Obtaining Spectral Data for Colorimetry

Yoshi Ohno
Optical Technology Division
National Institute of Standards and Technology
Gaithersburg, Maryland, USA

Spectral Color Measurement

(for objects and light sources)

Basis:

$$X = k \int \Phi(\lambda)\bar{x}(\lambda)\,d\lambda$$

$$Y = k \int \Phi(\lambda)\bar{y}(\lambda)\,d\lambda$$

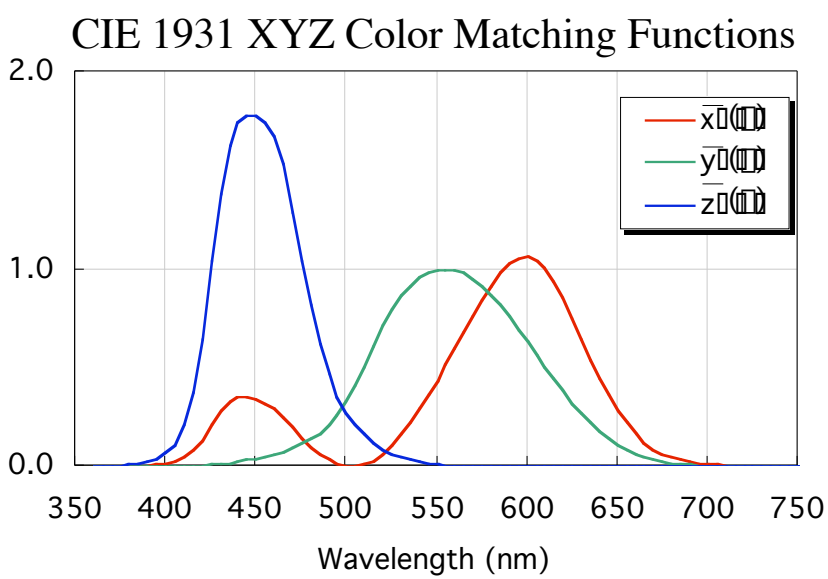
$$Z = k \int \Phi(\lambda)\bar{z}(\lambda)\,d\lambda$$

Real measurement:

$$X = k \sum_{i=0}^{n} \Phi(\lambda_i)\bar{x}(\lambda_i)\Delta\lambda$$

$$Y = k \sum_{i=0}^{n} \Phi(\lambda_i)\bar{y}(\lambda_i)\Delta\lambda$$

$$Z = k \sum_{i=0}^{n} \Phi(\lambda_i)\bar{z}(\lambda_i)\Delta\lambda$$



Question often asked:

What range of $\Delta\lambda$ acceptable?

(5 nm, 10 nm, or 20 nm ??)

Relevant documents:

CIE 15.2 /15.3 (TC1-48),
ASTM E308, TC1-38, TC1-57

Sources of errors (components of uncertainty) in spectral measurements

- Scanning interval (data interval) □□
- Bandpass of monochromator
- Wavelength errors (uncertainties)
- Noise of monochromator signal
- Stray light of monochromator
- Geometric conditions

□□ is an important parameter, but often discussed, only in terms of the calculation errors by itself.

□□ strongly affects other sources of errors.

As a result, wrong recommendations are often proposed...

Simulation Analysis

43 object color samples

- 14 samples used in CIE 13.3 [3]
- 11 samples of BCRA tiles
- 18 samples of Macbeth ColorChecker (excluding 6 achromatic samples)

9 light source samples

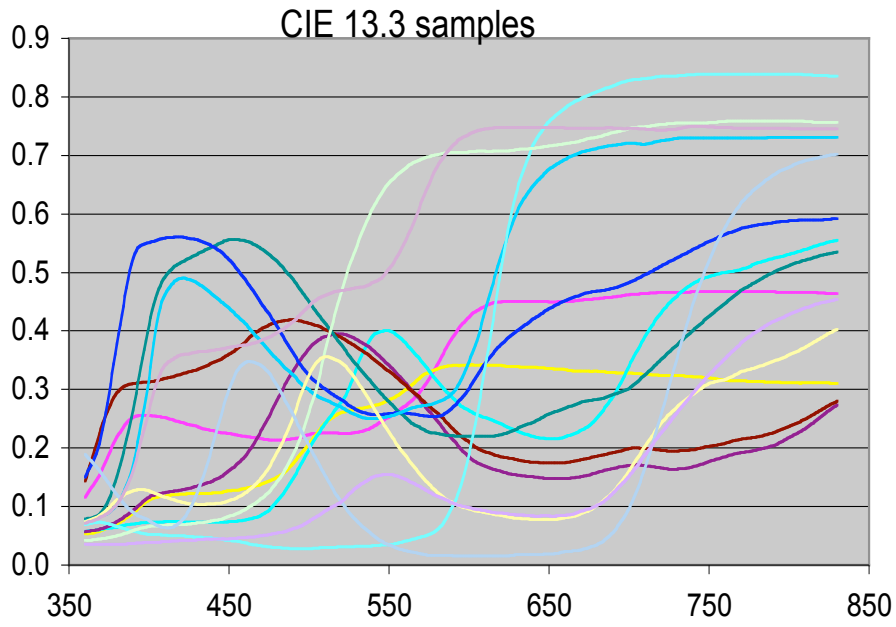
- Planckian (3000 K), Cool white FL (4300 K), Triphosphor FL(3260 K)
- LED (450 nm, 510 nm, 630 nm)
- LCD (blue, green, red)

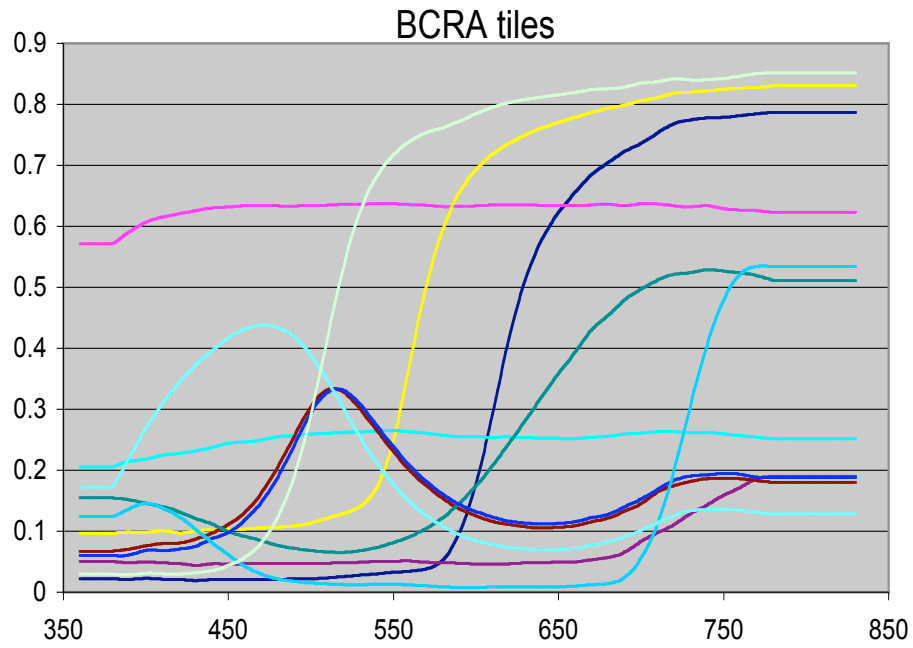
Results presented in color differences

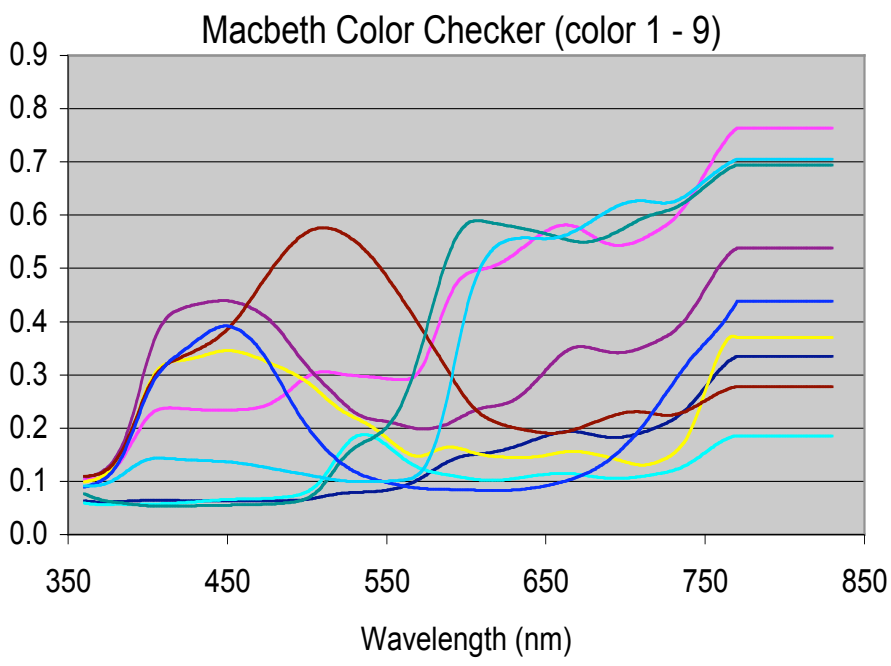
$$\Delta u'v' = \{(u'_{\text{measured}} - u'_{\text{true}})^2 + (v'_{\text{measured}} - v'_{\text{true}})^2\}^{1/2}$$

