

Color Consistency: a Quality Requirement for General Service Lamps (GSLs)

FORTALECIMIENTO DE ESTÁNDARES DE EFICIENCIA ENERGÉTICA EN ILUMINACIÓN
Primera Reunión y Taller Presencial del Grupo Técnico de Eficiencia Energética (GTEE)

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6 Nov 2019



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Issues to Consider

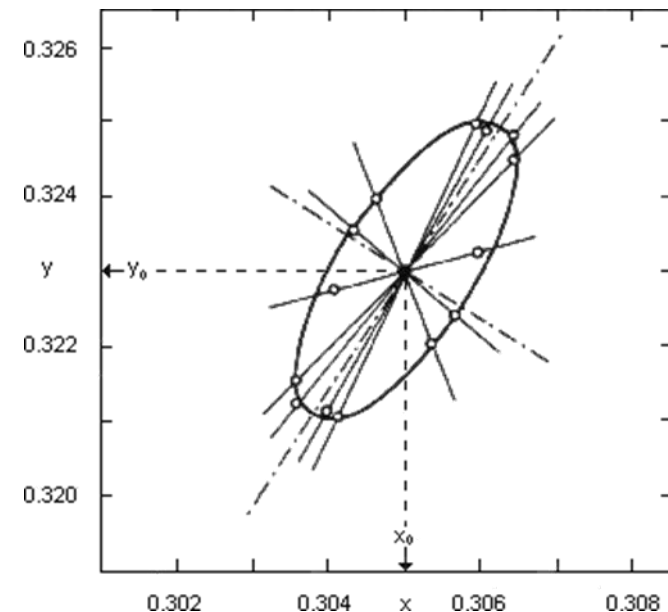
MacAdam Ellipses – the History

- A MacAdam ellipse is an area in a chromaticity diagram which contains all colors that are indistinguishable to the average human eye, from the color at the center of the ellipse
- Elliptical shape represents the just noticeable differences in chromaticity
- In the late 1930's, Dr. David L. MacAdam set up an experiment where a trained observer viewed two different colours, at a fixed luminance of about 48 cd/m²

