2017 Council of Optical Radiation Measurements
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Troy, NY

Analysis of Spectroradiometers - Inexpensive Handheld to Laboratory Grade

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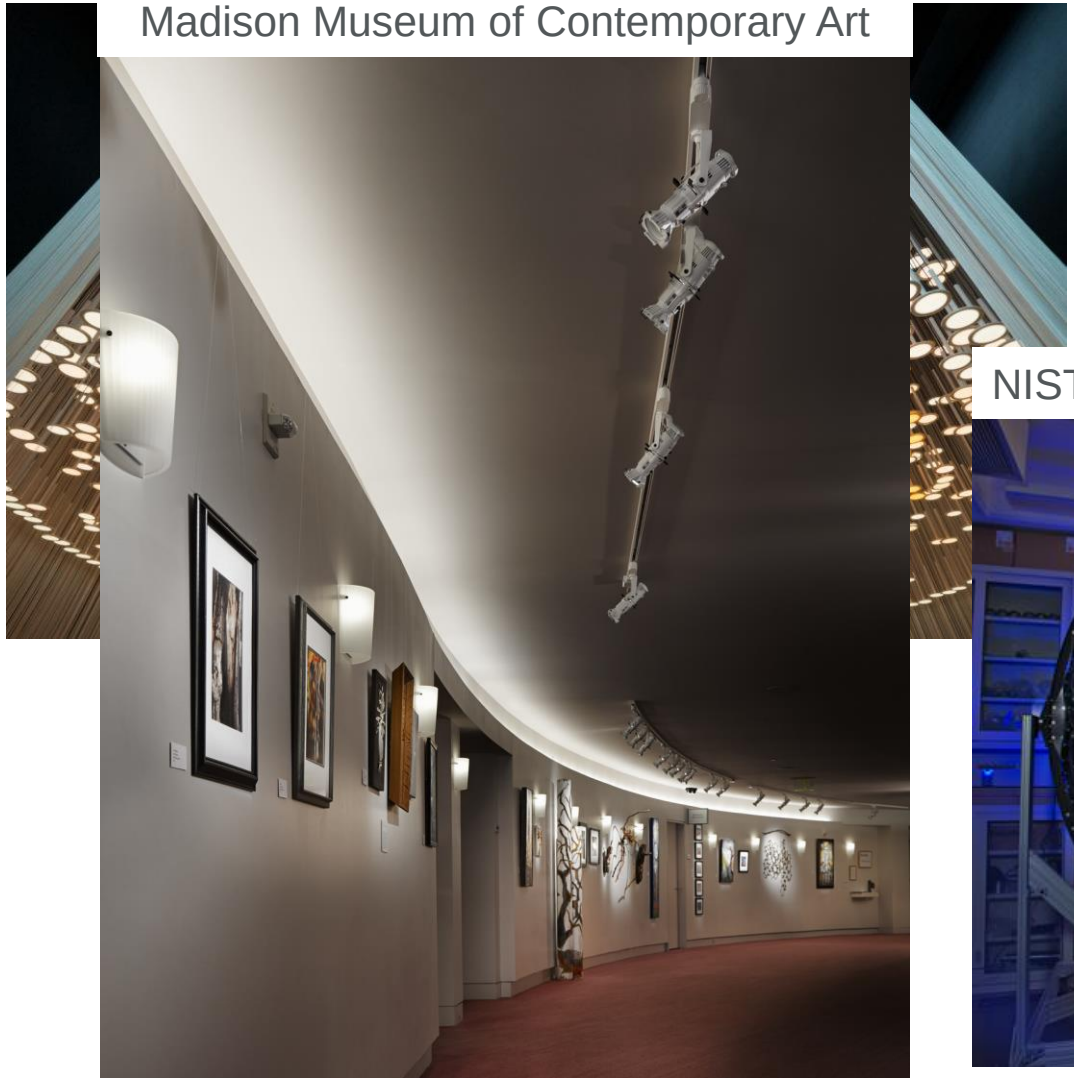
Light measurements

Madison Museum of Contemporary Art



Paul Lutkevich, Parsons Brinckerhoff

NIST Absolute Integrating Sphere System

Light measuring instruments

Light characteristics

- Illuminance (lx), Luminous flux (lm), Correlated color temperature – CCT (K)
- Spectral power distribution (W/m^2), Color rendering properties

Laboratory Instruments

- Spectroradiometers: High accuracy - expensive, fragile, multiple components

Field Instruments

- Tristimulus based: Inexpensive, robust – limited results
- Handheld spectroradiometers: Reasonable price – Accuracy & reliability?