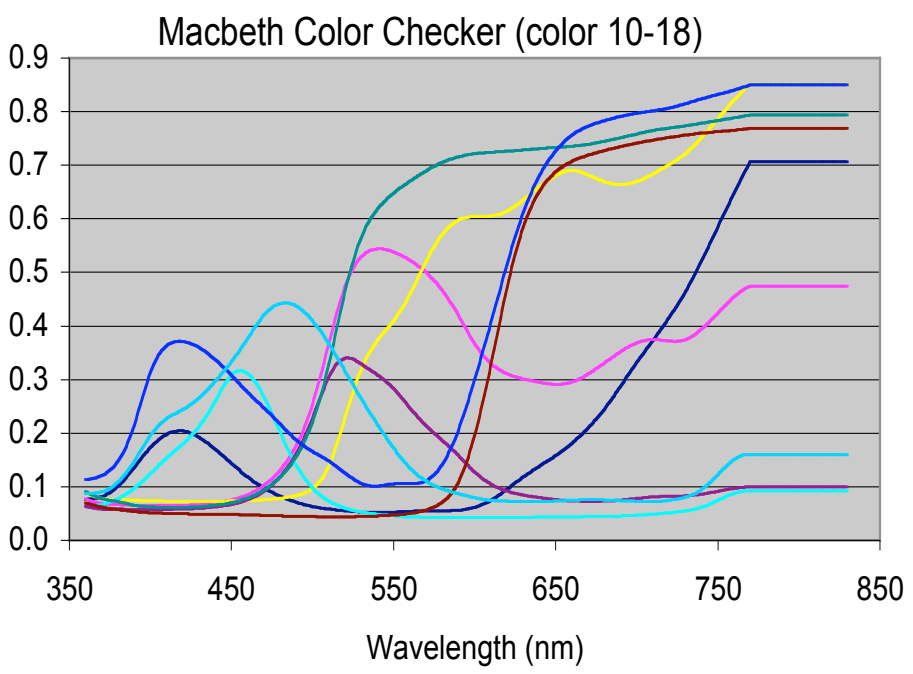
$$\Delta E^*_{ab}$$

Range: 360 - 830 nm


CIE 13.3 samples
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
450
550
650
750
850


BCRA tiles
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
450
550
650
750
850


Macbeth Color Checker (color 1 - 9)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
450
550
650
750
850
Wavelength (nm)


Macbeth Color Checker (color 10-18)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
450
550
650
750
850
Wavelength (nm)

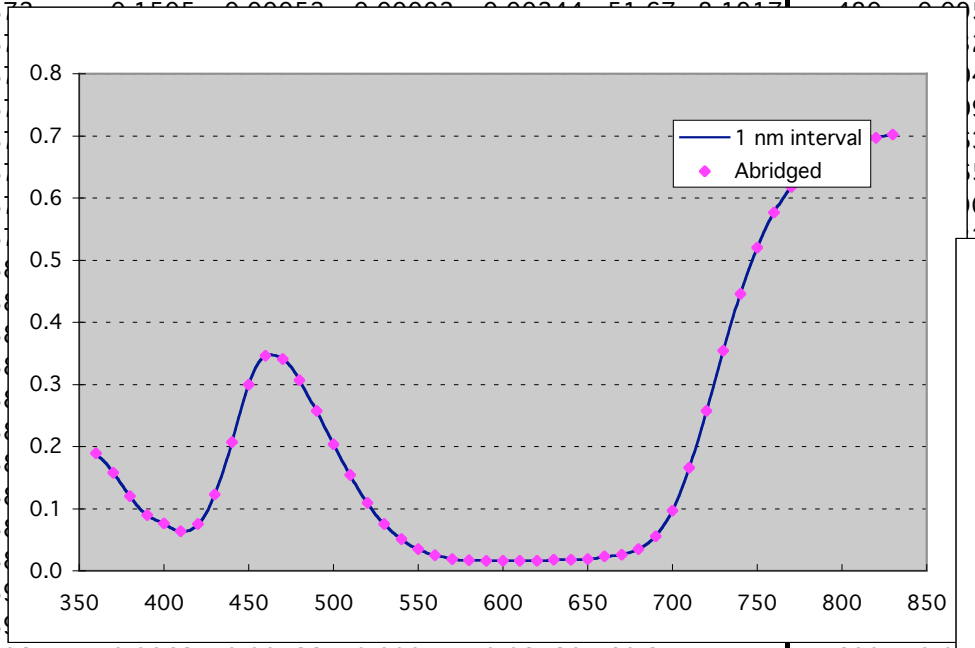
Analysis for sampling (data interval, abridgement)