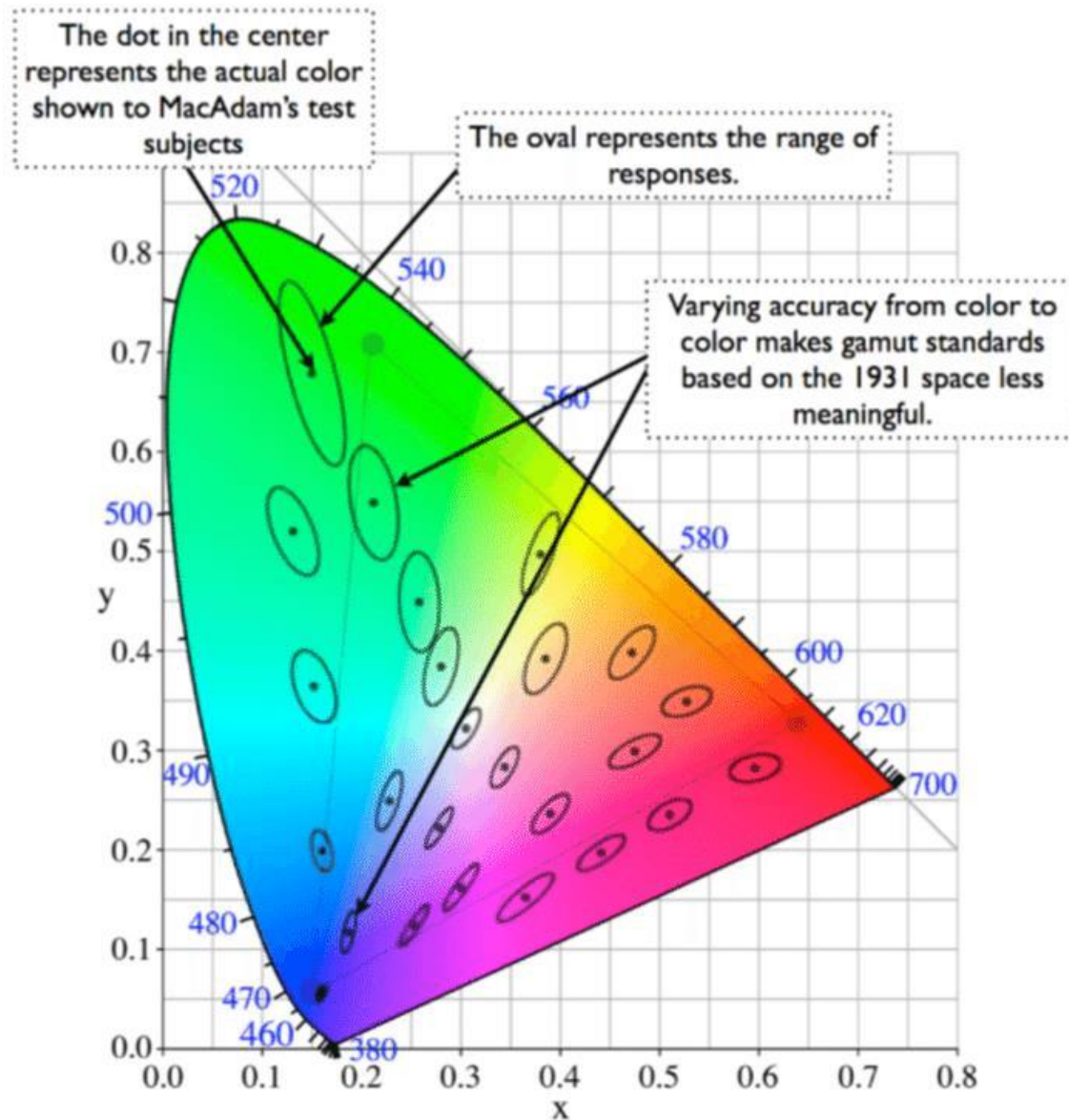


MacAdam Ellipses – the History

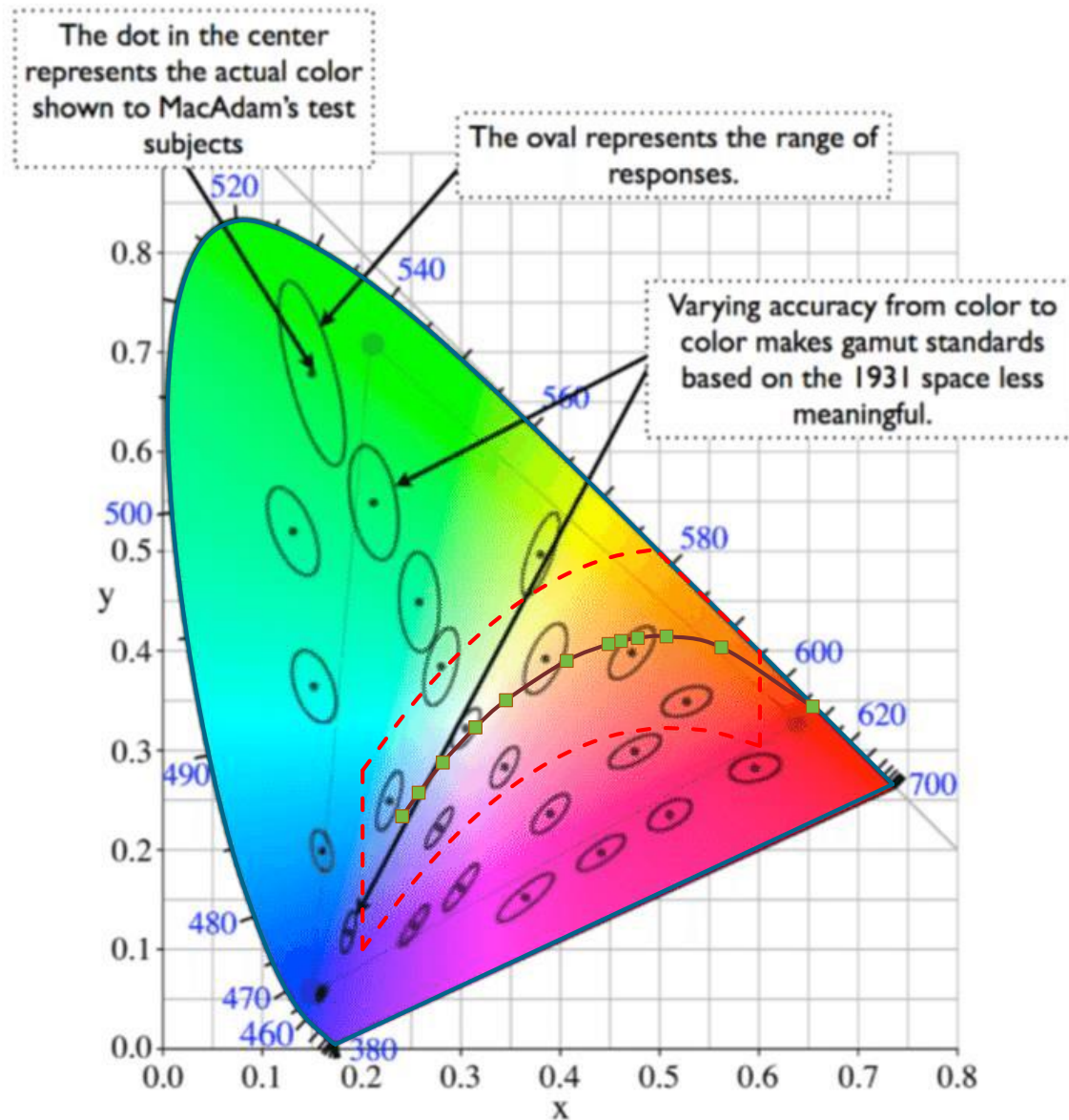
- Methodology:
 - One color (the "test" color) was fixed, and the other was adjustable by the observer. The observer adjusted the color until it matched the test color
 - MacAdam found that all of the matches made by the observer fell into an ellipse on the CIE 1931 chromaticity diagram
 - Measurements were made at 25 x,y chromaticity points on the diagram, and the size and orientation of the ellipses varied
 - Thus, there are 25 ellipses measured by MacAdam, as shown on the next slide