Scope of measurements

NIST calibrated stray-light corrected spectroradiometer

Multiple spectroradiometers

- Reference spectroradiometer ($45K) calibrated by another NMI
- Intermediate spectroradiometer ($10K) calibrated by NIST
- Low level spectroradiometer ($2.5K) calibrated by NIST
- 5 Handheld devices ($350-$5K) calibrated by manufacturer

Multiple light sources

- Halogen lamp (2200 K – 3200 K)
- Monochromatic LED lamps (Red – Green – Blue)
- White LED Lamps (3 phosphor, 1 RGB)
- Laser lines (Red – Green – Blue)

Measurement of Illuminant A

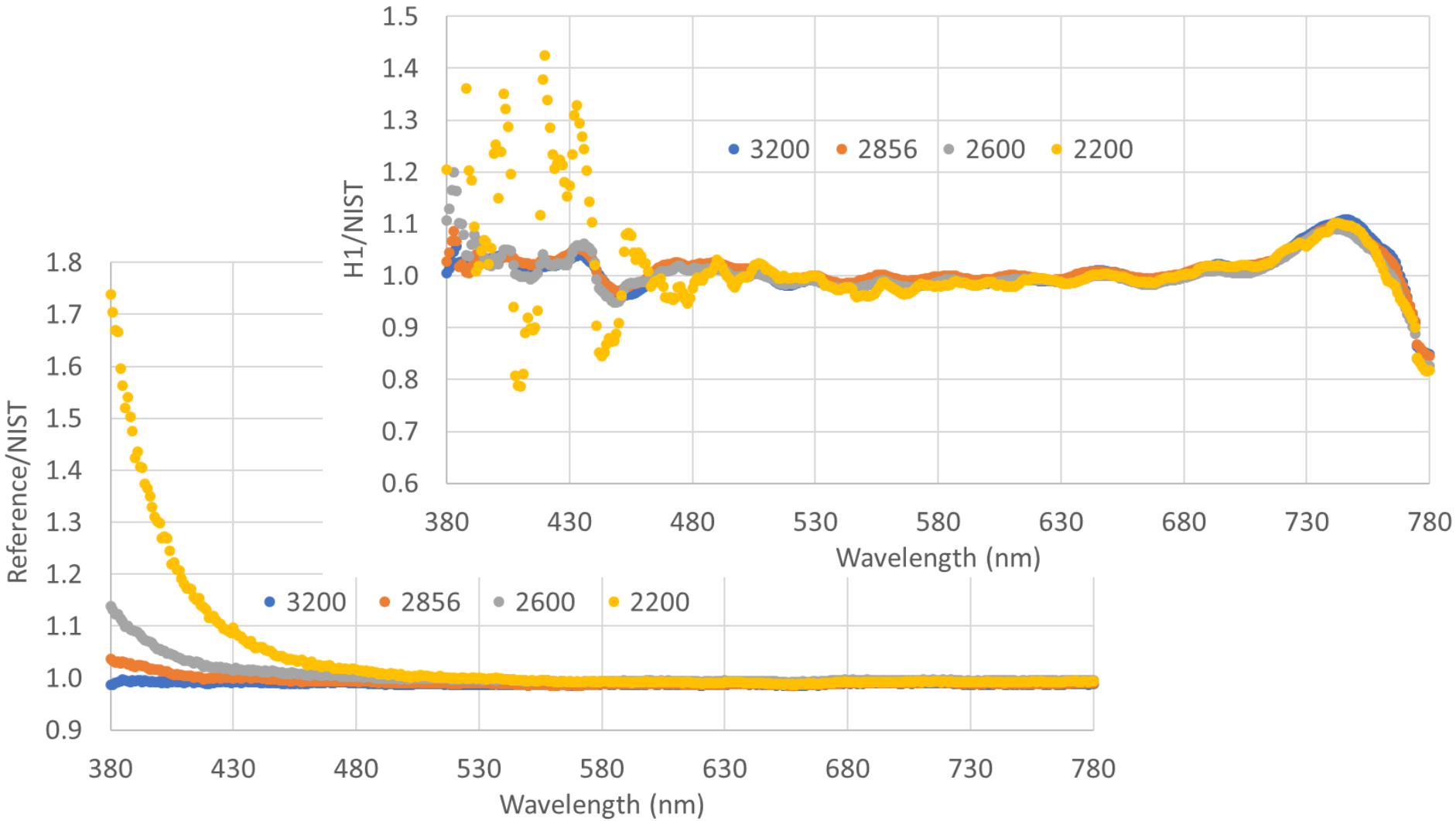
	x	s_x	y	s_y	CCT	s_{CCT}
NIST	0.44781	0.00003	0.40795	0.00003	2856.0	0.2
REF	0.44736	0.00003	0.40751	0.00003	2859.4	0.2
INT	0.44717	0.00008	0.40704	0.00009	2858.6	0.4
LOW	0.44781	0.00040	0.40796	0.00040	2856.1	7.0
H1	0.44790	0.00025	0.40849	0.00017	2858.9	3.3
H2	0.44774	0.00010	0.40725	0.00011	2851.5	0.4
H3	---	---	---	---	2887.7	4.4
H4	0.44655	0.00018	0.40725	0.00008	2868.9	2.3
H5	0.44658	0.00002	0.40778	0.00002	2873.9	0.3

