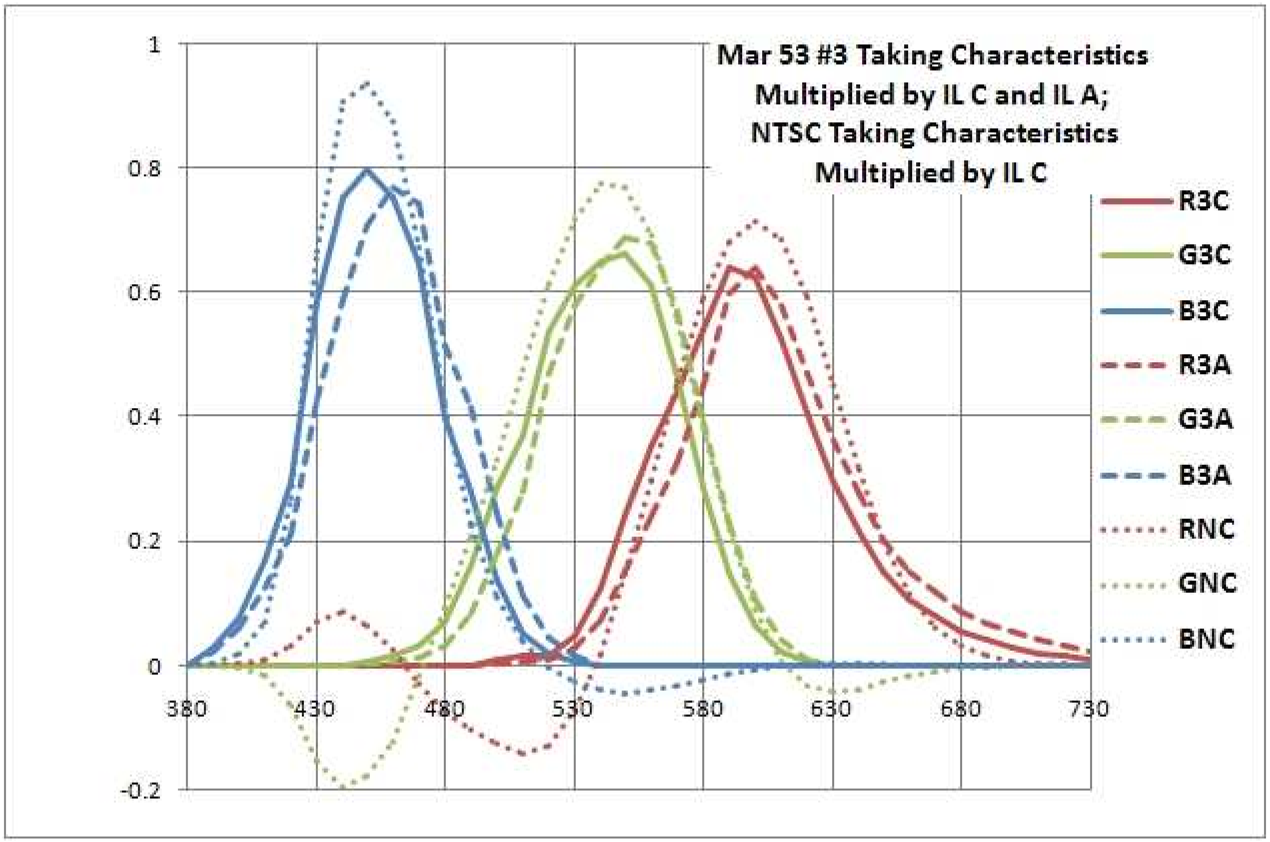
NTSC Taking Characteristics Normalized for Equal Area



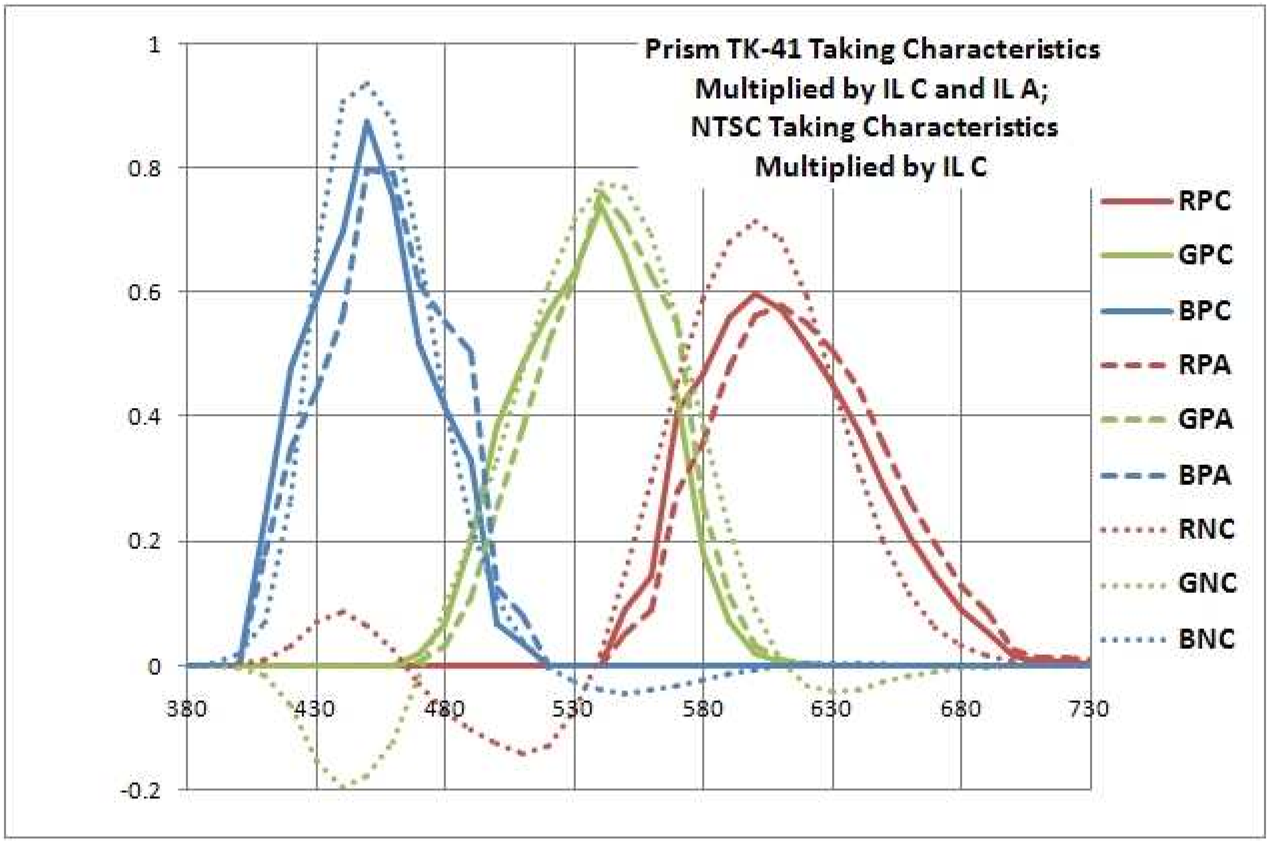
NTSC Taking Curves Multiplied by IL C (Dotted) and IL A (Solid) and Adjusted for White Balance



March 1953 Camera No.3 Taking Curves Multiplied by IL C (Solid) and IL A (Dashed), and Adjusted for White Balance Dotted Lines: NTSC Multiplied By IL C



Prism Camera Taking Curves Multiplied by IL C (Solid) And IL A (Dashed), and Adjusted for White Balance Dotted Lines: NTSC Multiplied By IL C



Camera Output Under New Illuminant

- Integrals (sums) over wavelength give balanced camera output for a particular object spectrum