MacAdam Ellipses – the 25 color points



MacAdam Ellipses – the 25 color points

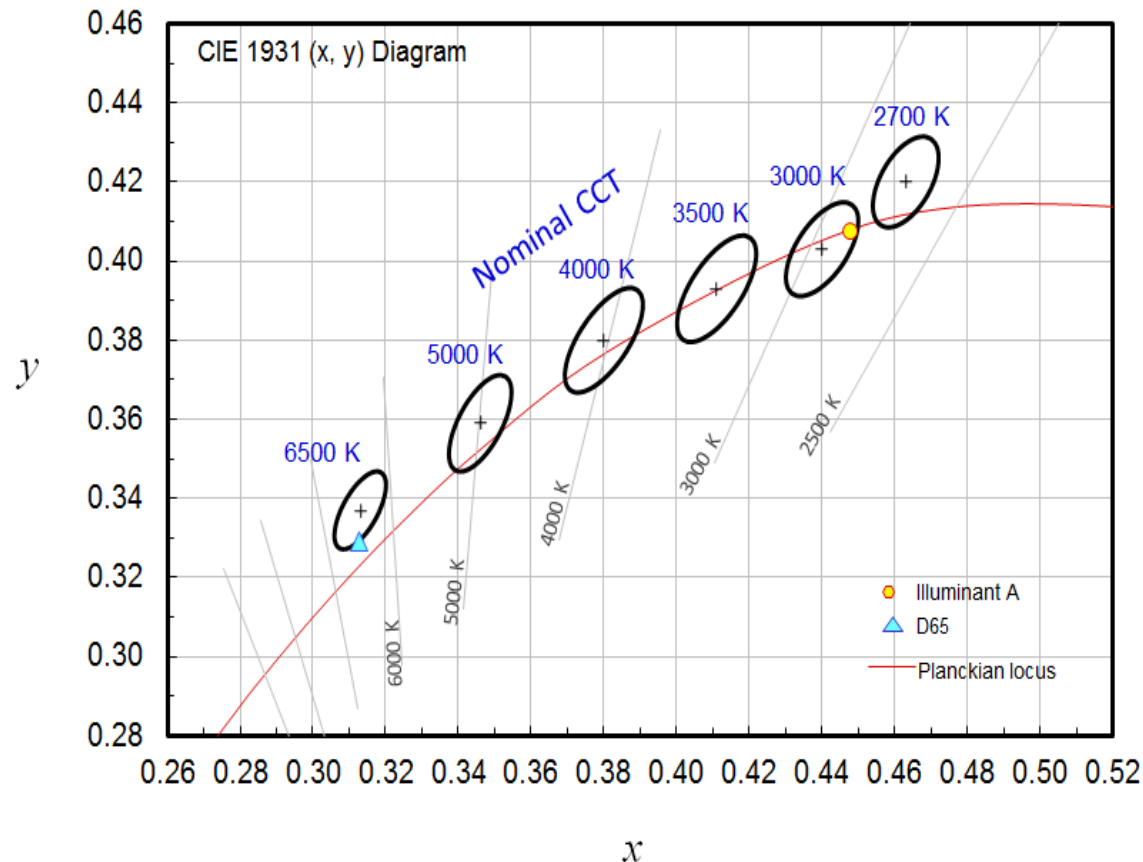


MacAdam Ellipses - Interpolating to other color points

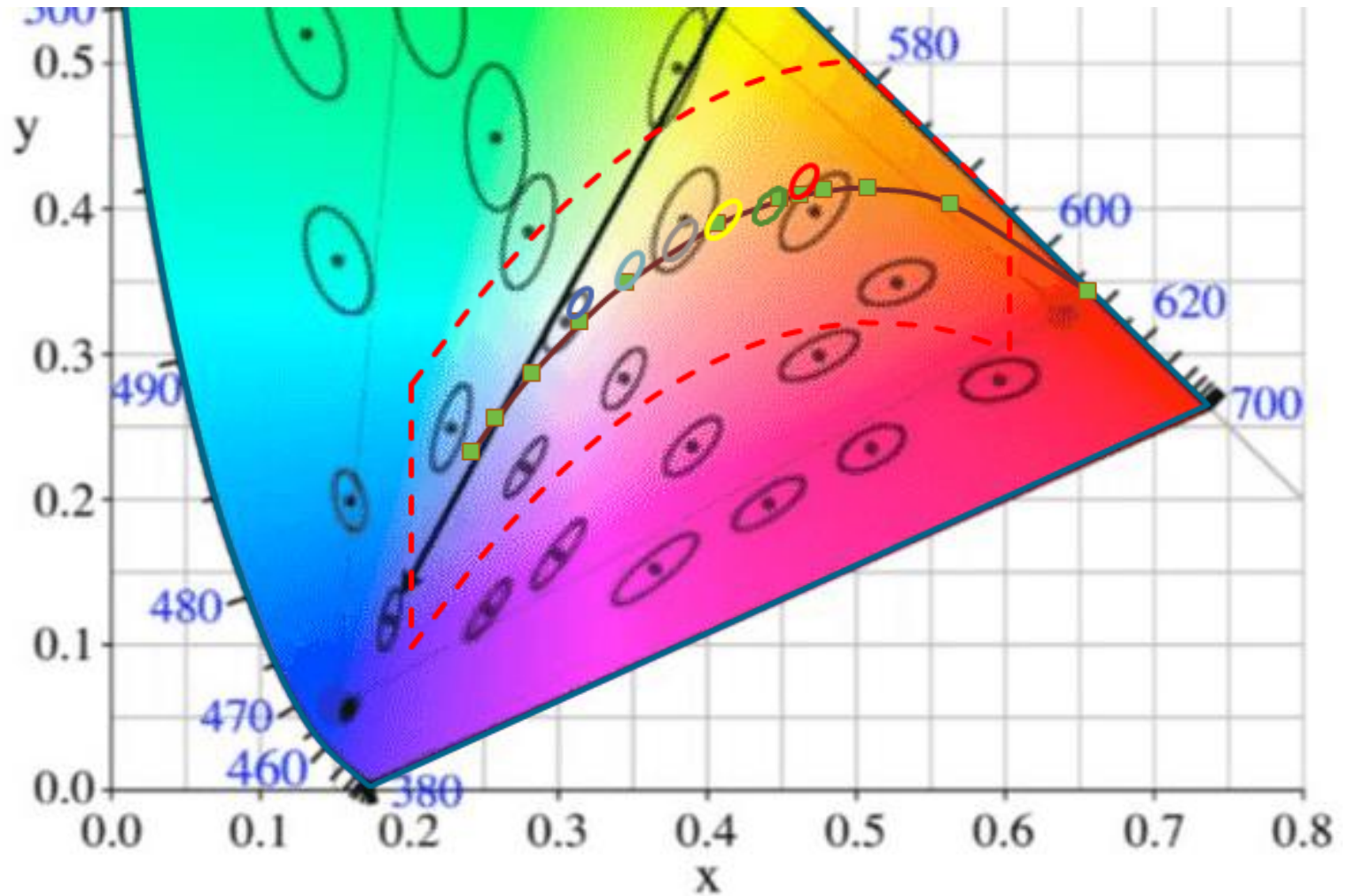
- Researchers studying this issues have to date concluded that there is no mathematical model from interpolating/extrapolating MacAdam ellipses (major & minor axes length and orientation) for other points in colour space

MacAdam Ellipses in Standards

- IEC 60081 (2002) - Performance Standard for Fluorescent Lamps defines 5-step MacAdam ellipses for six nominal CCTs.