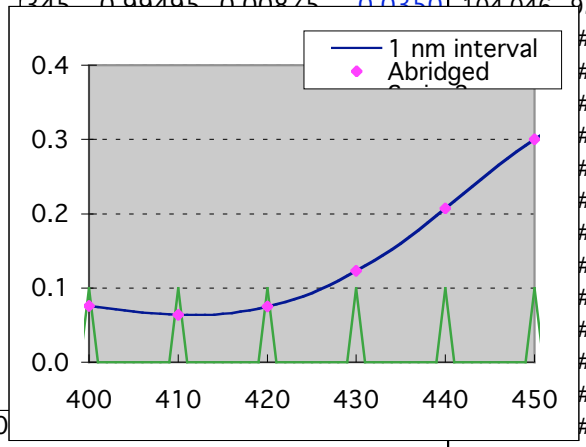
Test sample

12 TSC12

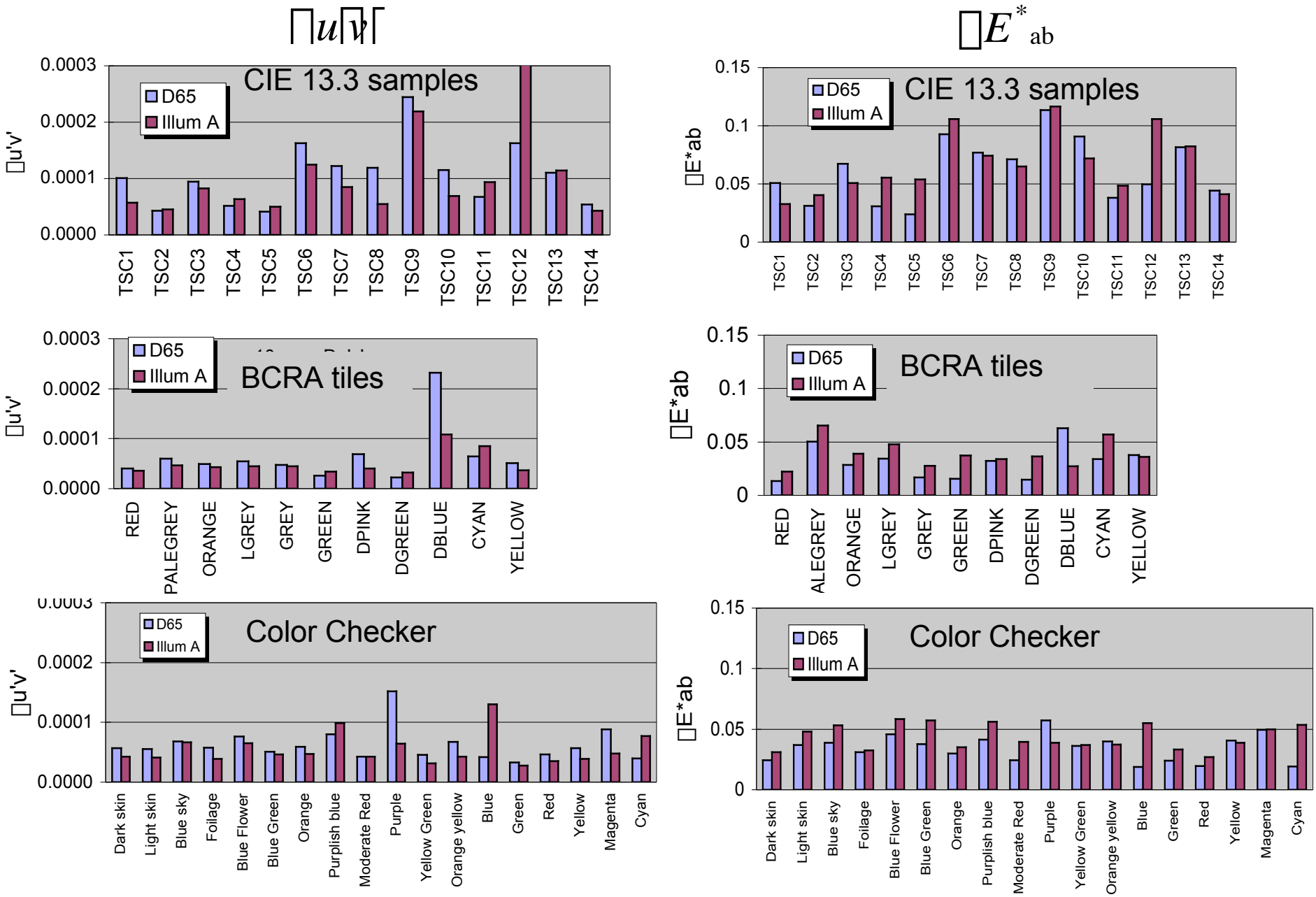
10 nm interval

Wavelength	1 nm interval	x bar(2°)	y bar(2°)	z bar(2°)	D65	A	wavelen	x-bar (2°)	y-bar (2°)	z-bar (2°)	Abridged	D65	A
360	0.1890	0.00013	0.00000	0.00061	46.64	6.1446	360	0.00013	0.00000	0.00061	0.1890	46.638	6.1446
361	0.1862	0.00015	0.00000	0.00068	47.18	6.2996	370	0.00041	0.00001	0.00195	0.1580	52.089	7.8214
362	0.1834	0.00016	0.00000	0.00077	47.73	6.4572	380	0.00137	0.00004	0.00645	0.1200	49.976	9.7951
363	0.1806	0.00018	0.00001	0.00086	48.27	6.6177	390	0.00424	0.00012	0.02005	0.0900	54.648	12.0853
364	0.1778	0.00021	0.00001	0.00097	48.82	6.7811	400	0.01431	0.00040	0.06785	0.0760	82.755	14.7080
365	0.1750	0.00023	0.00001	0.00109	49.36	6.9472	410	0.04351	0.00121	0.20740	0.0640	91.486	17.6753
366	0.1718	0.00026	0.00001	0.00122	49.91	7.1162	420	0.13438	0.00400	0.64560	0.0750	93.432	20.9950
367	0.1685	0.00029	0.00001	0.00137	50.45	7.2881	430	0.28390	0.01160	1.38560	0.1230	86.682	24.6709
368	0.1651	0.00033	0.00001	0.00154	51	7.4629	440	0.34828	0.02300	1.74706	0.2070	104.865	28.7027
369	0.1616	0.00037	0.00001	0.00173	51.54	7.6407	450	0.33620	0.03800	1.77211	0.3000	117.008	33.0859
370	0.1580	0.00041	0.00001	0.00195	52.09	7.8214	460	0.29080	0.06000	1.66920	0.3460	117.812	37.8121
371	0.1543	0.00046	0.00001	0.00218	51.88	8.0050	470	0.19536	0.09098	1.28764	0.3410	114.861	42.8693
37								564	0.13902	0.81295	0.3070	115.923	48.2423
37								201	0.20802	0.46518	0.2570	108.811	53.9132
37								490	0.32300	0.27200	0.2040	109.354	59.8611
37								930	0.50300	0.15820	0.1540	107.802	66.0635
37								327	0.71000	0.07825	0.1090	104.790	72.4959
37								550	0.86200	0.04216	0.0750	107.689	79.1326
37								040	0.95400	0.02030	0.0510	104.405	85.9470
37								345	0.99495	0.00875	0.0350	104.046	92.9120
38													######
38													######
38													######
38													######
38													######
38													######
38													######
38													######
38													######
39													######
39													######
392	0.0863	0.00533	0.00015	0.02520	60.27	######	680	0.0					######
393	0.0847	0.00598	0.00017	0.02828	63.08	######	690	0.02270	0.00821		0.0560	69.721	######



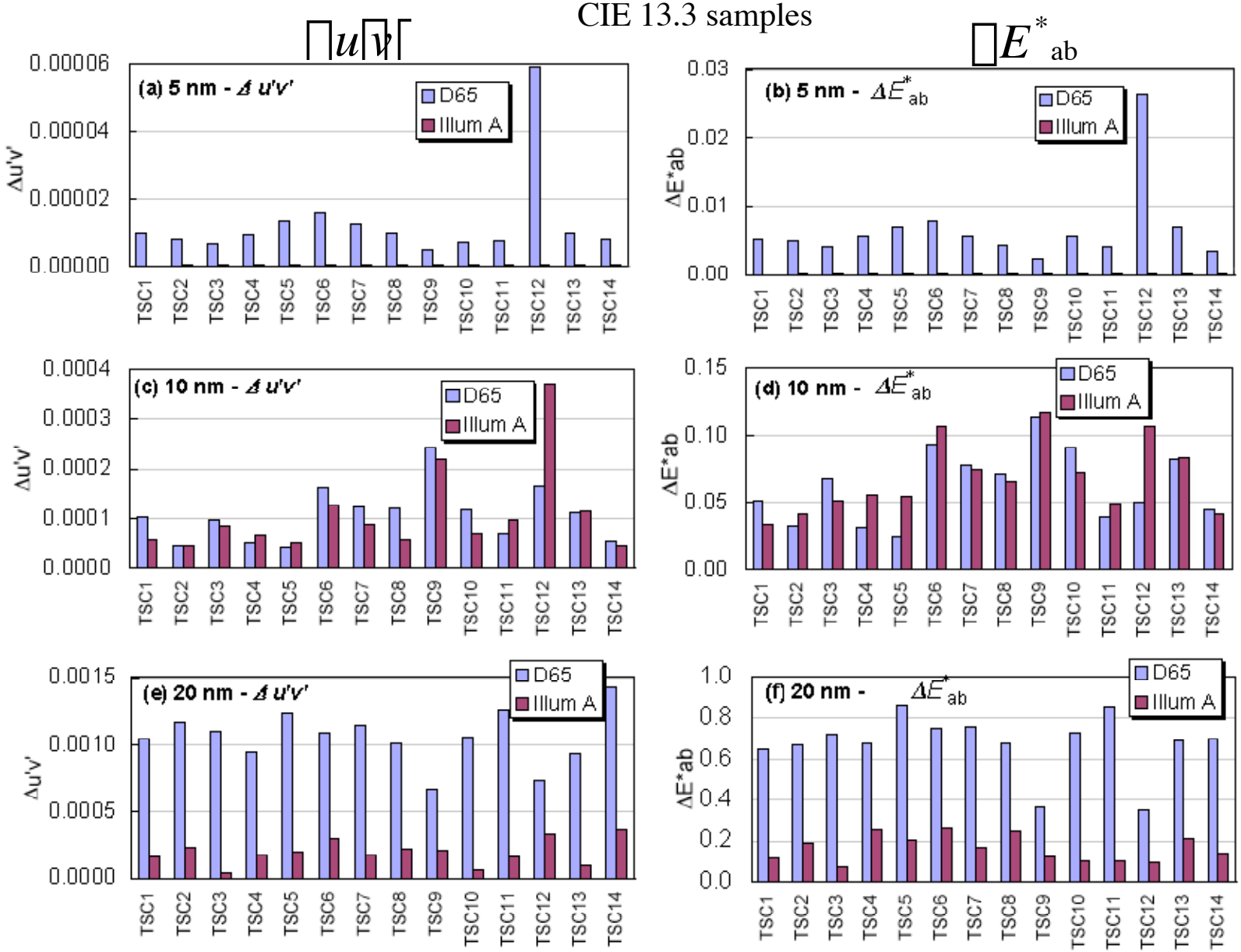


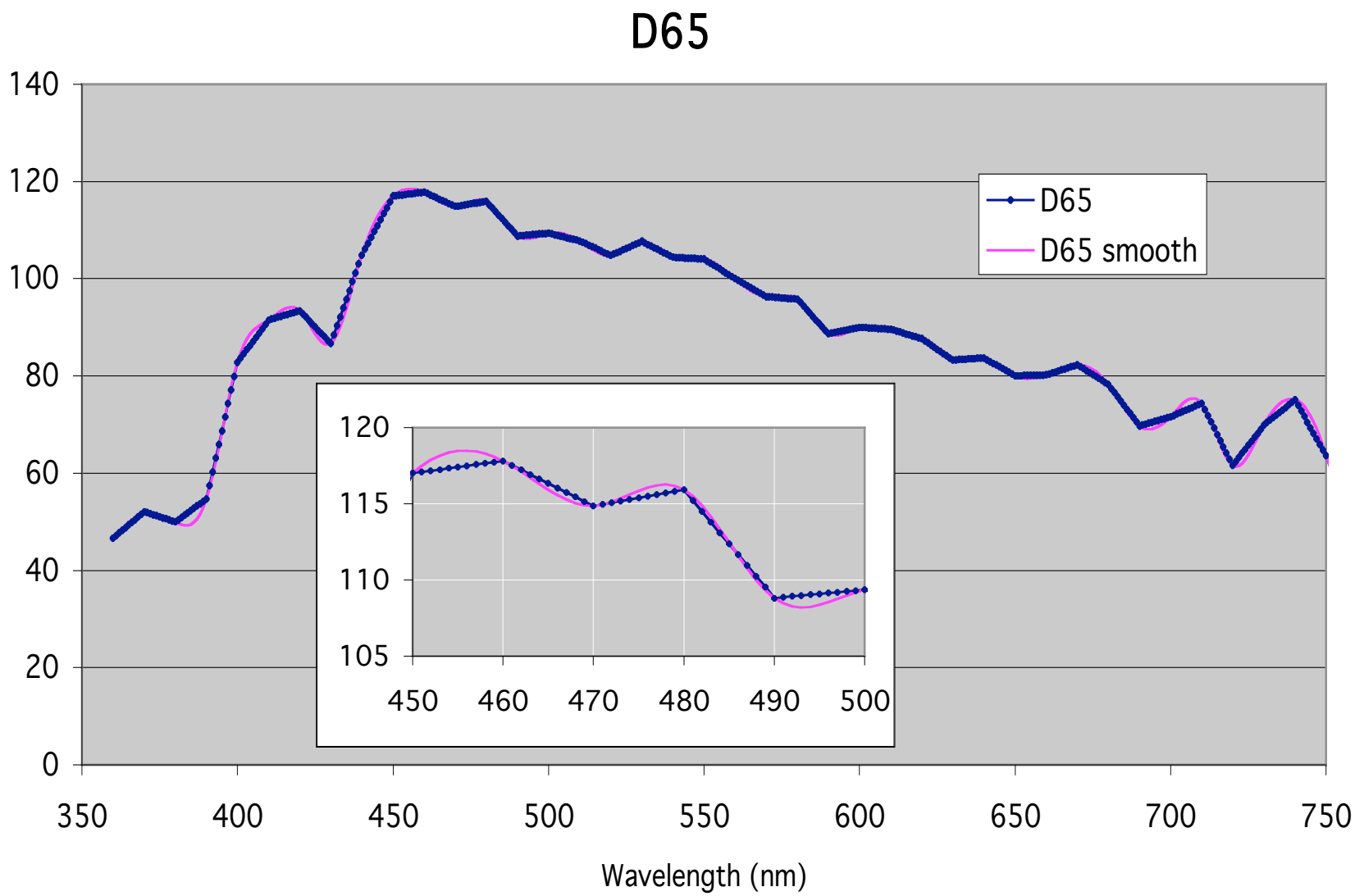
Errors caused by sampling at 10 nm interval