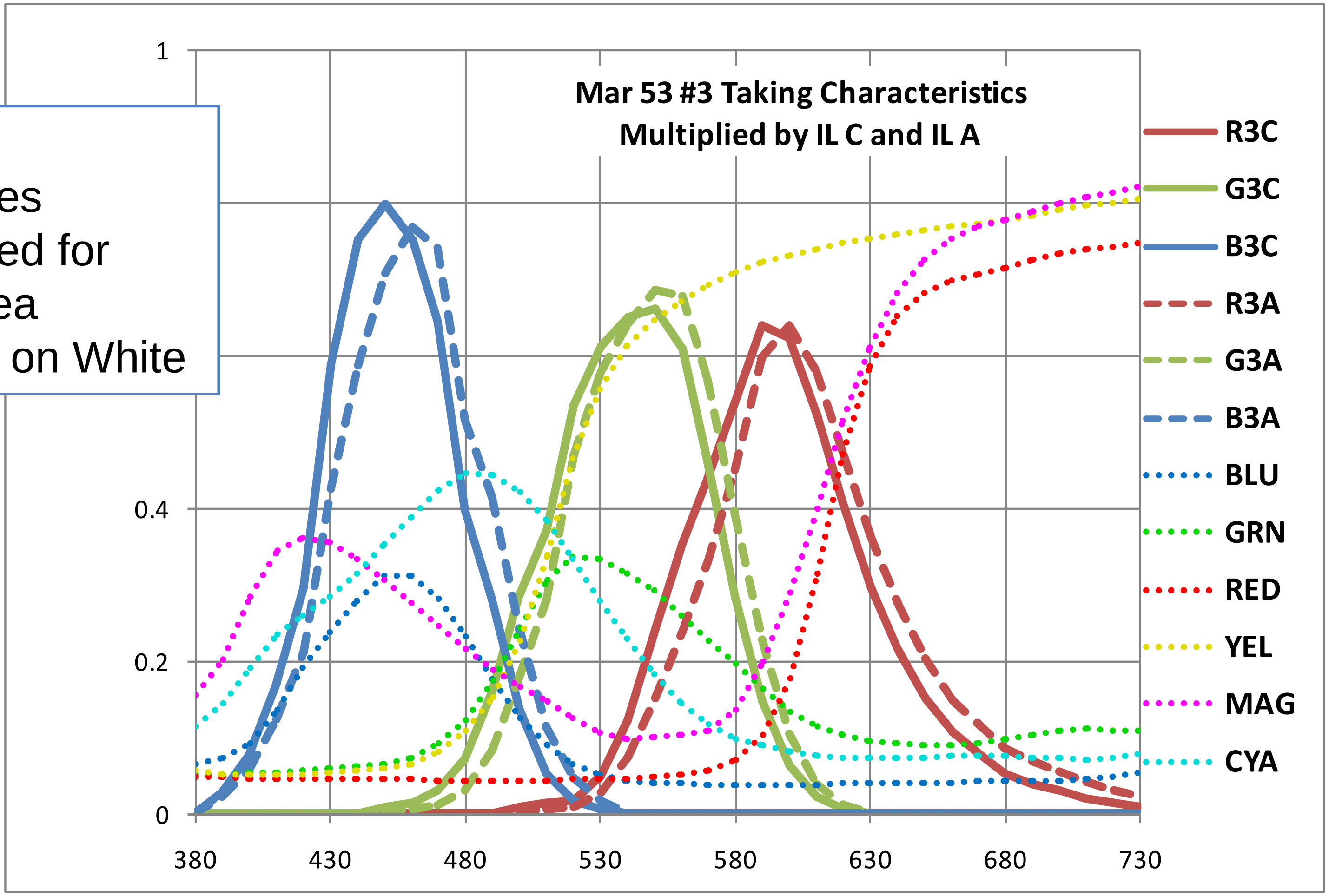
Σ R(λ) = Σ [O(λ) x Rbal(λ)] = R

Σ G(λ) = Σ [O(λ) x Gbal (λ)] = G

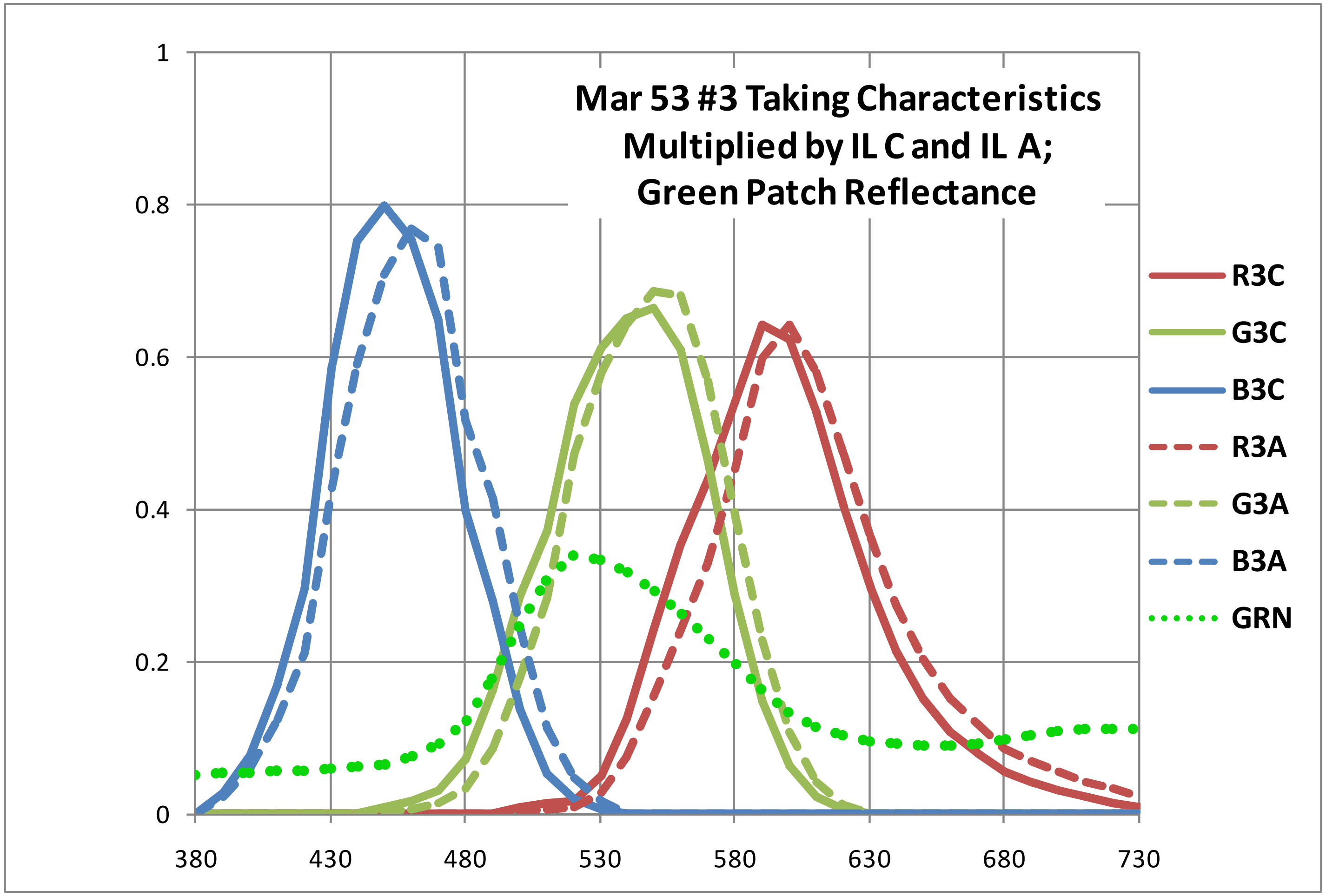
Σ B(λ) = Σ [O(λ)) x Bbal(λ)] = B

Mar 53 #3 Camera Multiplied by IL C or IL A, and Row #3 Patches

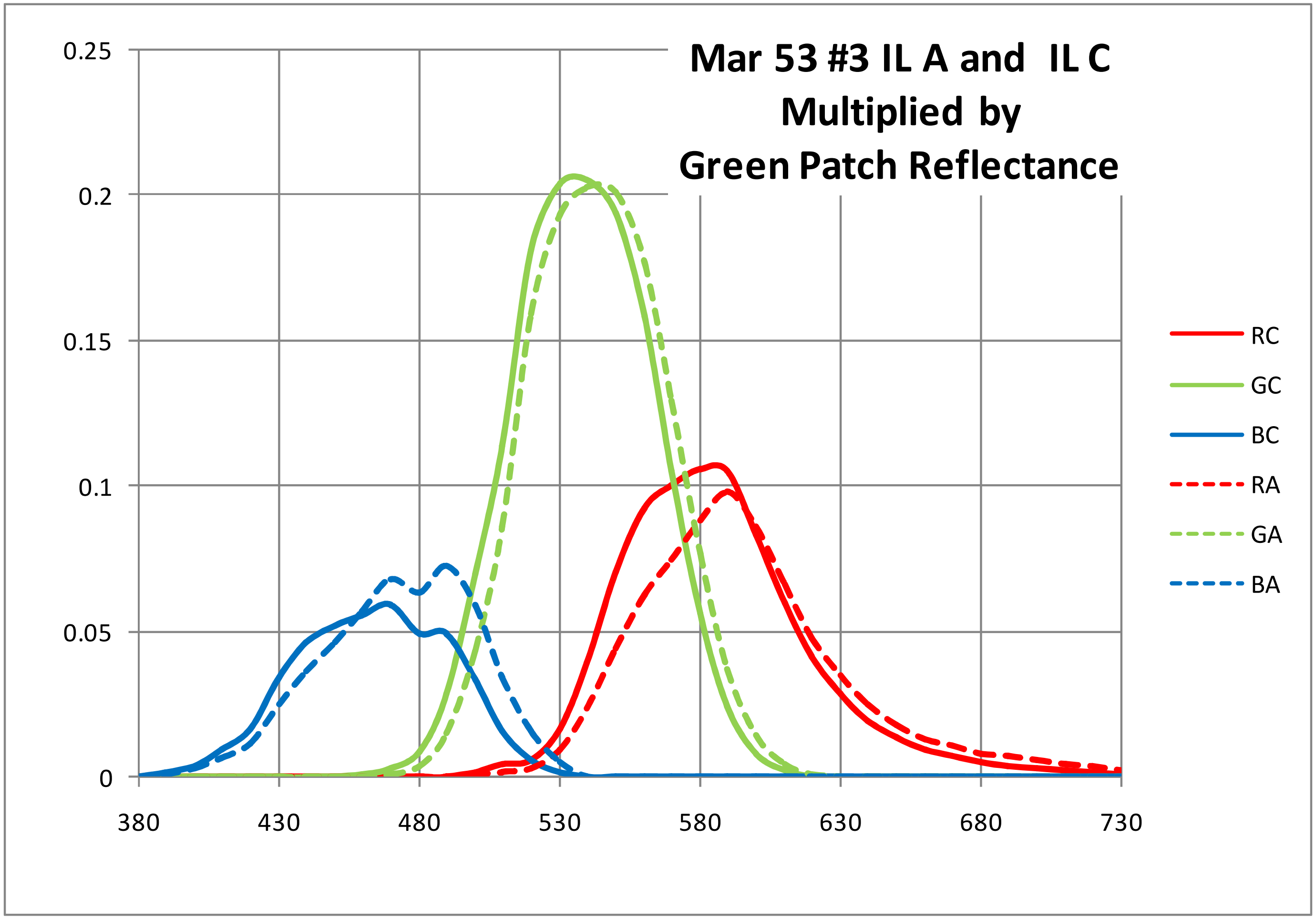
Camera Responses Normalized for Equal Area (R=G=B) on White