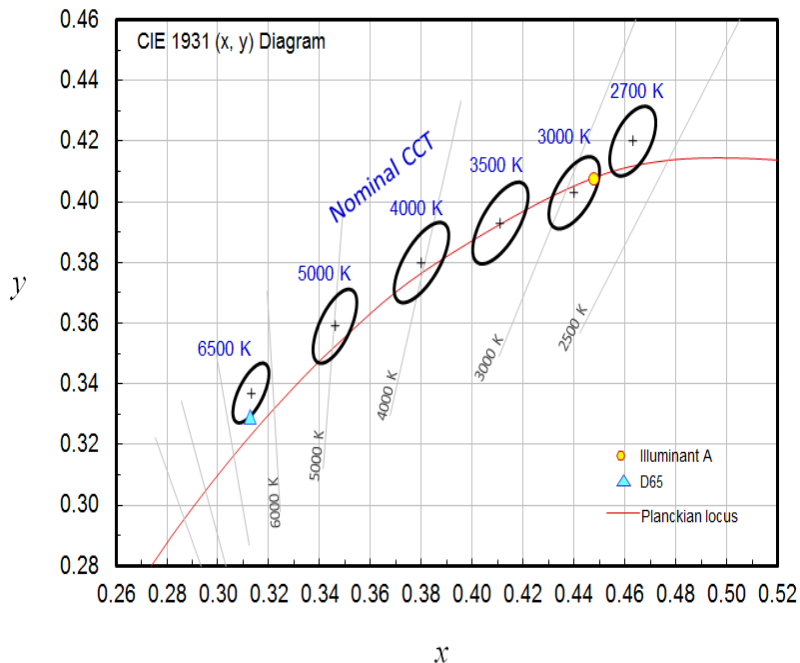


MacAdam Ellipses – Standards and the original color points

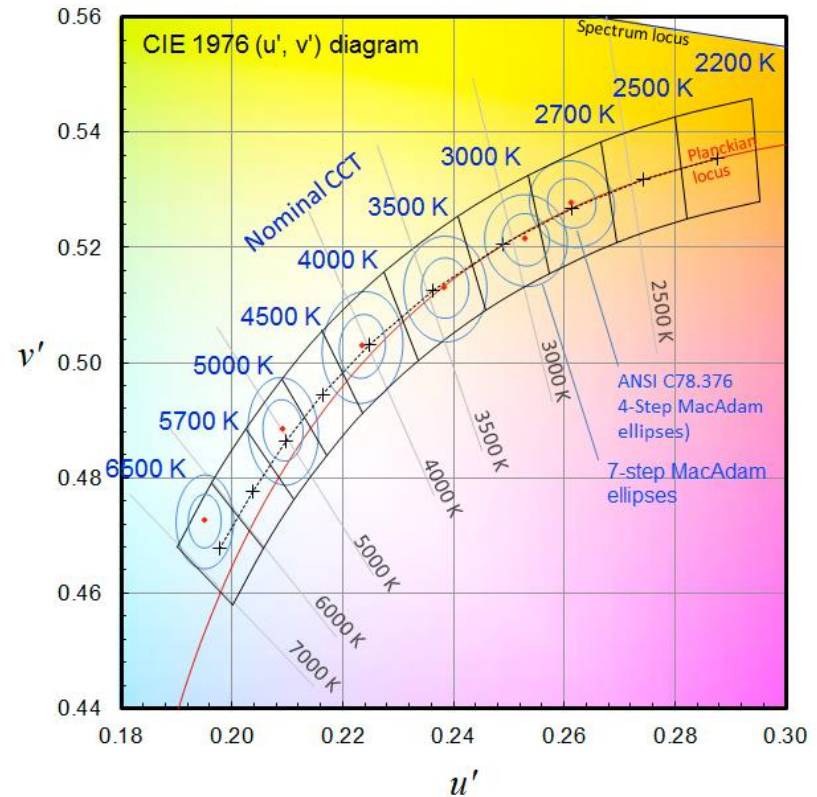


ANSI Quadrangles – C78.377-2017

IEC 60081 for Fluorescent Lamps (5 step MacAdam ellipses)



ANSI C78.377-2017 Chromaticity Specifications for Solid State Lighting Products



1st version 2008
(Ohno, Technical coordinator)