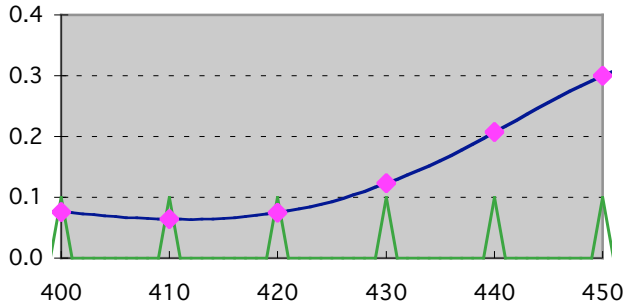
Errors caused by sampling at 5/10/20 nm intervals

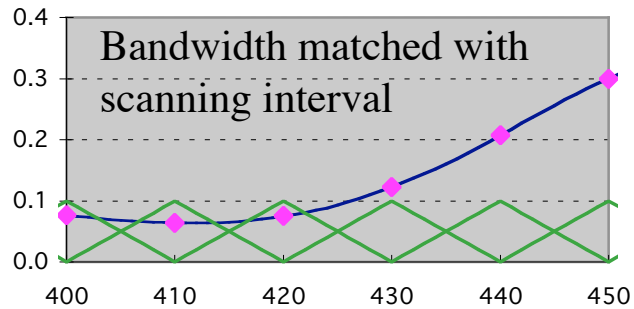
CIE 13.3 samples

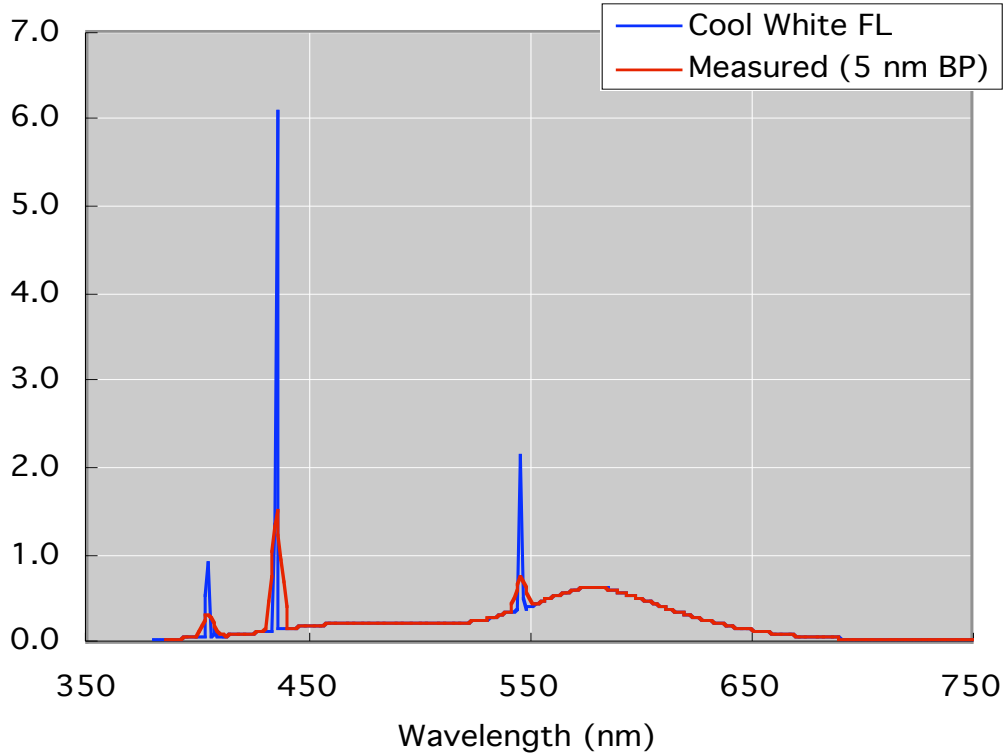


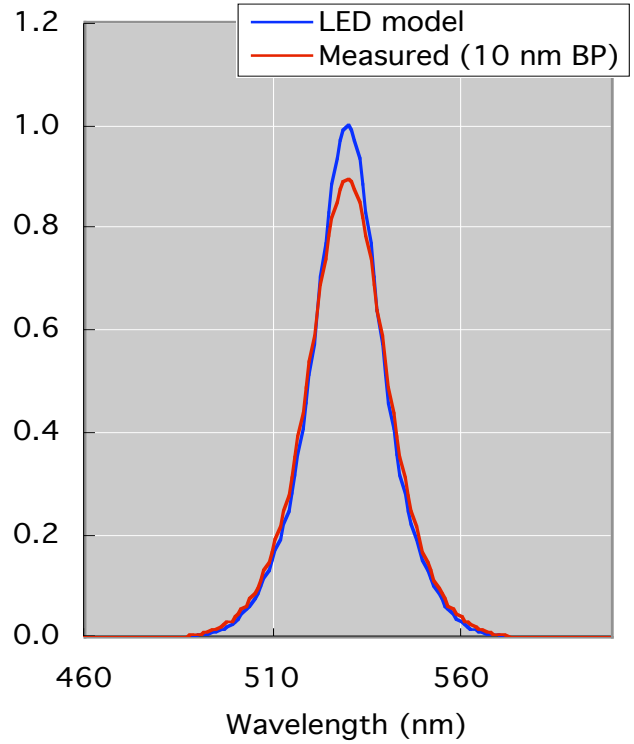

D65
140
120
100
80
60
40
20
0
350
400
450
500
550
600
650
700
750
Wavelength (nm)
D65
D65 smooth
120
115
110
105
450
460
470
480
490
500

Broadening of spectra caused by bandpass



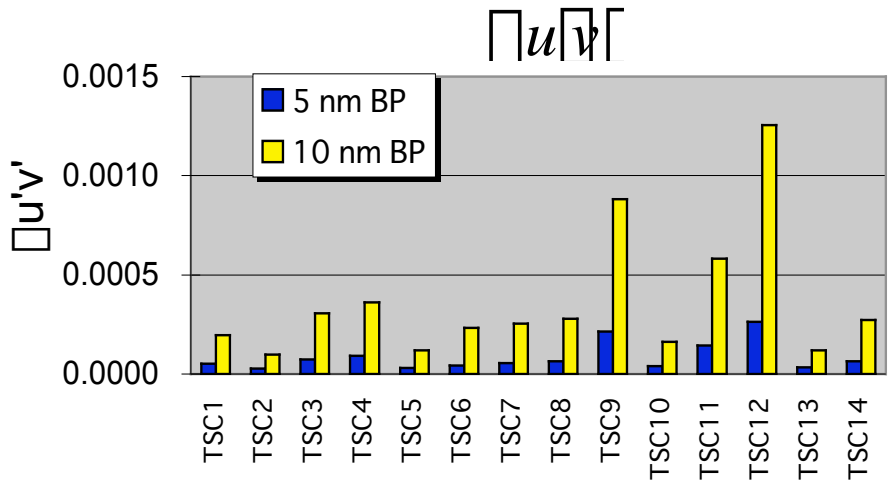


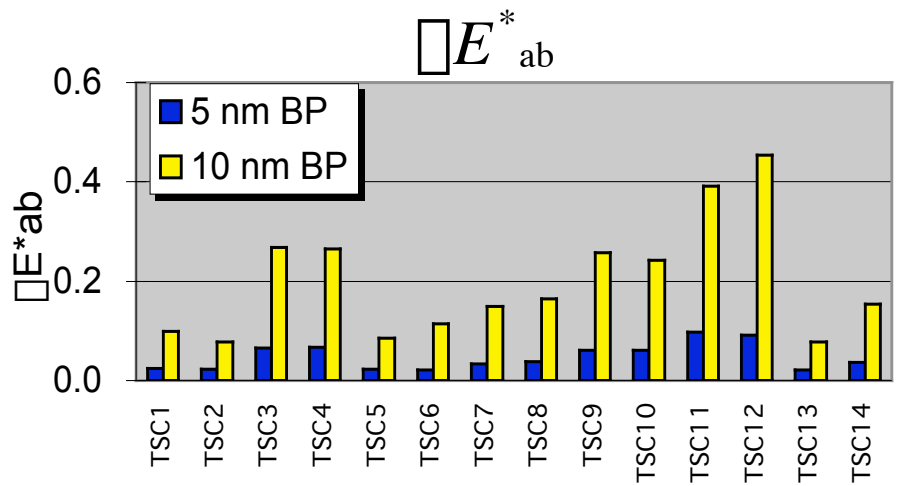




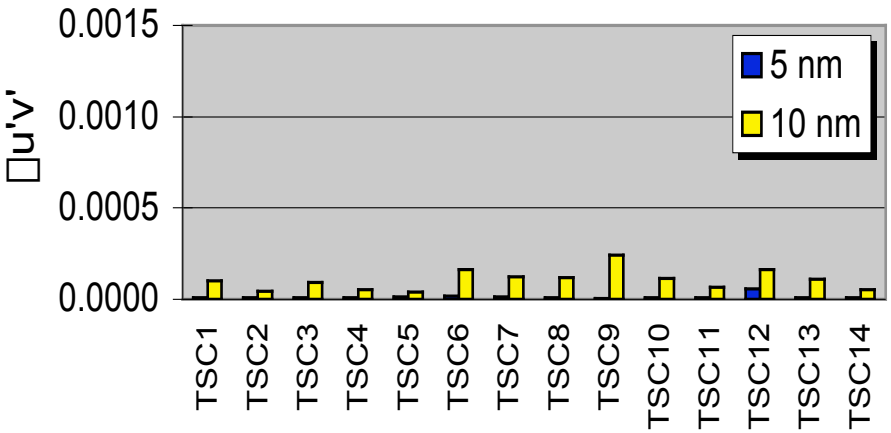
Errors due to bandpass - D65 reference, CIE13.3 samples -