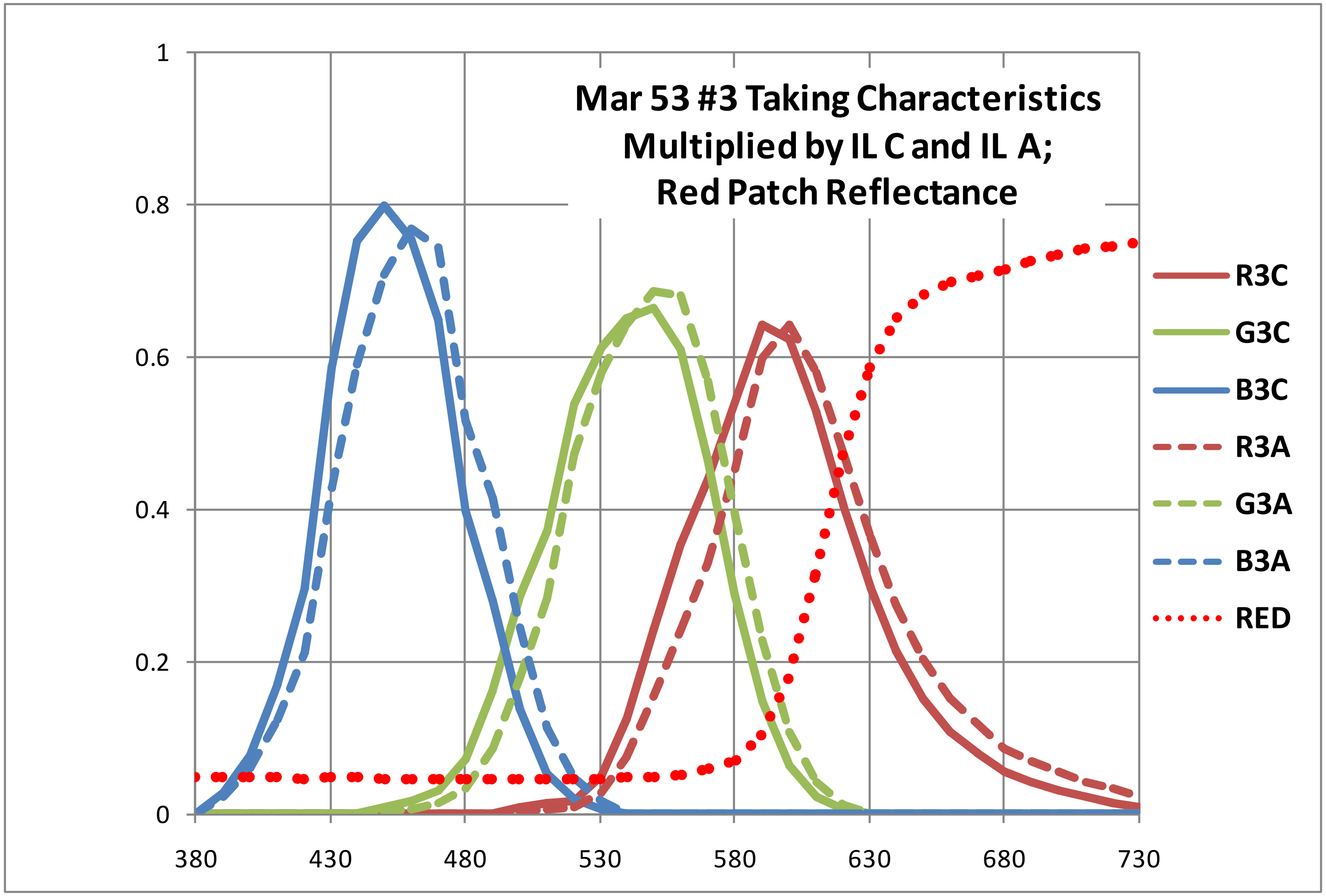
Mar 53 #3 Camera Multiplied by IL C or IL A, and Green Patch



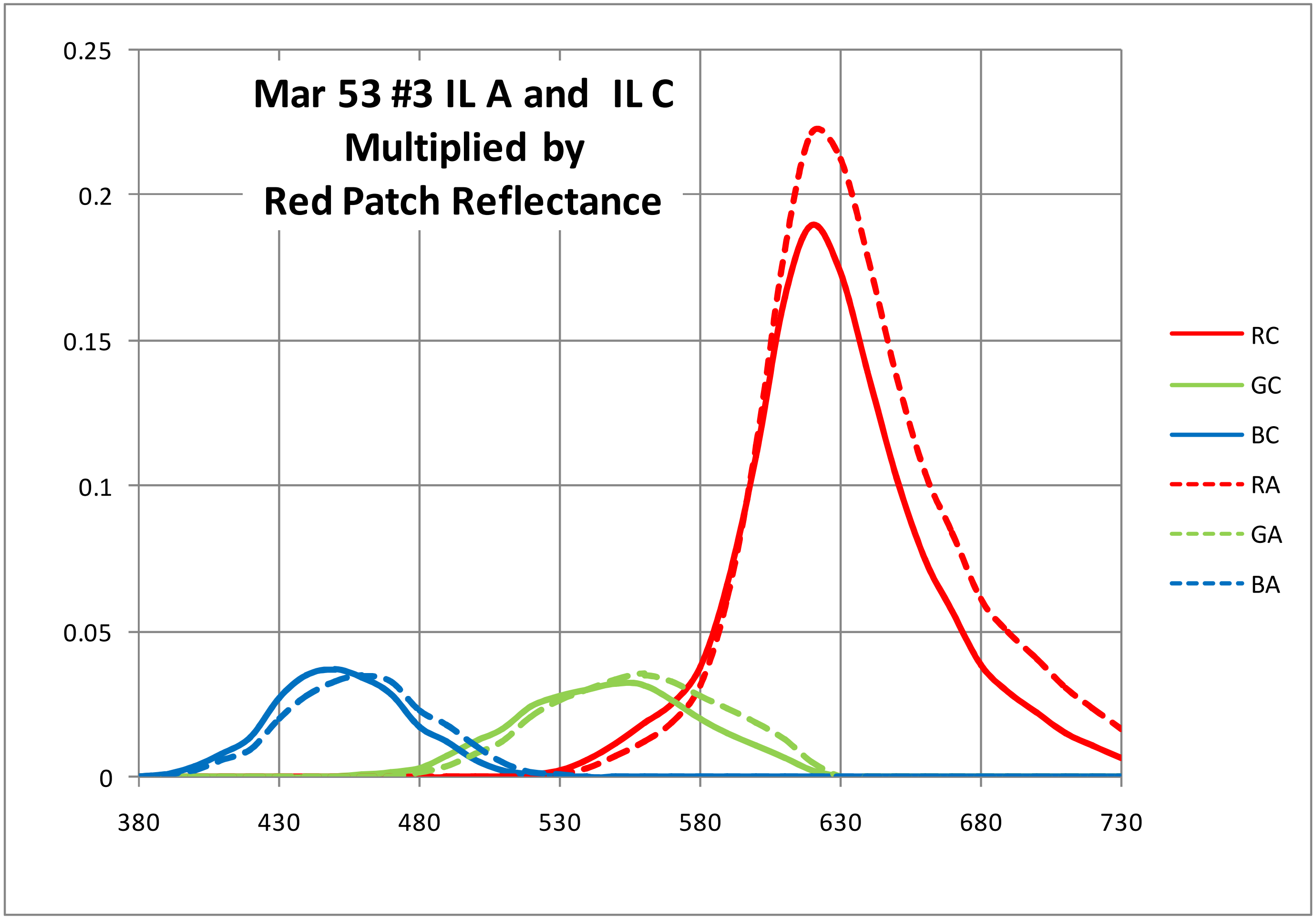
Mar 53 #3 Camera, Illuminant, and Green Patch Products



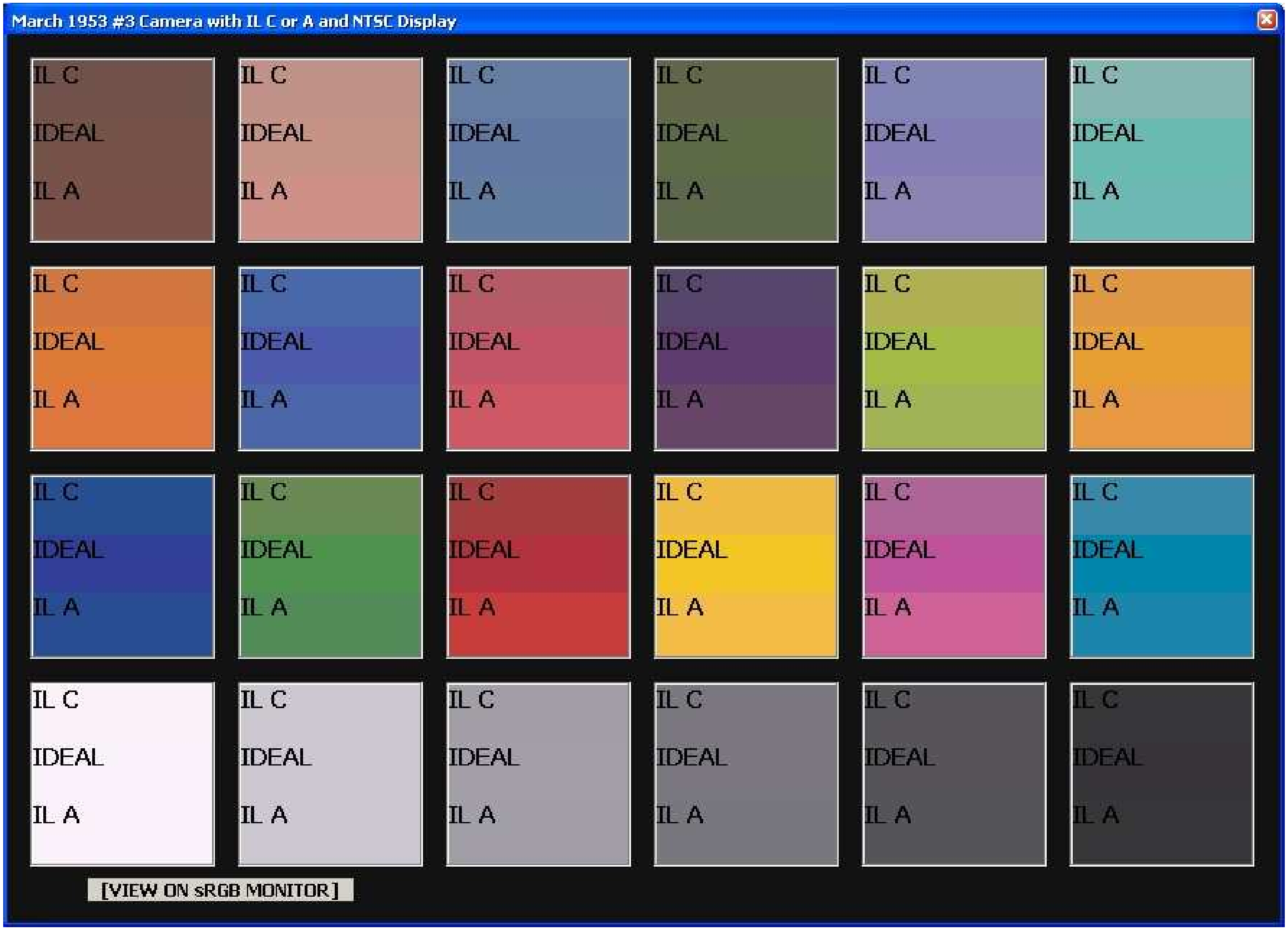
Mar 53 #3 Camera Multiplied by IL C or IL A, and Red Patch