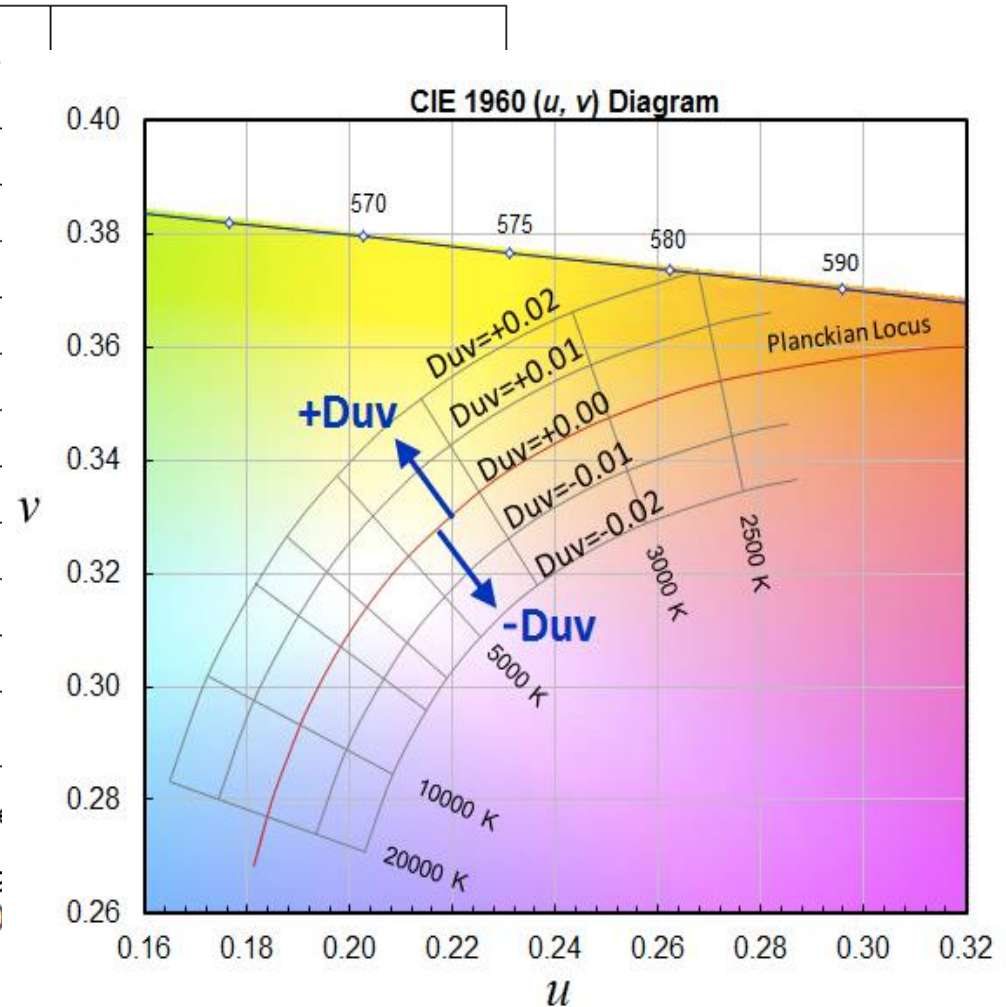
ANSI C78.377-2017

Table 1
Basic Nominal CCT Specification

Nominal CCT Category (K)	Target CCT and Tolerance (K)	Target Duv
2200	2238 ± 102	0.0000
2500	2460 ± 120	0.0000
2700	2725 ± 145	0.0000
3000	3045 ± 175	0.0001
3500	3465 ± 245	0.0005
4000	3985 ± 275	0.0010
4500	4503 ± 243	0.0015
5000	5029 ± 283	0.0020
5700	5667 ± 355	0.0025
6500	6532 ± 510	0.0031
Flexible CCT (2300 – 6400)	$T_F^{(1)} \pm \Delta T^{(2)}$	$D_{uv}(T_F)^{(3)}$