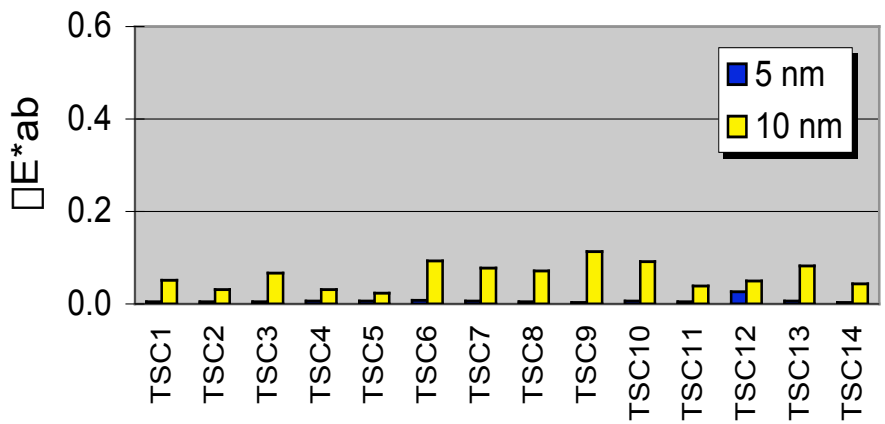
Bandwidth matched with scanning interval





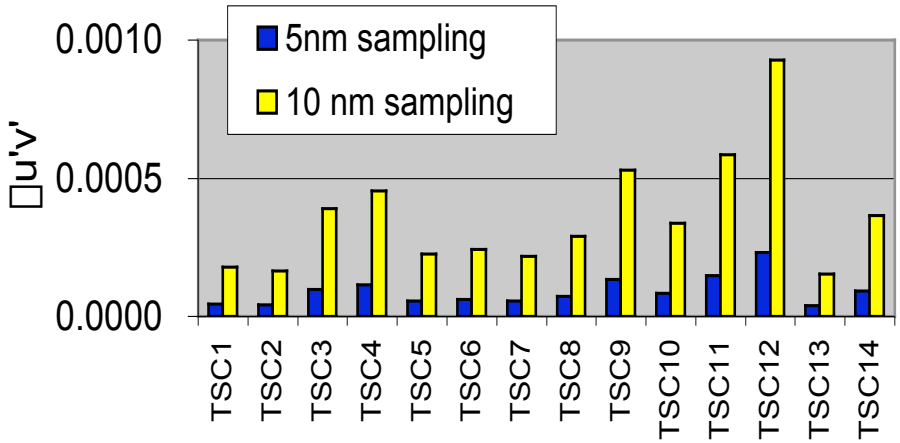
Errors due to sampling

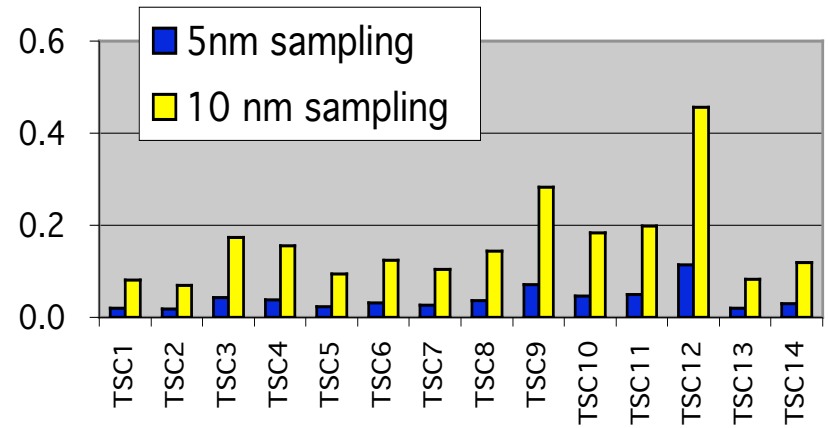




Uncertainties arising from 0.2 nm wavelength uncertainty

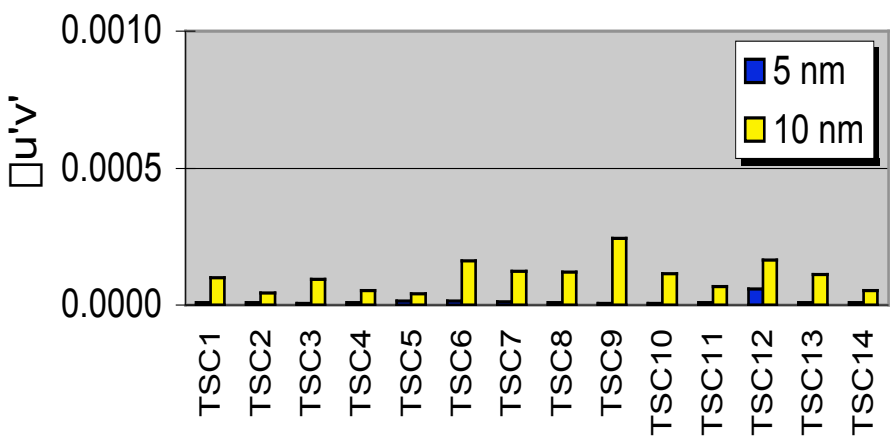
- D65 reference, CIE13.3 samples -

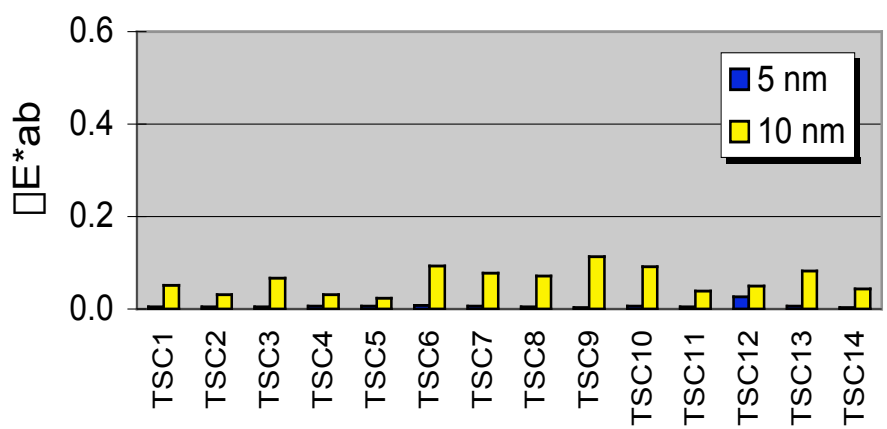




Y. Ohno, A Numerical Method for Color Uncertainty, Proc. CIE Expert Symposium 2001 on Uncertainty Evaluation, Jan. 2001, Vienna, Austria, 8-11 (2001)

Errors due to sampling at 5/10 nm intervals

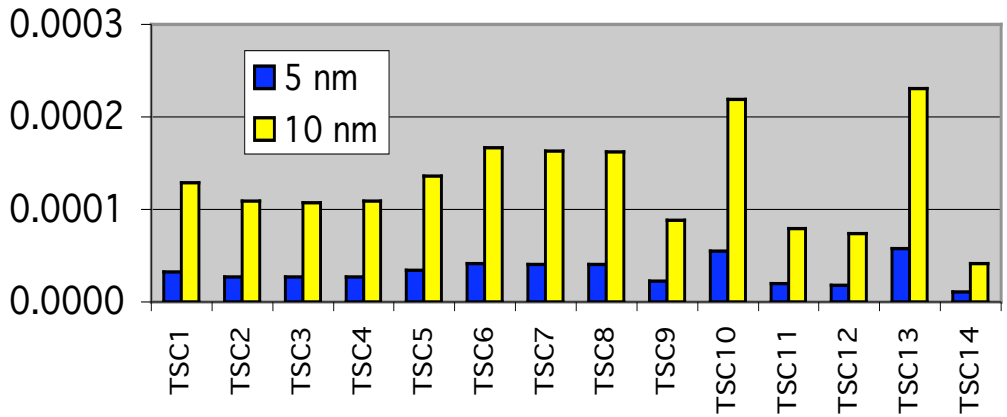




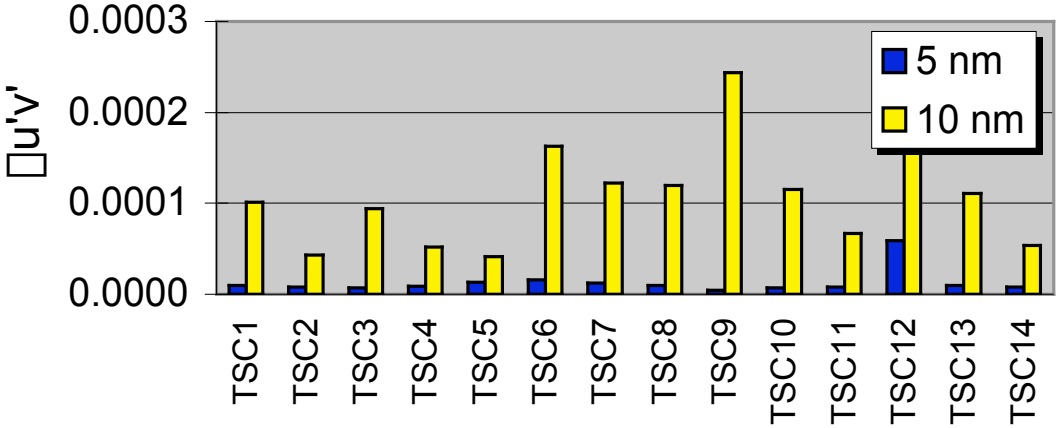
Uncertainties arising from 0.1 % noise in S(λ)

- D65 reference, CIE13.3 samples -

No correlation between values of S(λ)