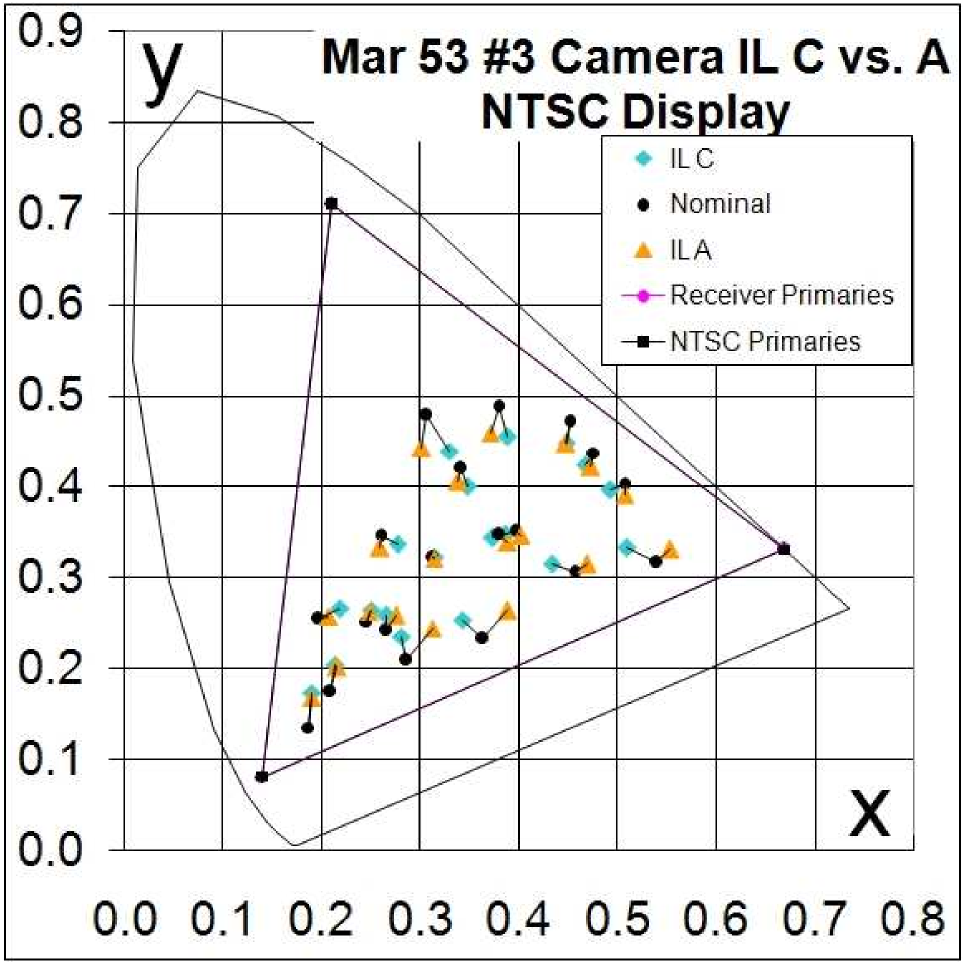
Mar 53 #3 Camera, Illuminant, and Red Patch Products



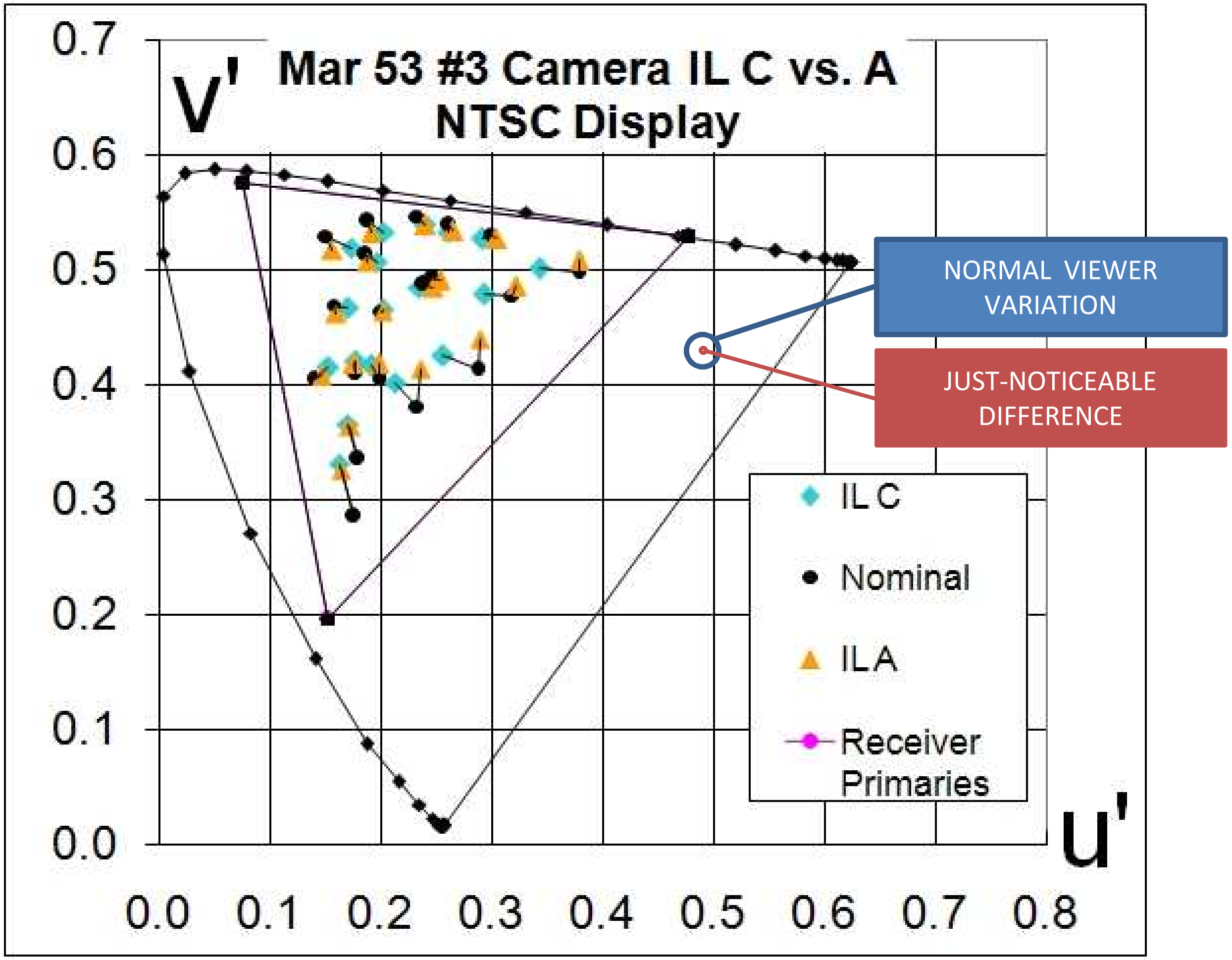
March 1953 Camera No.3 Under Illuminants C and A



March 1953 Camera No.3 Under Illuminants C and A



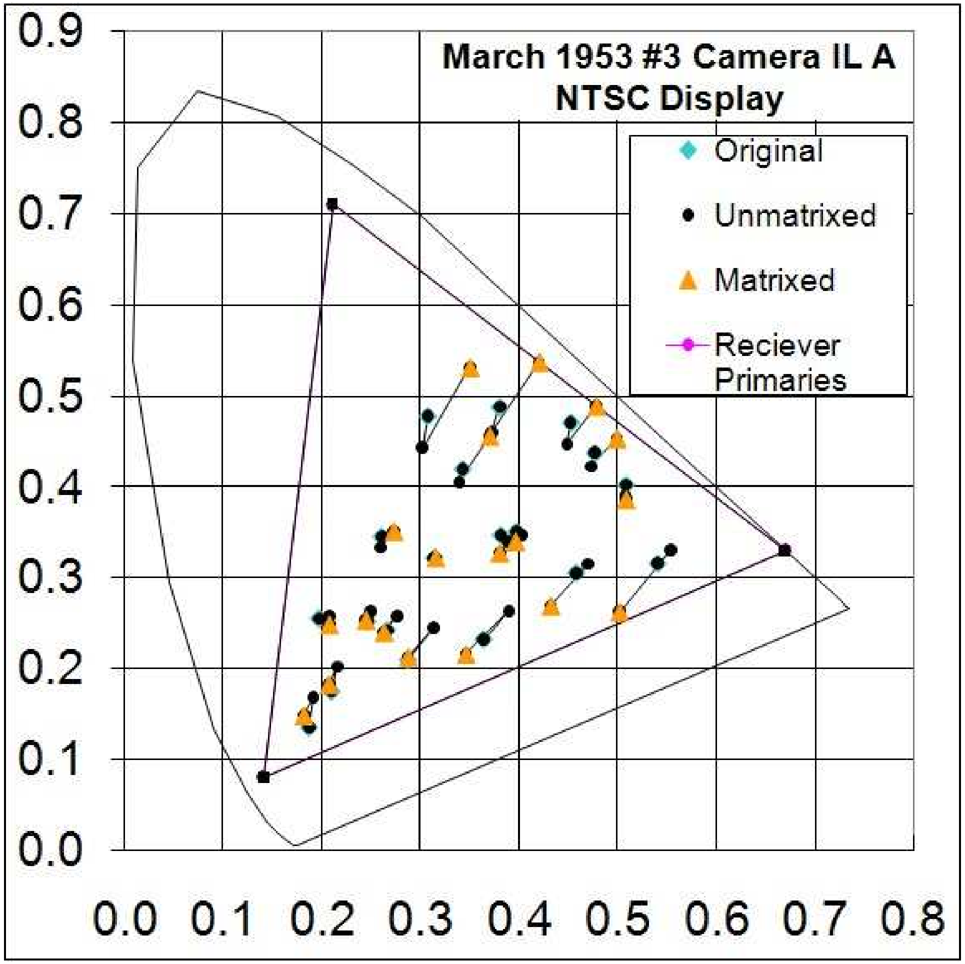
March 1953 Camera No.3 Under Illuminants C and A