- T_F is chosen to be at 100 K steps (2300, 2400, ..., 6400 K), as listed in Table 1.
- $\Delta T_F = 1.1900 \times 10^{-8} \times T_F^3 - 1.5434 \times 10^{-4} \times T_F^2 + 0.7168 \times T_F - 9$
- $D_{uv}(T) = 0$ for $T < 2870\text{K}$, $D_{uv}(T) = 57700 \times (1/T)^2 - 44.6 \times (1/T)$

Duv defined in ANSI C78.377

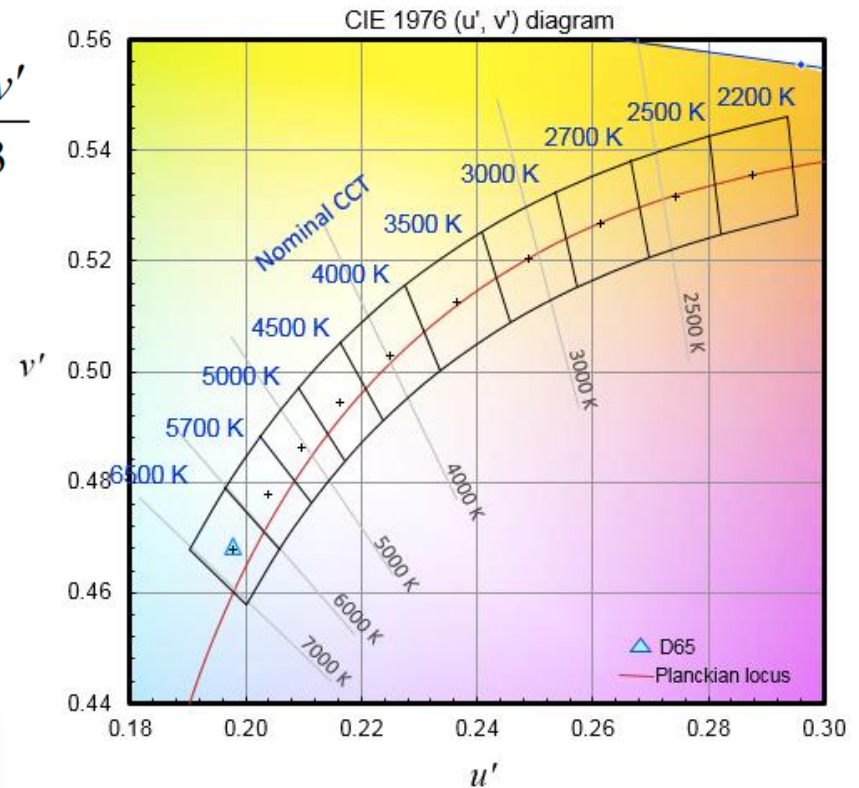
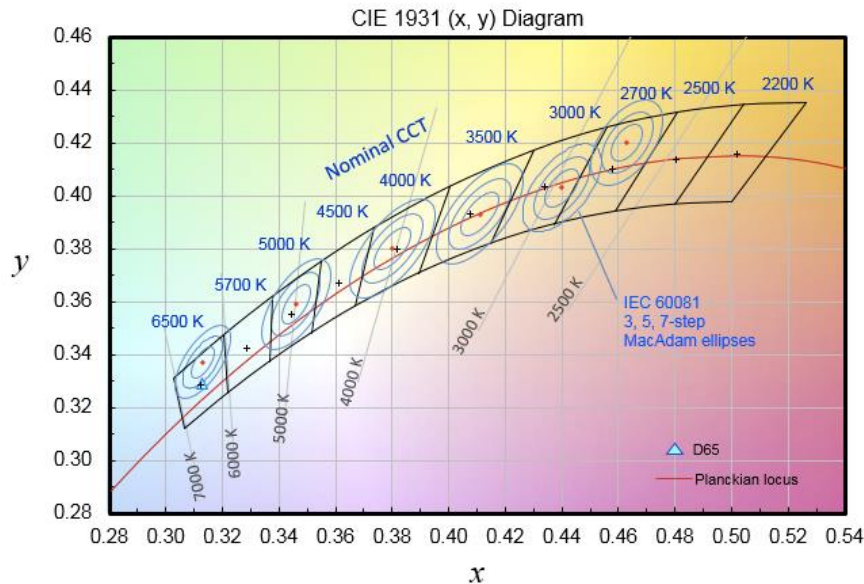