Measurement of 2200 K and 3200 K

	CCT	s_{CCT}
NIST	2200	0.2
REF	2210	0.2
INT	2156	0.5
LOW	2081	10.0
H1	2218	3.1
H2	2202	1.4
H3	2287	3.6
H4	2270	0.8
H5	2222	2.0

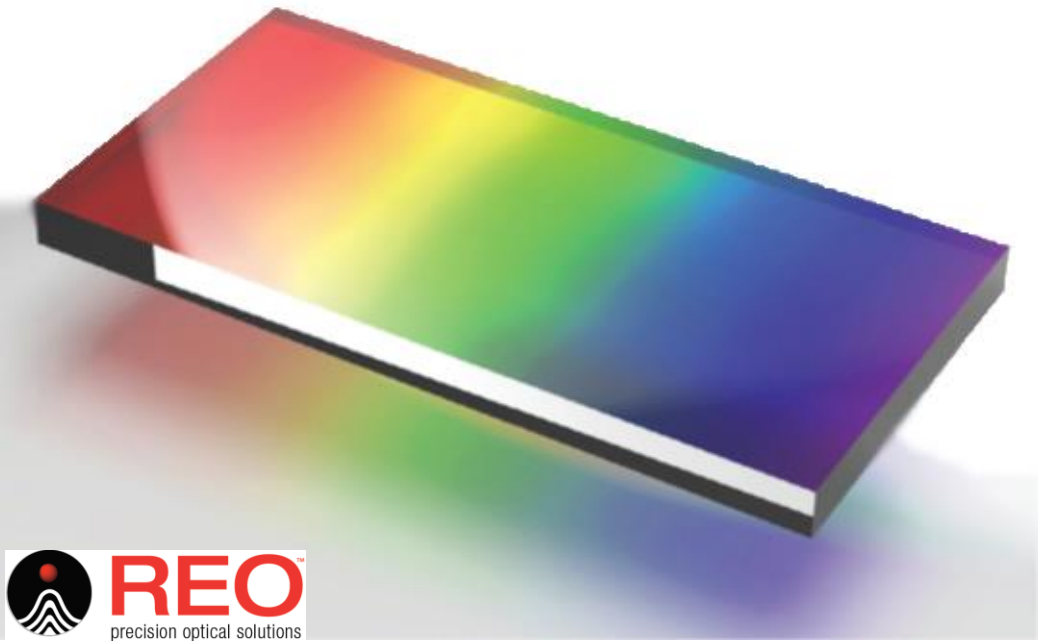
	CCT	s_{CCT}
NIST	3200	0.3
REF	3201	0.3
INT	3200	0.4
LOW	2883	14.4
H1	3203	3.8
H2	3195	0.6
H3	3230	2.6
H4	3217	1.0
H5	3222	0.4

Spectrum Ratio – 2200 K to 3200 K



What's inside?