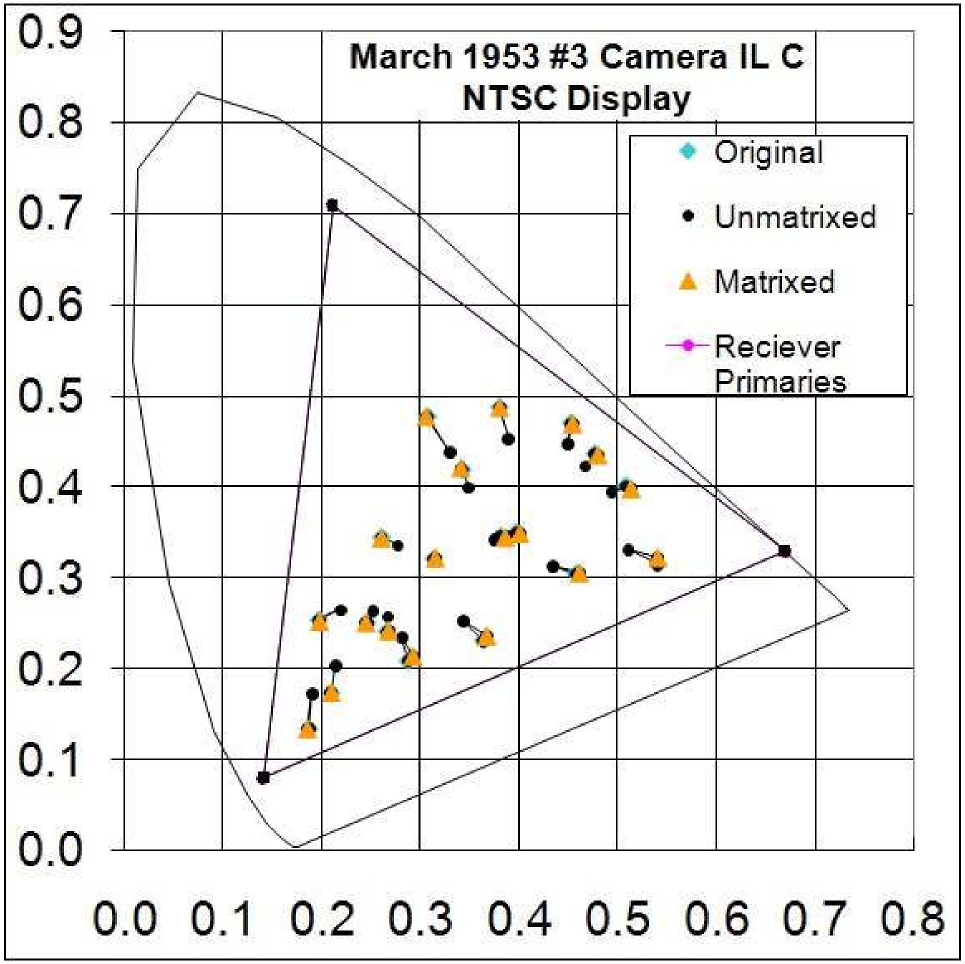
March 1953 Camera No.3 Under Illuminant A With Matrix

March 1953 Camera No.3 Under Illuminant C With Matrix

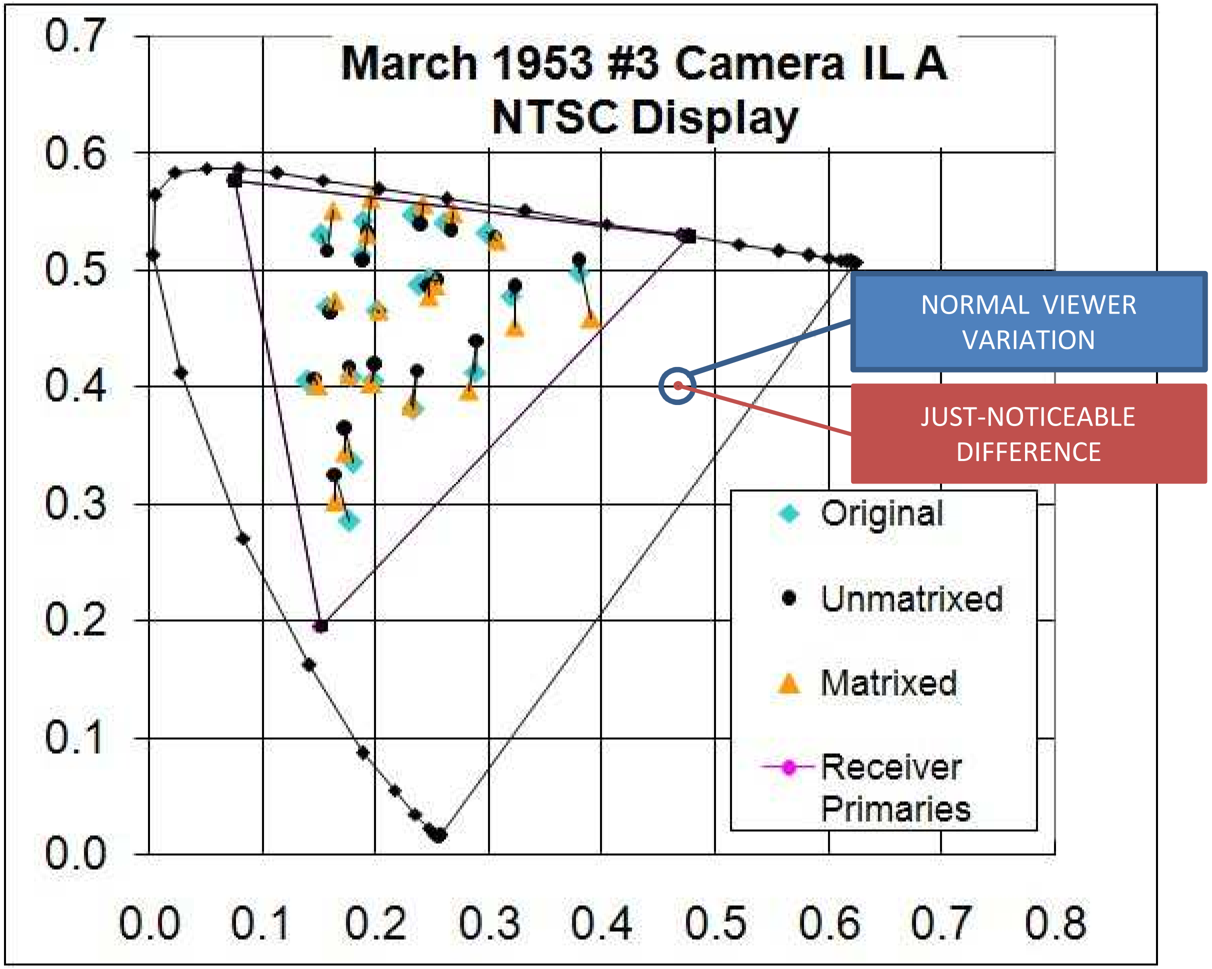
March 1953 Camera No.3 Under Illuminant A



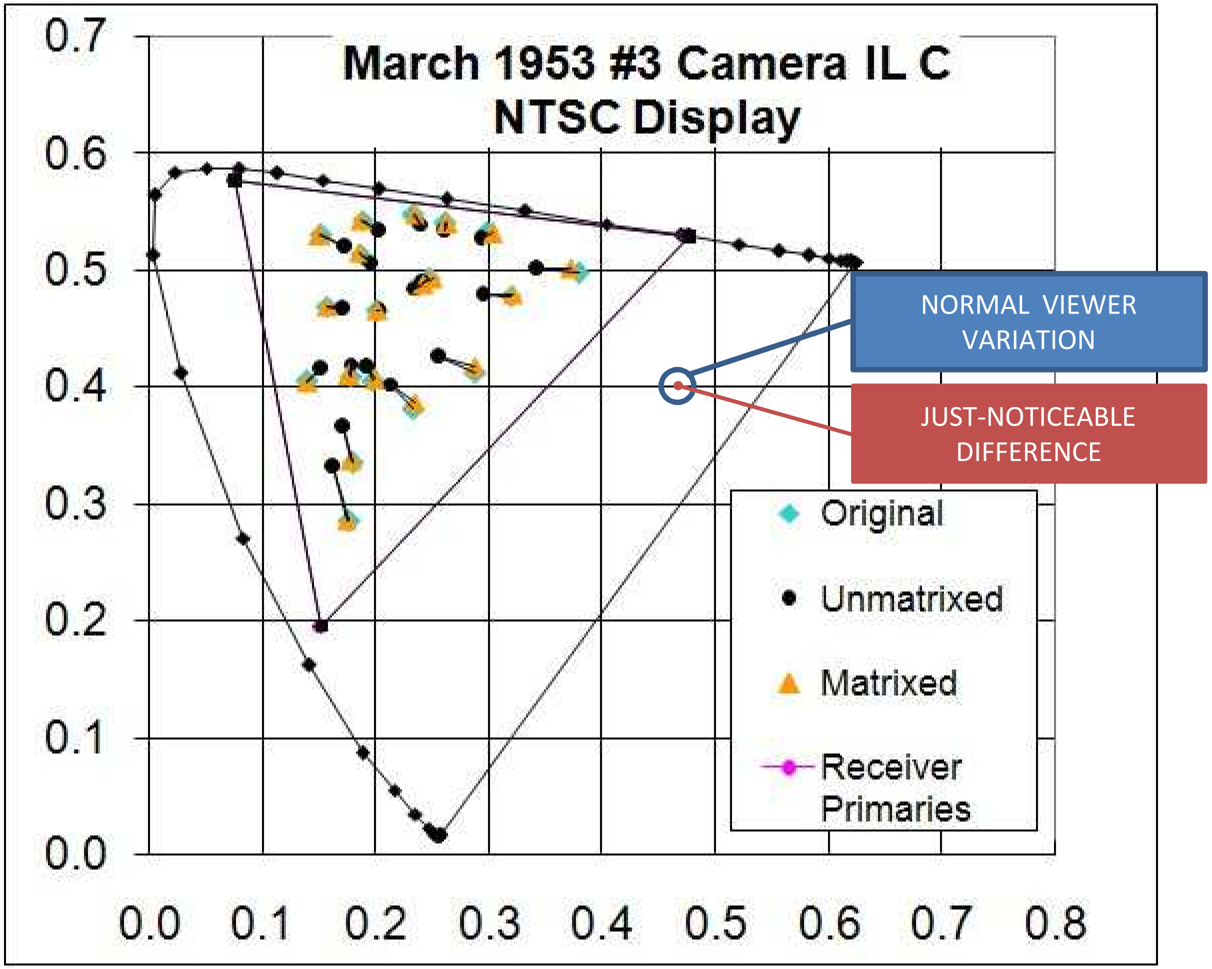
March 1953 Camera No.3 Under Illuminant C