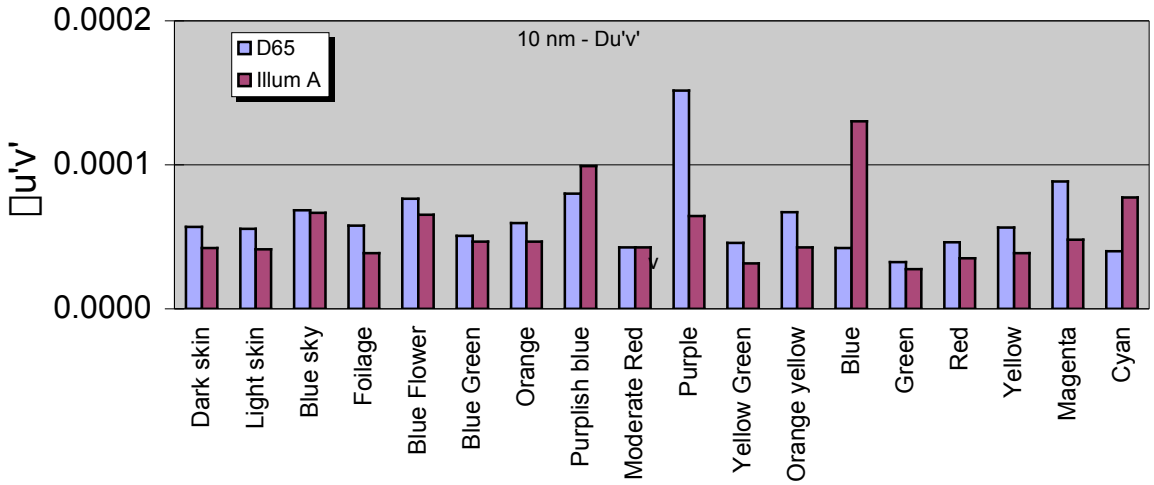


Errors due to sampling

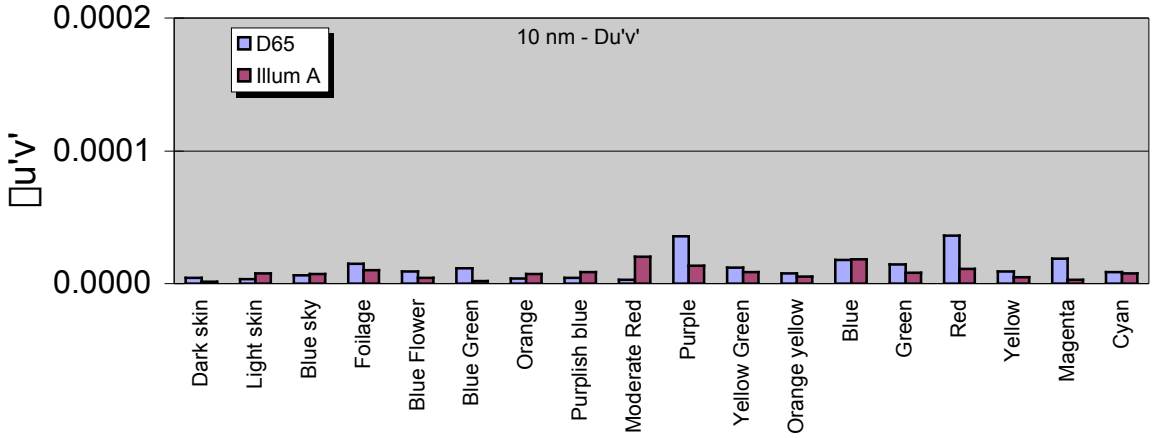


ASTM E308 (Table 5)

Original Error : 10 nm sampling / D65 ref / Color Checker

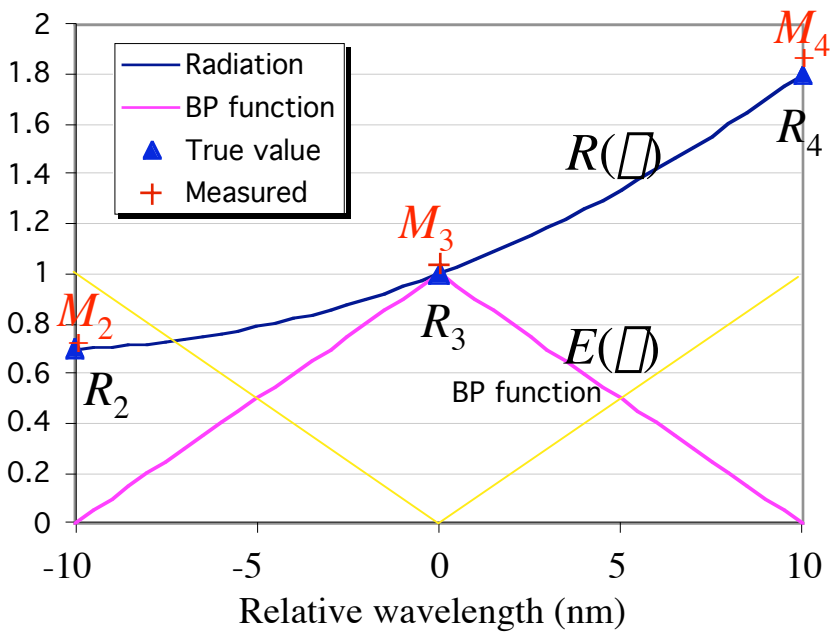


Uusing ASTM E308 Table 5



Stearns and Stearns' method

for bandpass correction (CR&A 1988)



$$R(\lambda) = (R_2/2 - R_3 + R_4/2)\,\lambda^2 + (R_4/2 - R_2/2)\,\lambda + R_3$$

Measured signal is given by

$$M_i = \int R(\lambda)\cdot E(\lambda)\ d\lambda$$

where $E(\lambda)$ is the bandpass function.
Solving these equations,

$$M_3 = R_2/12 + 10\,R_3/12 + R_4/12$$

$$M_2 = R_1/12 + 10\,R_2/12 + R_3/12$$

$$M_4 = R_3/12 + 10\,R_4/12 + R_5/12$$

By approximation $R_1 \approx M_1$, $R_5 \approx M_5$,

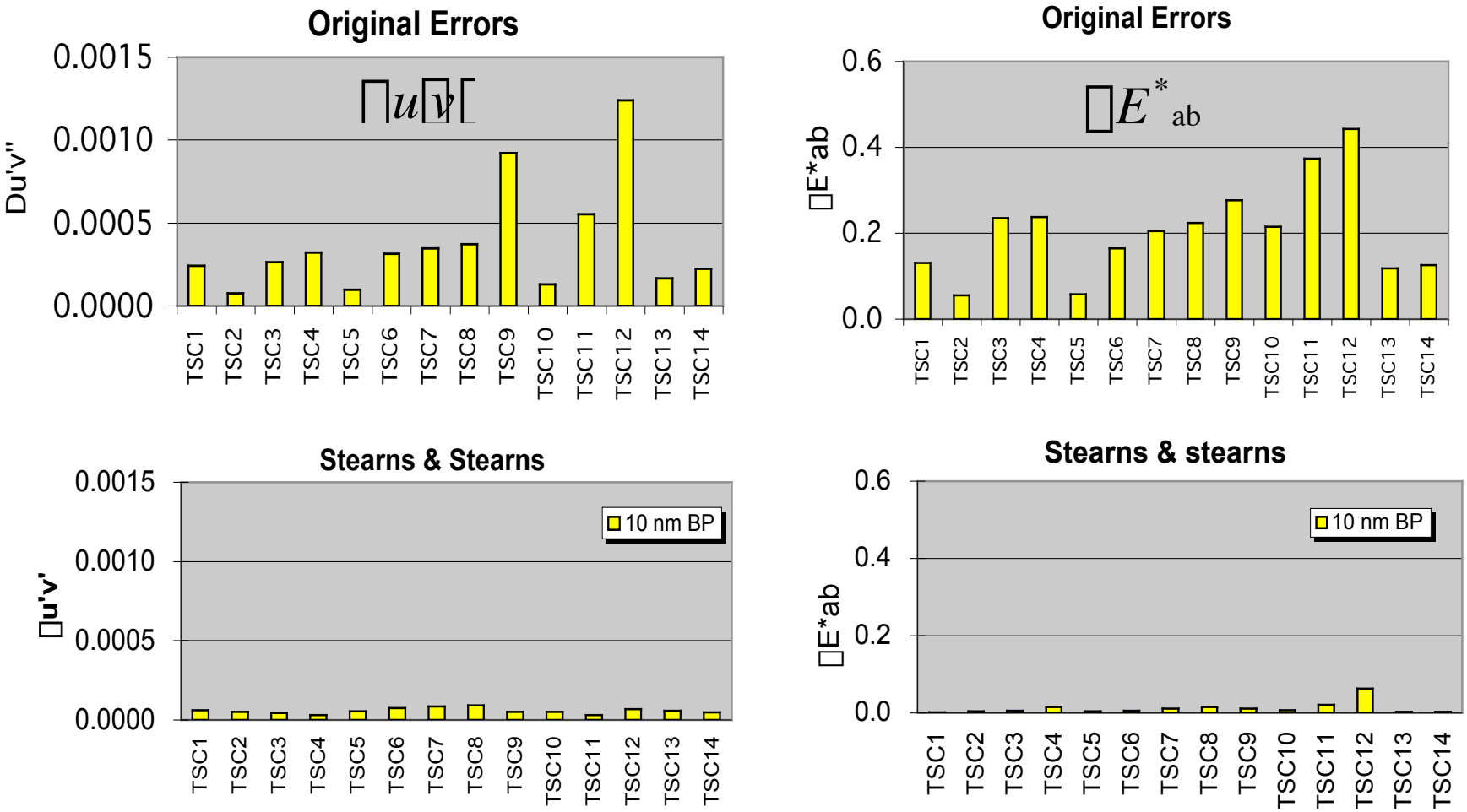
$$R_3 = \frac{1}{98}M_1 - \frac{12}{98}M_2 + \frac{120}{98}M_3 - \frac{12}{98}M_4 + \frac{1}{98}M_5$$

- This method gives results for zero bandwidth.
- Applies only to a triangular bandpass with perfectly matched scanning intervals.