Linear variable filter



Grating dispersion

Uncertainty in spectral measurements

Calibration

- Responsivity
- Wavelength

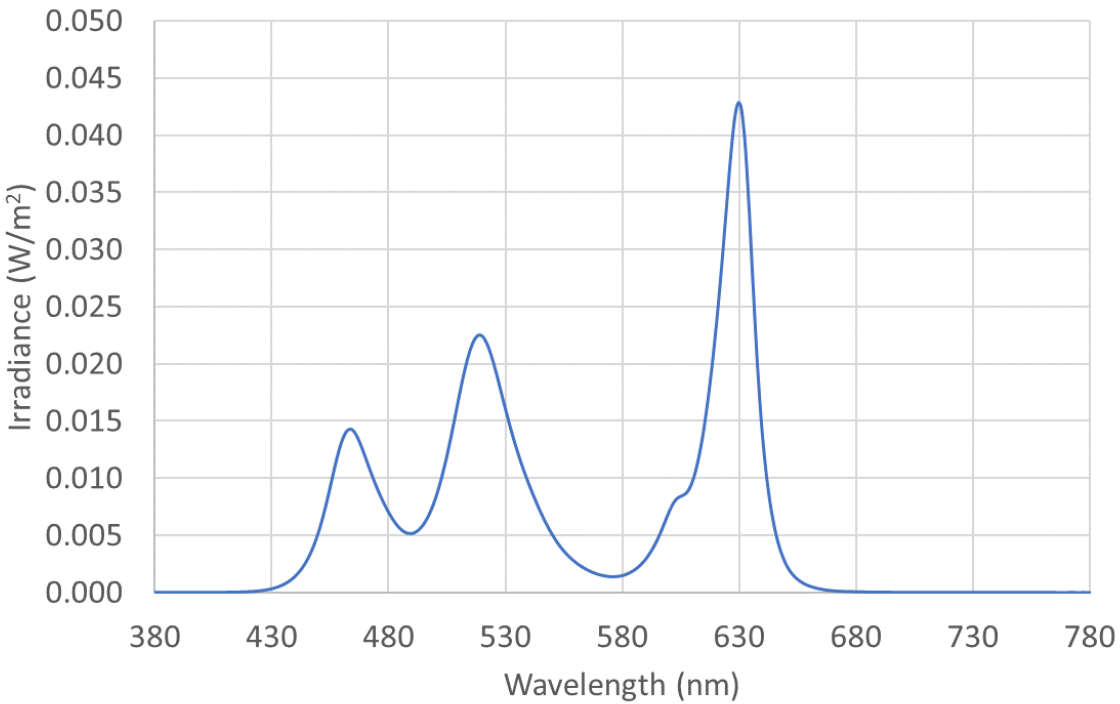
Stability

Linearity

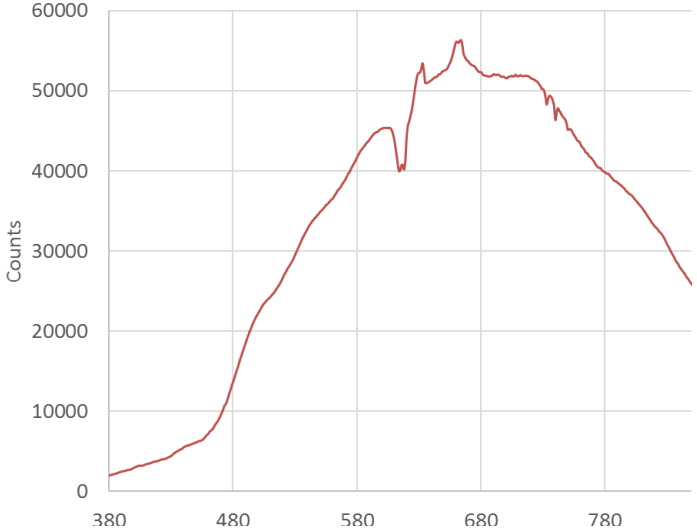