March 1953 Camera No.3 Under Illuminant A

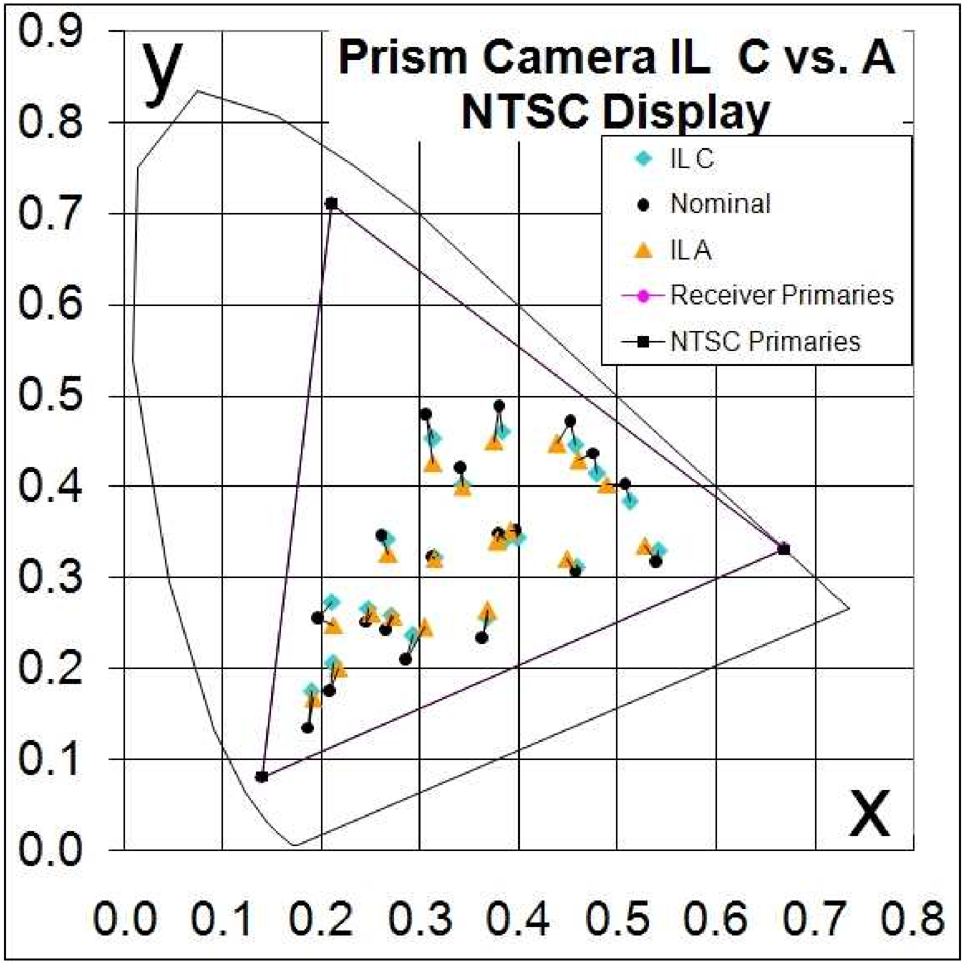


March 1953 Camera No.3 Under Illuminant C

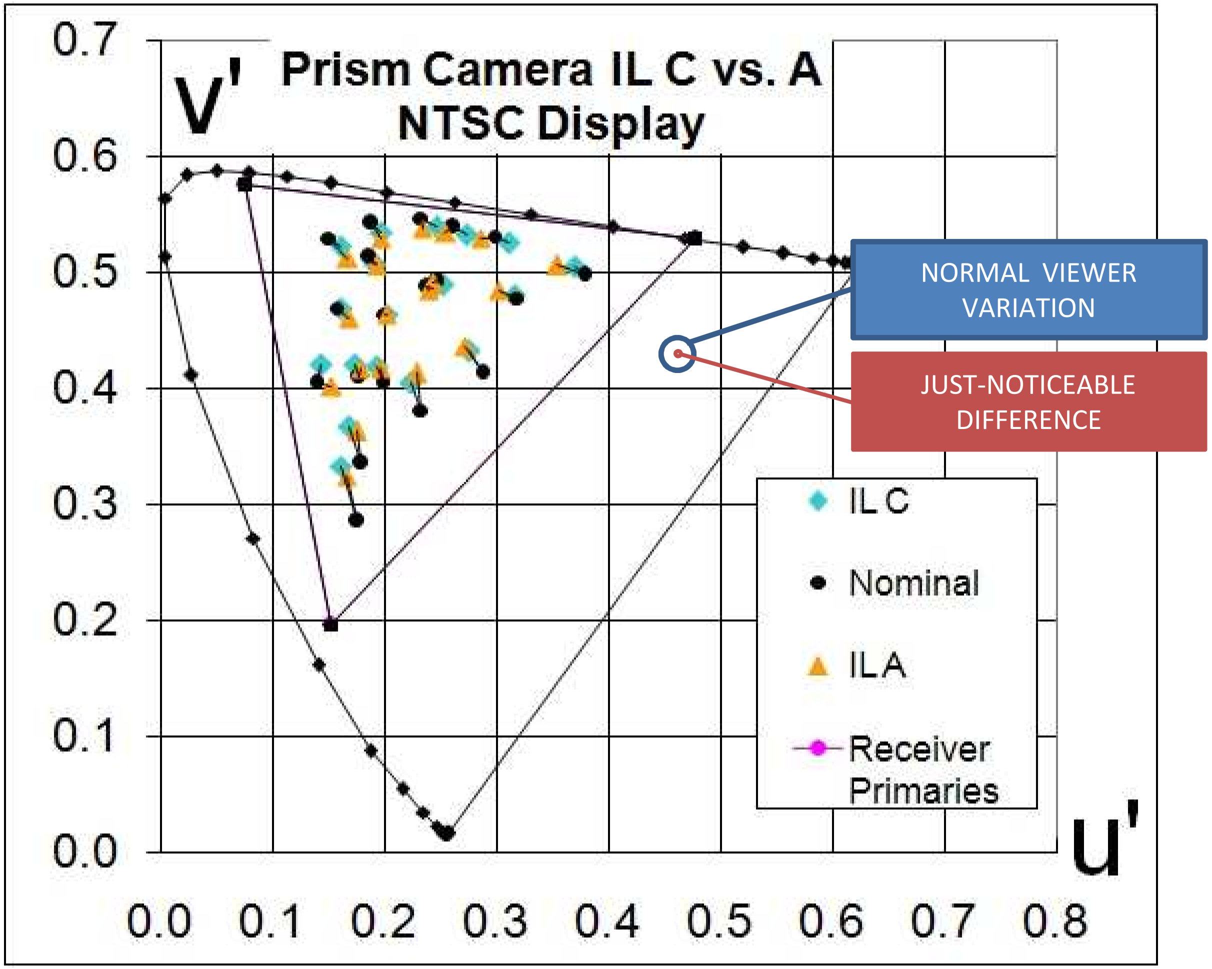


Prism Camera Under Illuminants C and A

Prism Camera Under Illuminants C and A



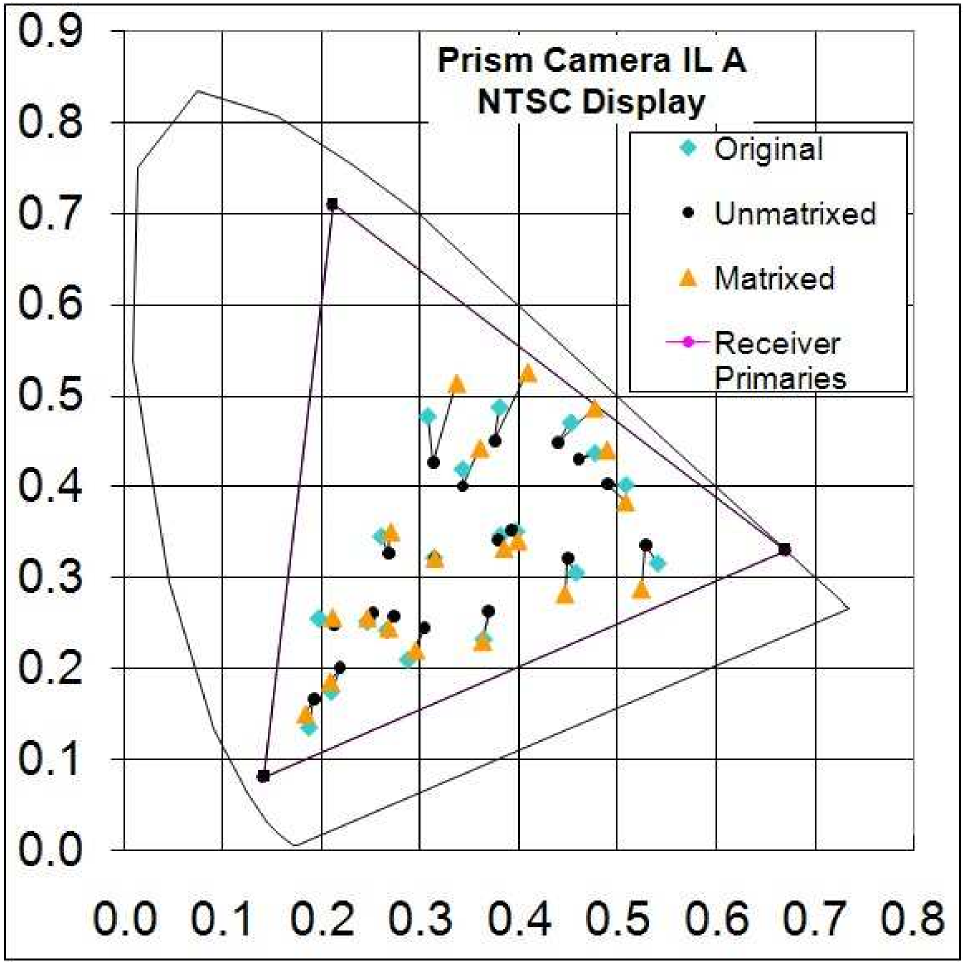
Prism Camera Under Illuminants C and A



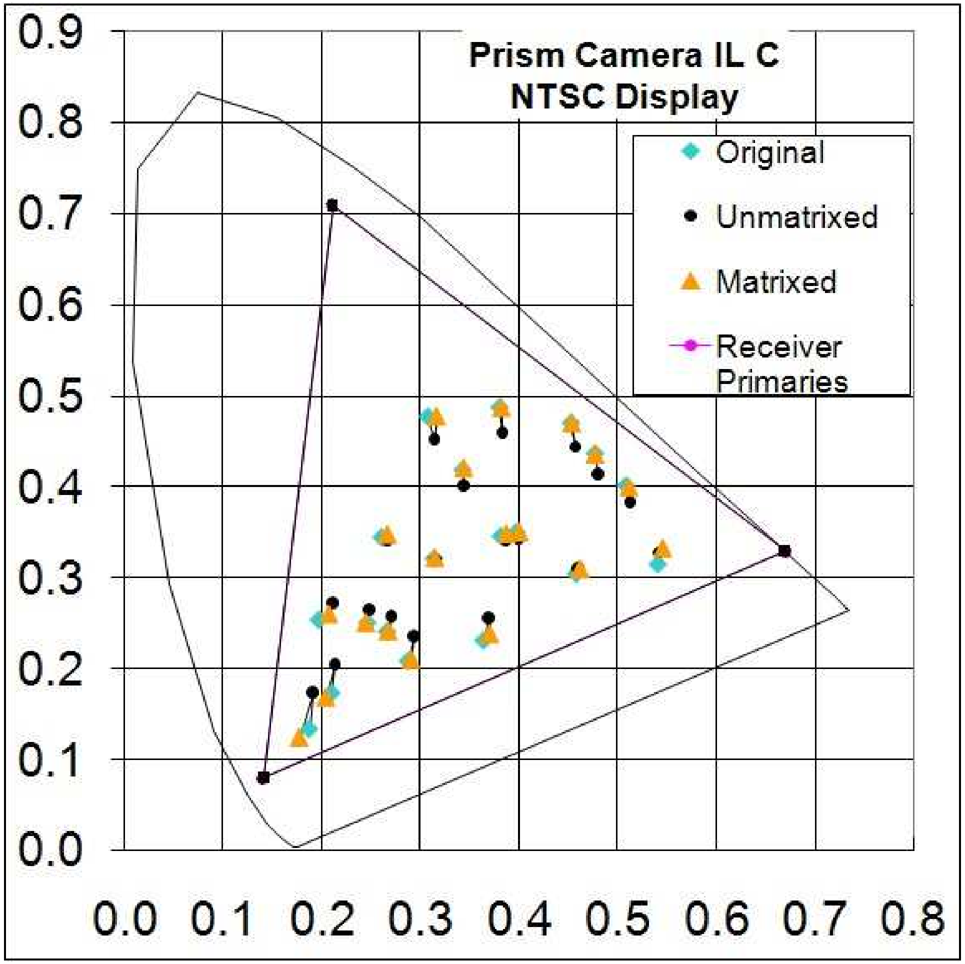
Prism Camera Under Illuminant A With Matrix