Correction for bandpass errors by Stearns & Stearns

–10 nm triangular bandpass / 10 nm interval –

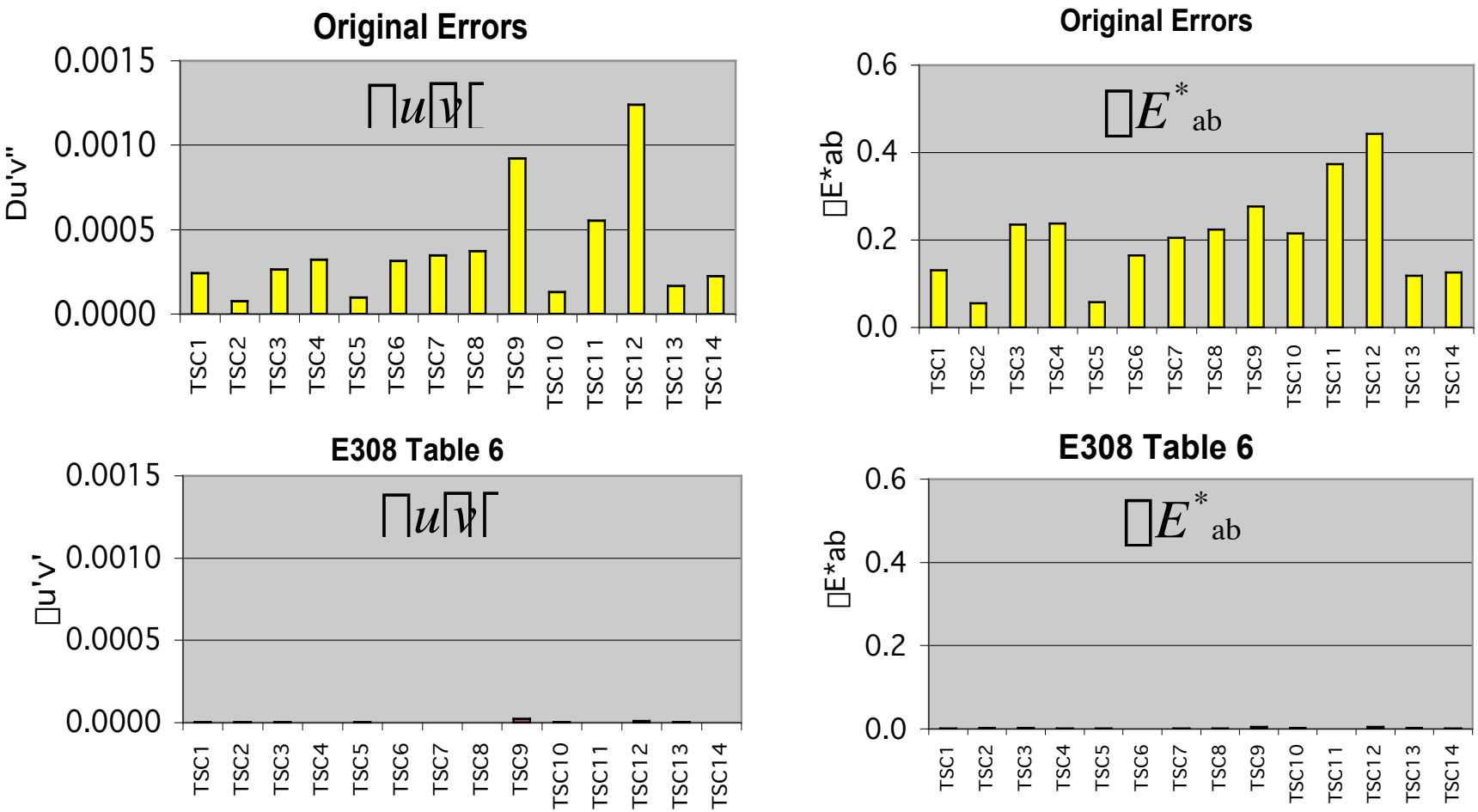
D65 reference



Correction for bandpass errors - ASTM E308 (Table 6)

–10 nm triangular bandpass / 10 nm interval –

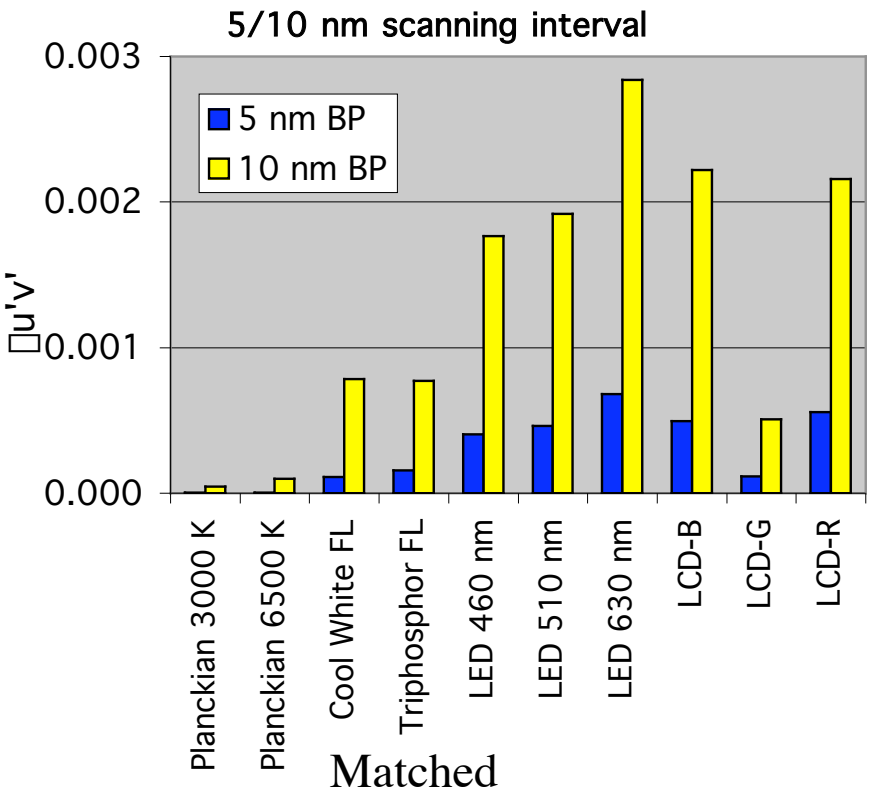
D65 reference

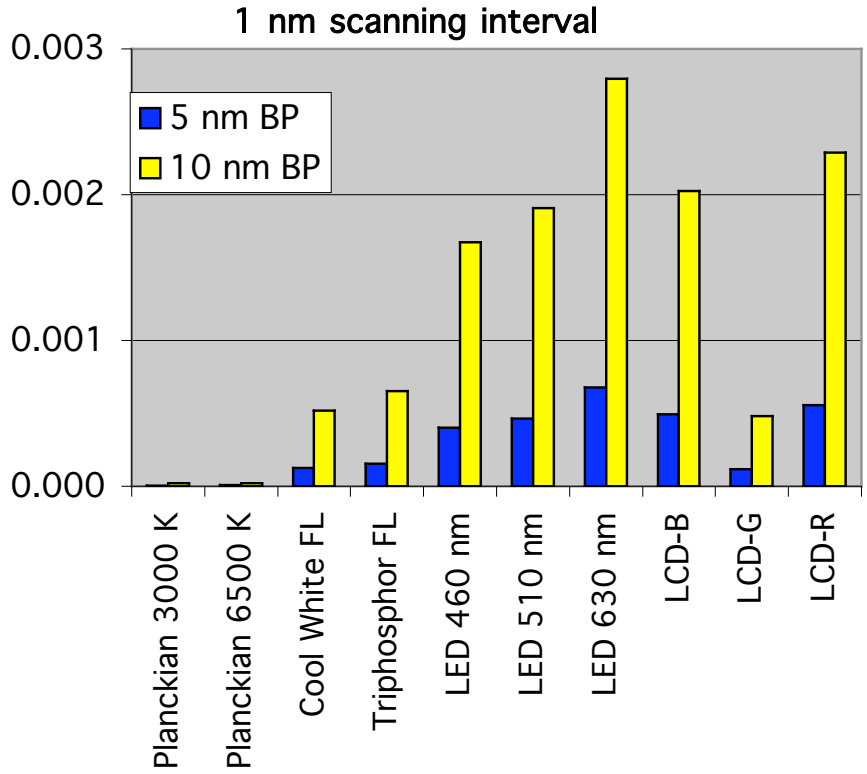


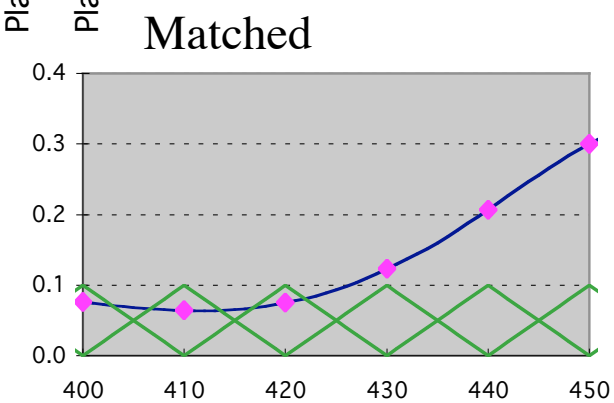
- Real measurements will not be this perfect.