Specifications expressed in (x, y) or (u', v')

- There is a mathematical relationship between the different systems for chromaticity
- **CIE 1976 (u', v')** Diagram is recommended

$$x = \frac{9u'}{(6u' - 16v' + 12)} \quad u = \frac{4x}{(-2x + 12y + 3)} \quad u = u'$$

$$y = \frac{2v'}{(3u' - 8v' + 6)} \quad v = \frac{6y}{(-2x + 12y + 3)} \quad v = \frac{2v'}{3}$$



CIE TN 001 Chromaticity Difference Specification

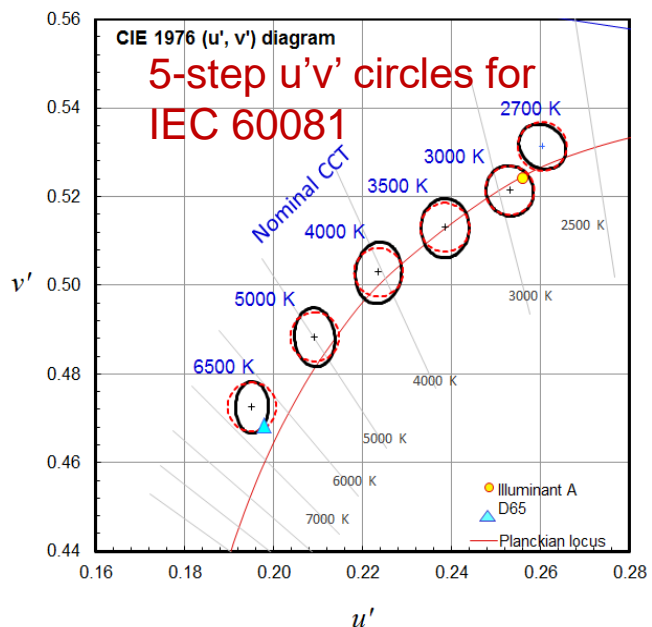
Published in July 2014



u'v' circle is recommended to replace MacAdam ellipses



- Requires 3 parameters
- No standards for interpolation
- Research by 1 subject



u'v' circle: a circle with radius r on CIE (u', v') diagram.

$$(u' - u'_c)^2 + (v' - v'_c)^2 = r^2$$

n-step u'v' circle: u'v' circle with a radius $n \times 0.0011$.

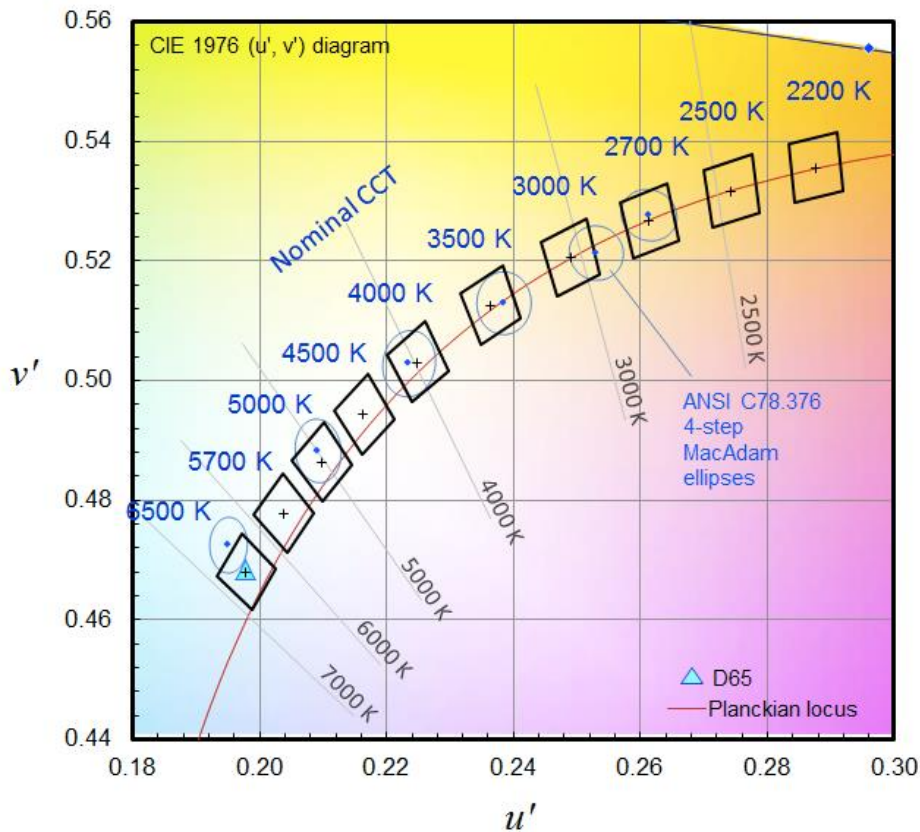
$$(u' - u'_c)^2 + (v' - v'_c)^2 = (0,0011 \cdot n)^2$$

(This corresponds to n -step MacAdam ellipses.)