Prism Camera Under Illuminant C With Matrix

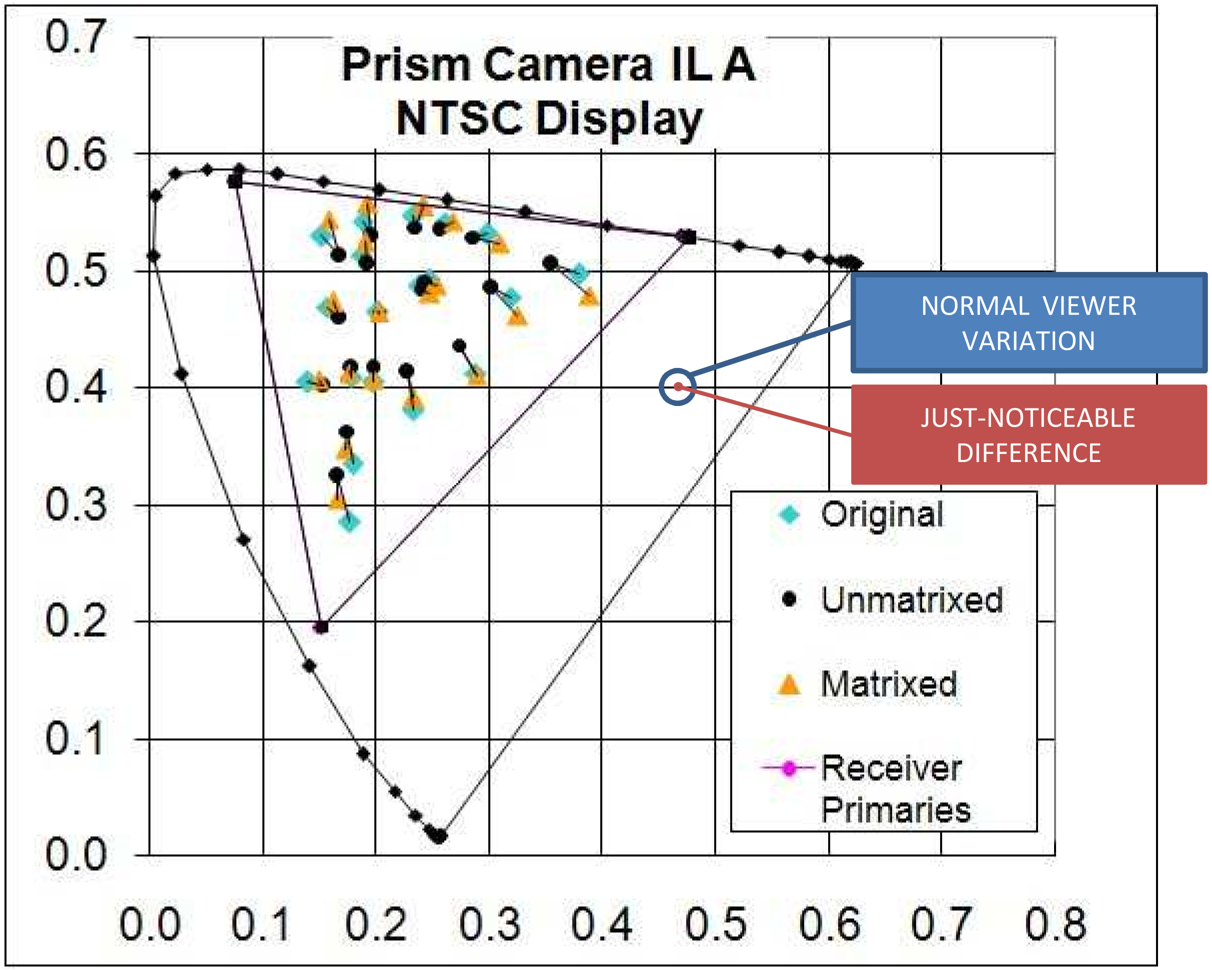
Prism Camera Under Illuminant A



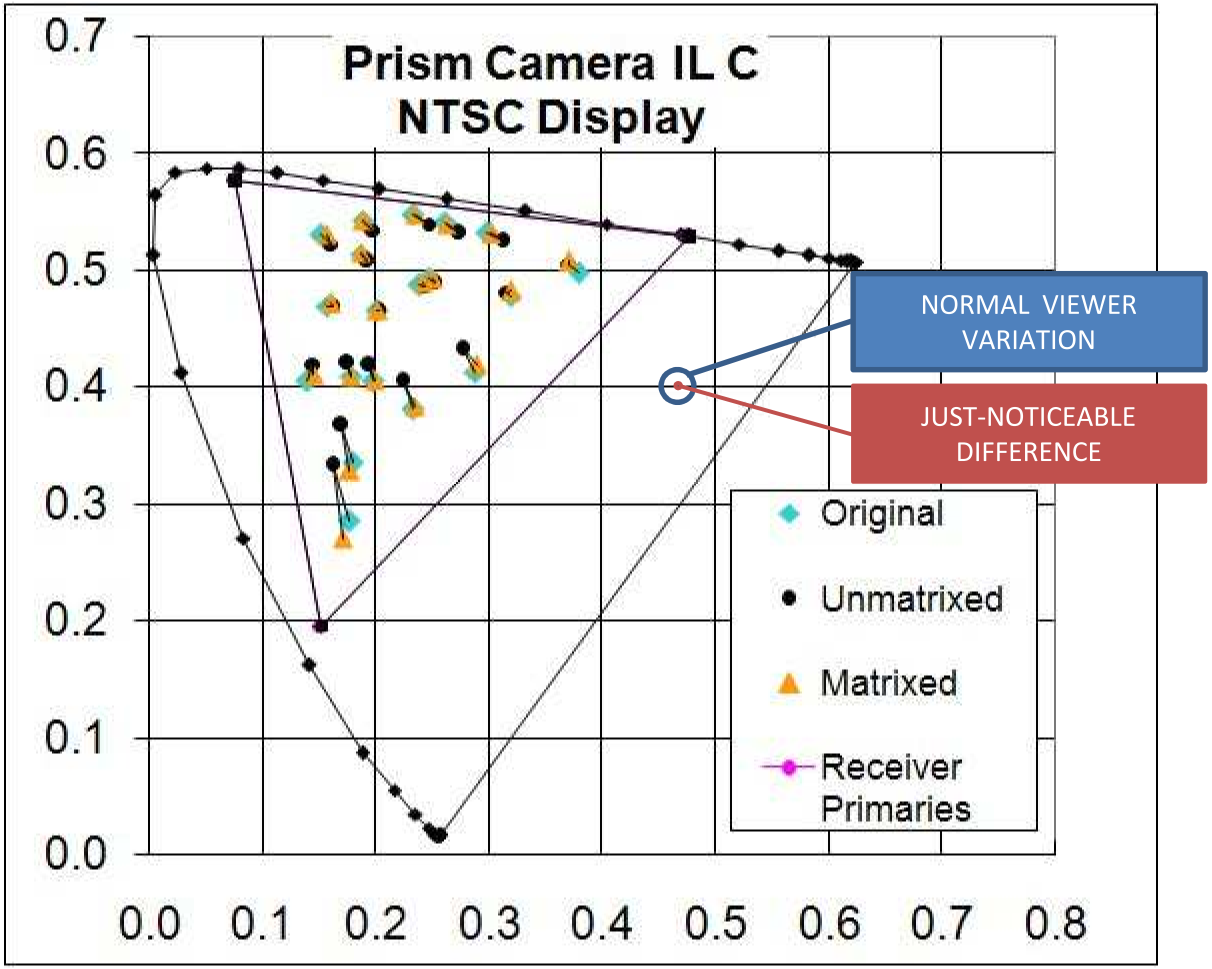
Prism Camera Under Illuminant C



Prism Camera Under Illuminant A



Prism Camera Under Illuminant C



Veggie Market Original

Veggie Market as seen by Prism camera under IL A

Conclusions…

Conclusions

- Computerized calculations have allowed reproduction of early color TV camera characteristics on current displays
- Color distortions due to receiver phosphors and white point were considerably larger than those due to camera response
- The greatest shortcomings of early image orthicon cameras were noise and non-ideal gamma correction characteristics

Conclusions

- Early image orthicon cameras had close to ideal (non-matrixed) spectral response due to use of highly absorptive trimming filters. However, this arrangement resulted in reduced camera sensitivity.
- Later prism optics were more efficient, and still obtained good color on a test chart although RGB responses were less ideal

Conclusions

- Color distortions could have been improved by use of matrixing in the camera, but SNR would have been degraded
- Color distortions due to camera response were small enough to be corrected to a great degree by small adjustments of receiver hue and color level
- Any large color distortions (especially hue distortions) in early broadcasts should be attributed to factors other than camera response

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- Pete Deksnis
- Wayne Luplow
- Ed Reitan

Thank You

Questions?

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References

[Ref01] **Jay Adrick, private communication** regarding program at Xavier University, 2007

[Ref02] **TV Display Phosphors/Primaries – Some History**, LeRoy DeMarsh, Journal SMPTE, December 1993

[Ref03] **Cathode-Ray-Tube Phosphors: Principles and Applications**, Simon Larach and Austin E. Hardy, Proceedings of the IEEE, Vol. 61, No.7, July 1973

[Ref04] Before the Federal Communications Commission, Washington D.C., **Petition of Radio Corporation of America and National Broadcasting Company, Inc. for Approval of Color Standards for the RCA Color Television System**, June 25, 1953

[Ref05] **Optical System Diagram for MI-40534 Color Camera**, http://home.att.net/~pldexnis/potpourri2/lastpage6.html

[Ref06] **Color Television Engineering**, John W. Wentworth, McGraw-Hill Book Company, Inc., 1955, pp.292-293

[Ref07] **The Reproduction of Colour**, Third Ed., R.W. G. Hunt, Fountain Press, 1975

[Ref08] **Color Science**, 2nd Ed, G. Wyszecki and W.S. Stiles, John Wiley & Sons, 1982

[Ref09] **Color Television, Selections from the Journal of the SMPTE**, Richard S. O'Brien, Ed., Society of Motion Picture and Television Engineers, 1970

[Ref10] **IEC 61966-2-1 Multimedia systems and equipment - Colour measurement and management - Part 2-1**: Colour management - Default RGB colour space – sRGB

[Ref11] **ITU-R BT.709-5**, Parameter values for the HDTV standards for production and international programme exchange

[Ref12] **Optimum Color Analysis Characteristics and Matrices for Color Television Cameras with Three Receptors**, A. H. Jones, Journal SMPTE, Vol. 77, February 1968

[Ref13] **Colour Error Reduction in Video Systems**, R.J. Green and S.J. Ismail, IEEE Transactions on Broadcasting, Vol. 36 No. 1, March 1990

[Ref14] **NTIA Technical Memorandum TM-04-406**, Color Correction Matrix for Digital Still and Video Imaging Systems,Stephen Wolf, U.S. DEPARTMENT OF COMMERCE, December 2003

References

[Ref15] **Spectral Response of Color Cameras**, I. Bosonoff and W. J. Derenbecher, Radio Corporation of America, April 10, 1953

[Ref16] **Measurements of TK-41C camera prism assembly**, Jay Ballard [private communication, 2007]

[Ref17] **5820 Image Orthicon** (specification data sheets), Tube Division, Radio Corporation of America, Harrison, New Jersey (5820 -10-56), also similar data sheets for image orthicons type 5826, 6474, and 7037