Bandpass

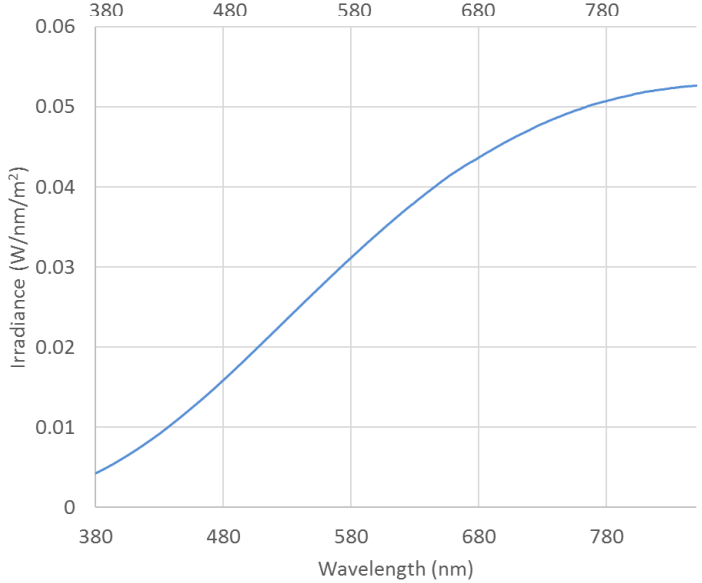
Spectral stray-light

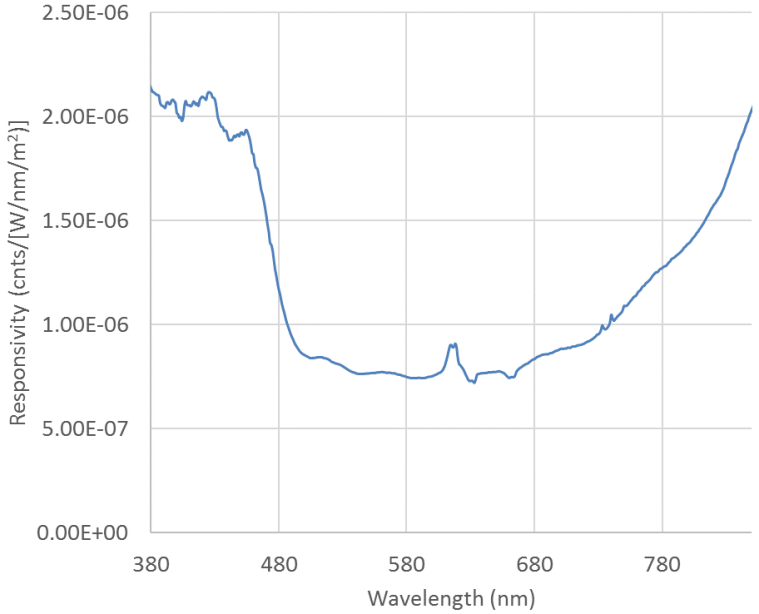
- Dispersion scatter
- Infrared and UV scatter
- Out-of-band transmittance