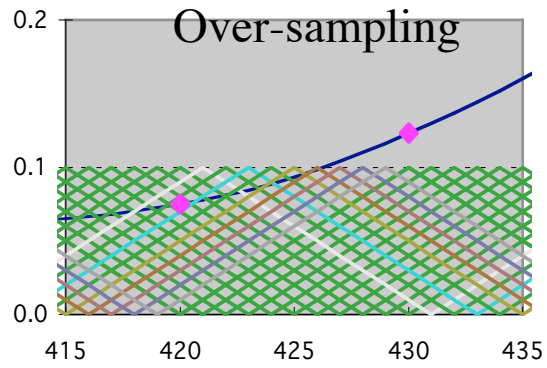
For Light Sources

– Errors due to bandpass of spectrometer –



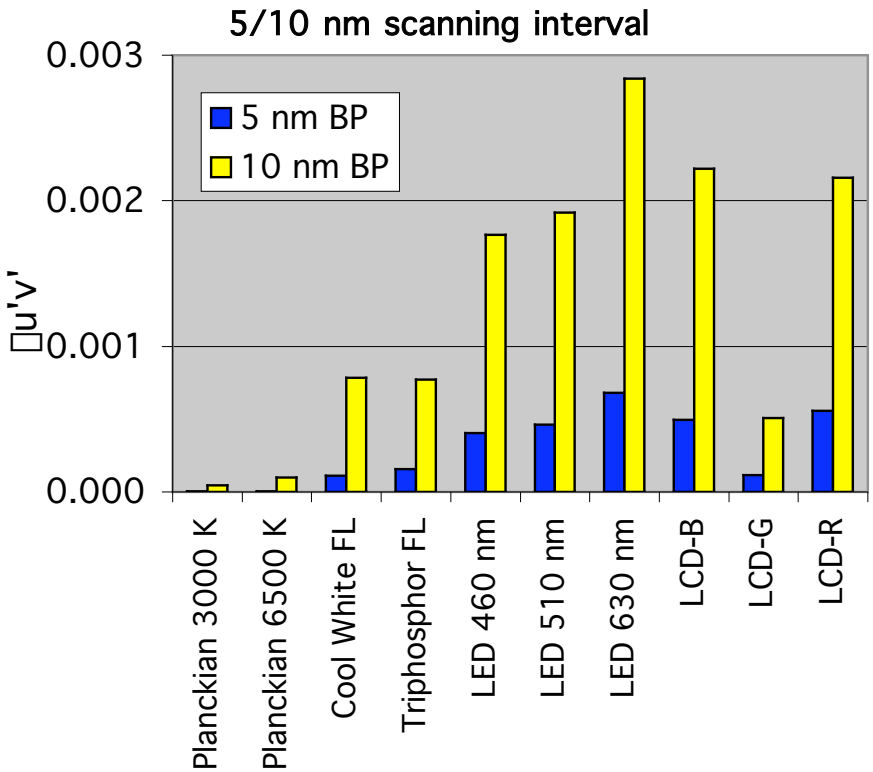




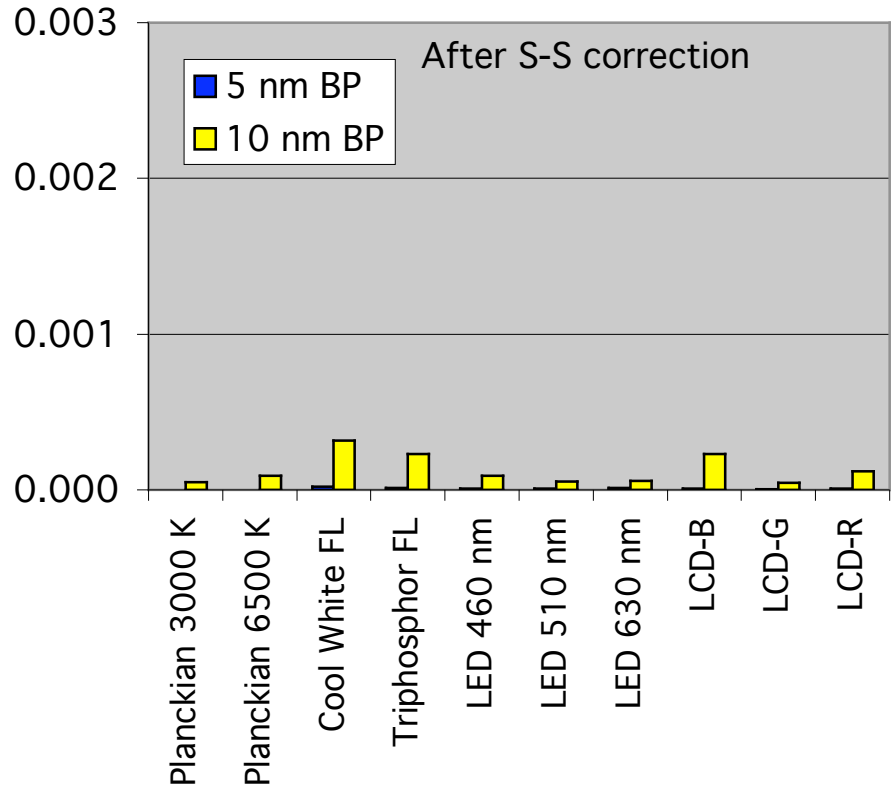


Correction by Stearns and Stearns' method

Original errors

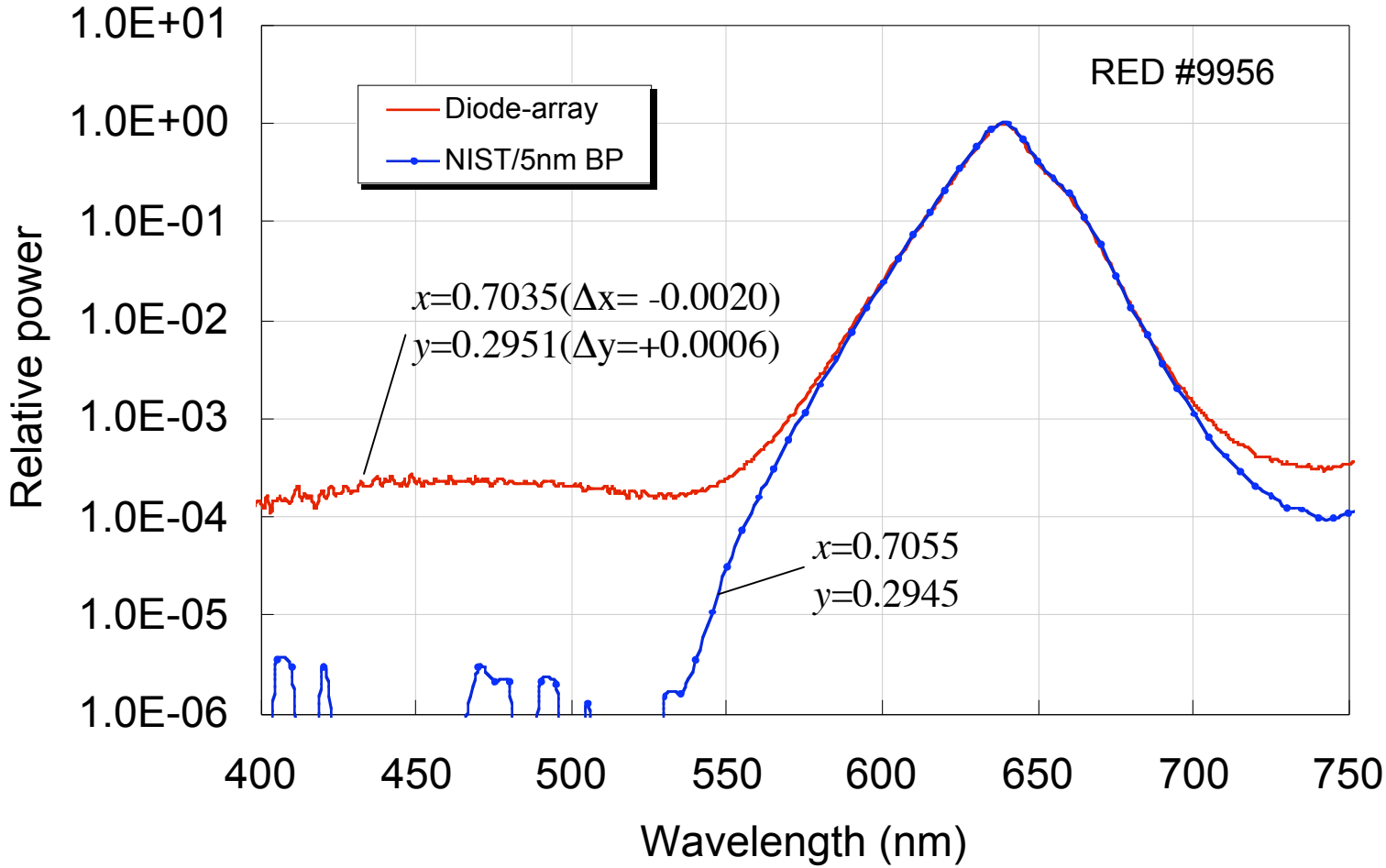


After S-S correction



In real instruments, correction will not be this perfect.

Effect of Stray Light in the Monochromator



Conclusions

- 5 nm bandpass / 5 nm interval or smaller is acceptable for most practical color measurements (with no need for any corrections).
- Bandpass error (>5 nm), if not corrected, is the dominant source of error for colorimetry.
- Stearns and Stearns' method (or ASTM E308 Table 6 for object color) is very effective for both object color and light sources.
- Bandwidth and sampling interval must be matched for the S-S method or ASTM E308 Table 6. (not easy for all wavelengths)
- For intervals | |5 nm, sampling errors are practically negligible. There is no need for interpolation.
- Sampling intervals > 5 nm are not recommended for high accuracy applications (even though ASTM E308 tables are used) because of larger errors due to other components.

Message

Look at overall uncertainty of measurement, not just data interval alone.

Don't spend energy on calculation errors that are negligibly small (compared with other components).

Spectrometer parameters are tied to the design of instruments and are chosen for intended applications.

Unnecessary standardization (over-specification) on these parameters should be avoided.