[Ref18] **Handbook of Chemistry and Physics**, 69th Ed., 1988 1989, CRC Press, Inc., "Transmission of Corning Colored Filters" and "Transmission of Wratten Filters", pp. E-406 to E-420

[Ref19] **SMPTE Standard 0303M-2002**, Television – Color Reference Pattern

[Ref20] http://www.babelcolor.com/main_level/ColorChecker.htm#How_about_data

[Ref21] **Review of Work on Dichroic Mirrors and Their Light-Dividing Characteristics**, Mary Ellen Widdop, Journal SMPTE, Vol. 60, April 1953

[Ref22] **Measuring Colour**, R.W.G. Hunt, Halsted Press Div. of John Wiley & Sons, 1987

[Ref23] **The Performance Characteristics of Yttrium Osysulfide – A New Red Phosphor for Color Television**, Austin E. Hardy, IEEE Transactions on Electron Devices, Vol ED-15, No. 11, November 1968

[Ref24] http://www.color.org/sRGB.xalter

[Ref25] **Television Receiver White Color: A Comparison of Picture Quality with White References of 9300 K and D6500**
Zwick, D.M.; Broadcast and Television Receivers, IEEE Transactions on, Volume BTR-19, Issue 4, Nov. 1973 pp. 205 – 213

[Ref26] **A Second Generation Color Tube Providing More Than Twice the Brightness and Improved Contrast**
Fiore, J.P.; Kaplan, S.H.; Broadcast and Television Receivers, IEEE Transactions on, Volume BTR-15, Issue 3, Oct. 1969 pp. 267 – 276

[Ref27] **Computing Colorimetric Errors of a Color Television Display System**
Neal, C.B.; Consumer Electronics, IEEE Transactions on, Volume CE-21, Issue 1, Feb. 1975 pp. 63 – 73

[Ref28] **An Analysis of the Necessary Decoder Corrections for Color Receiver Operation with Non-Standard Receiver Primaries**
Parker, N. W.; IEEE Transactions on Broadcast and Television Receivers, Volume BTR-12 No.1, April 1966; Reprinted in Consumer Electronics, IEEE Transactions on, Volume CE-28, Issue 1, Feb. 1982 pp. 74 – 83

References

Note: [Ref29 –Ref36] can be found at
http://www.ebu.ch/en/technical/publications/tech3000_series/index.php

[Ref29] **t3213 EBU Standard for Chromaticity Tolerances for Studio Monitors** - first edition 1975

[Ref30] **t3218 Colour Telecines, Methods of Measurement and Specifications** - third edition 1988

[Ref31] **t3237 Methods of Measurement of the Colorimetric Fidelity of Television Cameras** - first edition 1983

[Ref32] **t3237-s1 Methods of Measurement of the Colorimetric Fidelity of Television Cameras - Supplement 1**, Measurement Procedures - second edition 1989

[Ref33] **t3238 Methods of Measuring the Main Characteristics of Television Cameras** - first edition 1983

[Ref34] **t3263 Specification of Grade-1 Colour Picture Monitors** - second edition (editorial corrections 2006)

[Ref35] **t3273 Methods of Measurement of the Colorimetric Performance of Studio Monitors** - first edition 1993

[Ref36] **t3320 User requirements for Video Monitors in Television Production** 2007

[Ref37] **Colorimetric Performance of Non-Standard Television Receiver with Customer Adjustment**, Bretl, W.E., Consumer Electronics, IEEE Transactions on, Volume CE-25, Issue 1, Feb. 1979 pp. 100 – 110 [mistakenly listed as “Breti” in some indexes]

[Ref38] **Broadcast Camera Equipment for Monochrome and Color Television**, Radio Corporation of America, Broadcast and Television Equipment Division, Camden, NJ, 1956

[Ref39] **Color Television Theory, Equipment, Operation: Manual for Television Technical Training,** Second Edition, 1959, Radio Corporation of America

[Ref40] **RCA Photosensitive Devices and Cathode-Ray Tubes**, Form No. CRPD-105A, 1958, Radio Corporation of America

[Ref41] **Image Orthicons for Color Cameras**, R. G. Neuhauser and A. A. Rotow, Proc. IRE, Vol 42 No.1, January 1954, pp. 161-165

[Ref42] **A Study of the Need for Color Controls on Color TV Receivers in a Color TV System Operating Perfectly**, Hirsch, Charles J., IEEE Transactions on Broadcast and Television Receivers, November 1964, pp. 71-96