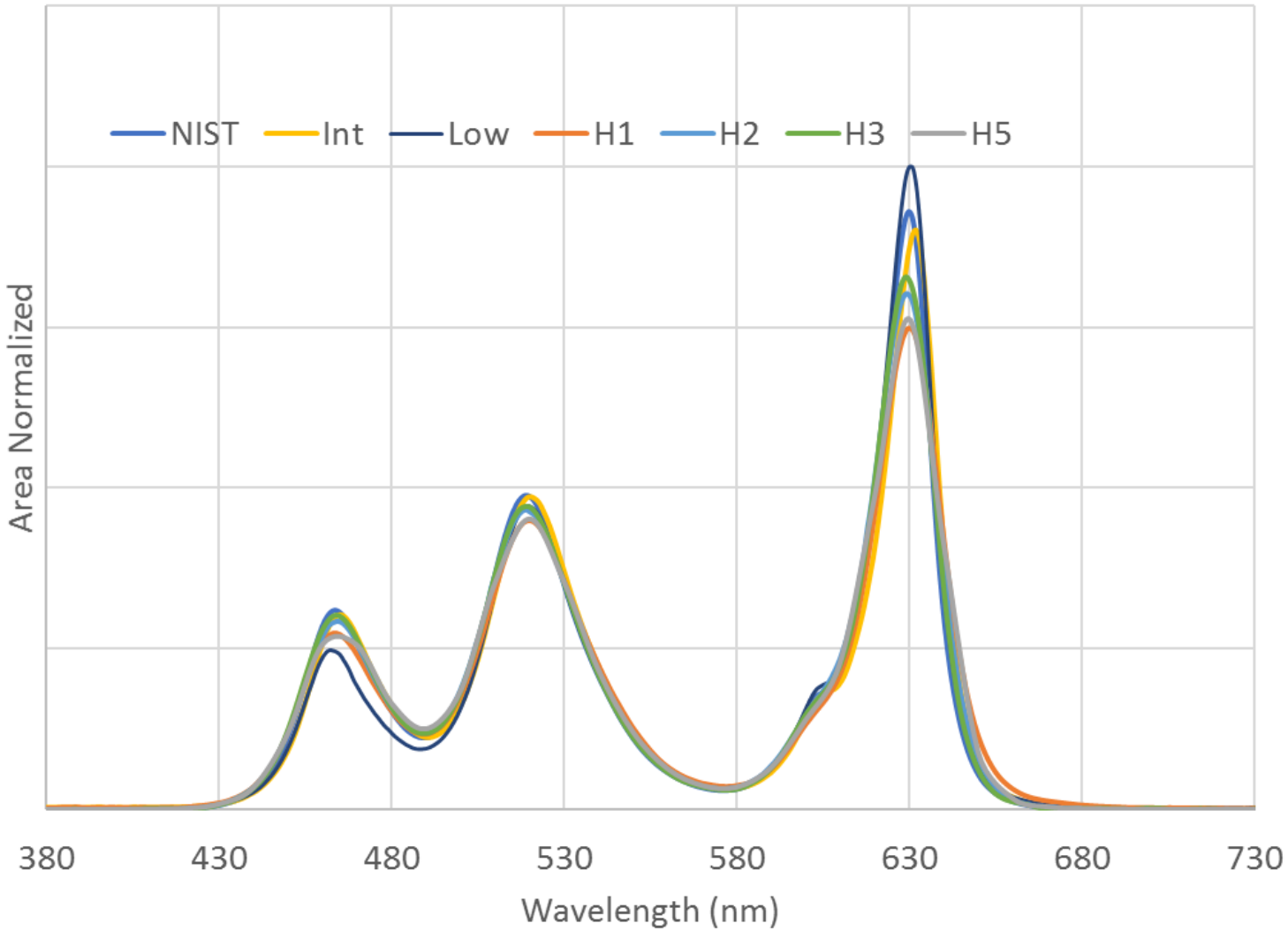
Calibration



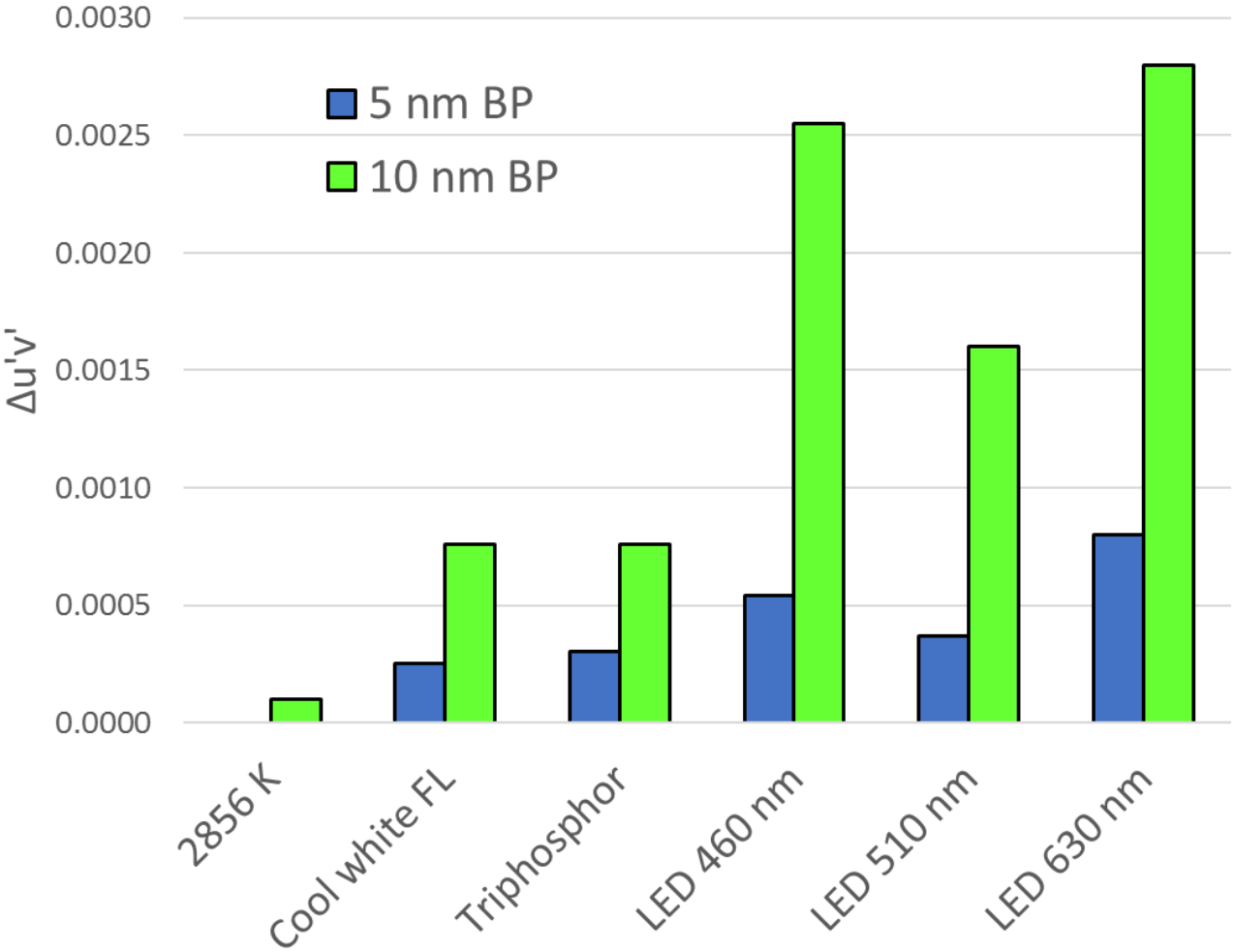




Bandpass


NIST
Int
Low
H1
H2
H3
H5
Area Normalized
380
430
480
530
580
630
680
730
Wavelength (nm)

Bandpass - error

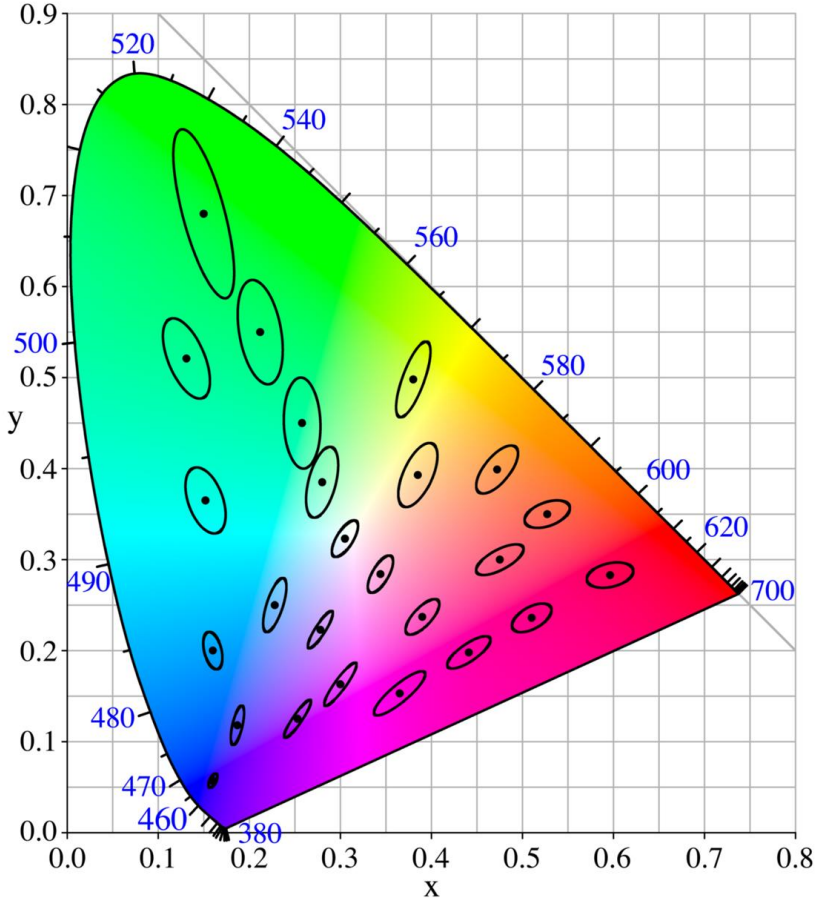


Bandpass of 5 nm (FWHM) is acceptable for colorimetry of most light sources.

Error is proportional to the square of bandwidth increase.

5 nm interval

Just noticeable differences – Macadam ellipses



Approximation (ellipses)