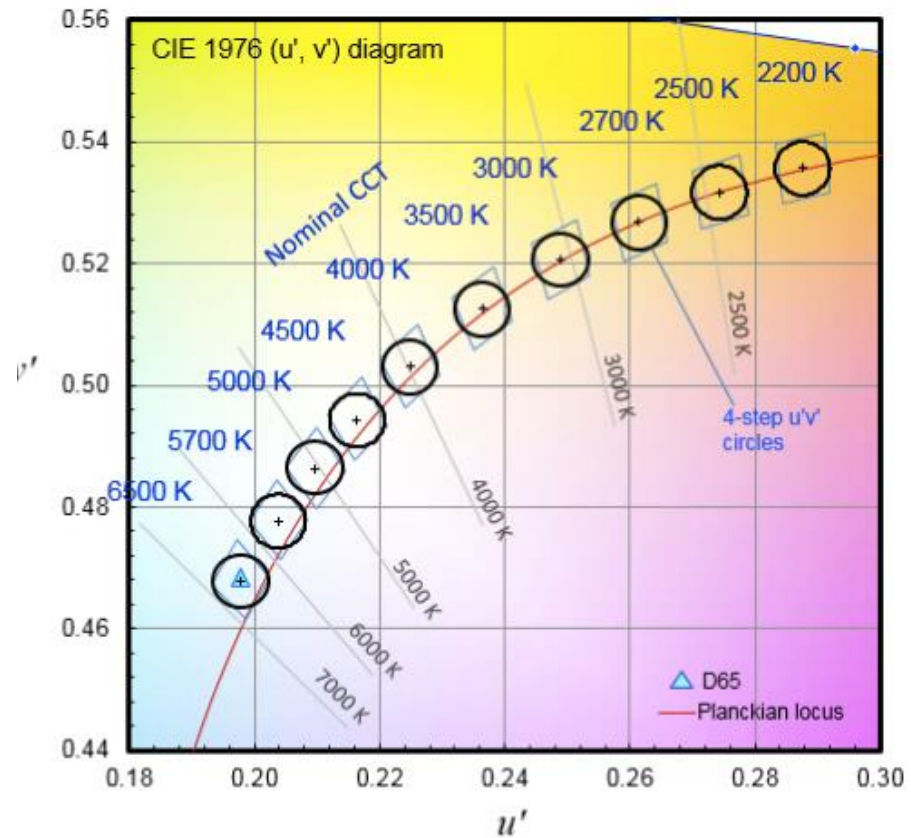
CIE TN 001: [Freely available on CIE website](#)

Annex B, C for Smaller Tolerances

Annex B. 4-step quadrangles



Annex C. 4-step $u'v'$ circles



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Issues to Consider

Recommended Regulation Requirement

- Requirement is based on ANSI Quadrangles

Table 1
Basic Nominal CCT Specification

Nominal CCT Category (K)	Target CCT and Tolerance (K)	Target Duv	Duv Tolerance
2200	2238 ± 102	0.0000	T_x : CCT of the source For $T_x < 2870\text{K}$ 0.000 ± 0.0060 For $T_x \geq 2870\text{K}$ $D_{uv}(T_x)^3 \pm 0.0060$
2500	2460 ± 120	0.0000	
2700	2725 ± 145	0.0000	
3000	3045 ± 175	0.0001	
3500	3465 ± 245	0.0005	
4000	3985 ± 275	0.0010	
4500	4503 ± 243	0.0015	
5000	5029 ± 283	0.0020	
5700	5667 ± 355	0.0025	
6500	6532 ± 510	0.0031	
Flexible CCT (2300 – 6400)	$T_F^{1)} \pm \Delta T^{2)}$	$D_{uv}(T_F)^3)$	

- T_F is chosen to be at 100 K steps (2300, 2400, ..., 6400 K), excluding the first ten CCTs listed in Table 1.
- $\Delta T_F = 1.1900 \times 10^{-8} \times T_F^3 - 1.5434 \times 10^{-4} \times T_F^2 + 0.7168 \times T_F - 902.55$
- $D_{uv}(T) = 0$ for $T < 2870\text{K}$, $D_{uv}(T) = 57700 \times (1/T)^2 - 44.6 \times (1/T) + 0.00854$ for $T \geq 2870\text{K}$.

EU Regulation Requirement

- MacAdam Ellipses are an old metric system which is not optimal for LED lighting
- The European Lighting regulation however is continuing to use this metric – however, six steps rather than five steps

Colour consistency for LED and OLED light sources	Variation of chromaticity coordinates within a six-step MacAdam ellipse or less.
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- The Technical Committee may consider this requirement, or a slightly more stringent one (five-step MacAdam ellipse, as required in the draft South African regulation)

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Issues to Consider

Issues to consider?

- MacAdam Ellipses are a workable solution and could be appropriate
- Newer and better metrics are available
 - ΔCCT and Duv quadrangles
 - $\Delta u', v'$ circles
- Perhaps consider having a review clause in the regulation which highlights the fact that colour consistency metrics may change in the future
 - no additional (re)testing is required just change in colour system metrics

Thank you, any questions?

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