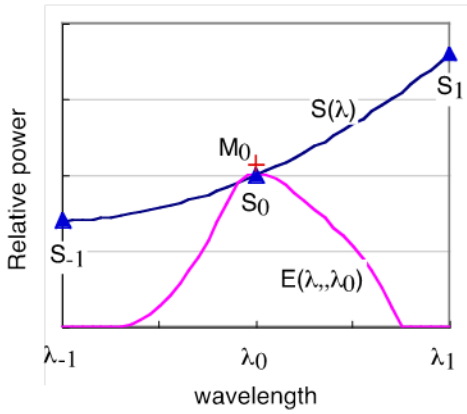
Δu'v' = 0.0011

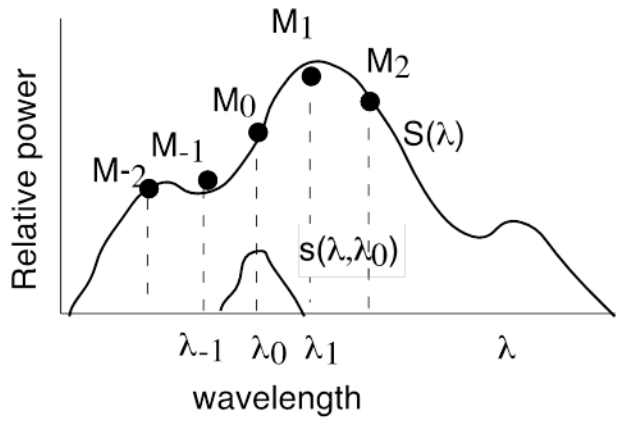
2200 K	ΔCCT = 16 K
2856 K	ΔCCT = 25 K
3200 K	ΔCCT = 30 K
4300 K	ΔCCT = 48 K
6500 K	ΔCCT = 95 K

Bandpass - correction

Flexible bandpass correction method (Extension of S-S method by Ohno & Gardner)

Works with any bandpass function (asymmetric, not matched)





$$I_0 = \int s(\lambda, \lambda_0)\ \mathrm{d}\lambda$$

$$I_1 = \int s(\lambda, \lambda_0)\lambda\ \mathrm{d}\lambda$$

$$I_2 = \int s(\lambda, \lambda_0)\ \lambda^2\ \mathrm{d}\lambda$$

$$a_{-1} = \frac{1}{2}\left(\frac{I_2}{\Delta\lambda^2} - \frac{I_1}{\Delta\lambda}\right)$$

$$a_0 = \frac{1}{2}\left(I_0 - \frac{I_2}{\Delta\lambda^2}\right)$$

$$a_1 = \frac{1}{2}\left(\frac{I_2}{\Delta\lambda^2} + \frac{I_1}{\Delta\lambda}\right)$$

$\Delta\lambda$: scan interval

$$S_0 = b_{-2} \cdot M_{-2} + b_{-1} \cdot M_{-1} + b_0 \cdot M_0 + b_1 \cdot M_1 + b_2 \cdot M_2$$

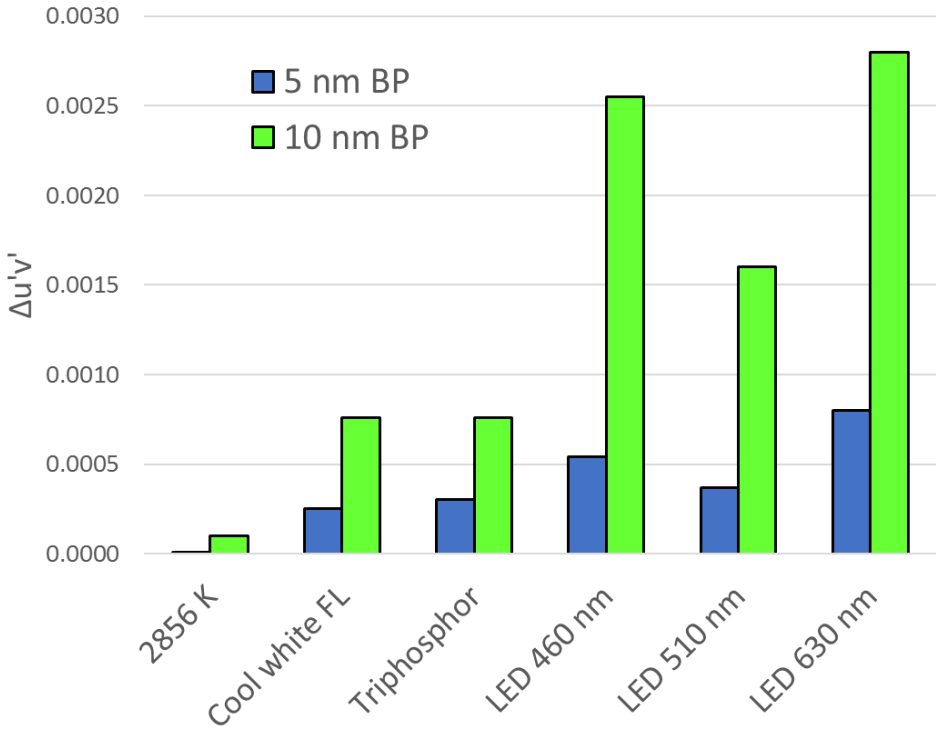
with $b_{-2} = \frac{a_{-1}^2}{X},\ b_{-1} = -\frac{a_{-1}}{X},\ b_0 = \frac{a_0}{X},\ b_1 = -\frac{a_1}{X},\ b_2 = \frac{a_1^2}{X},$

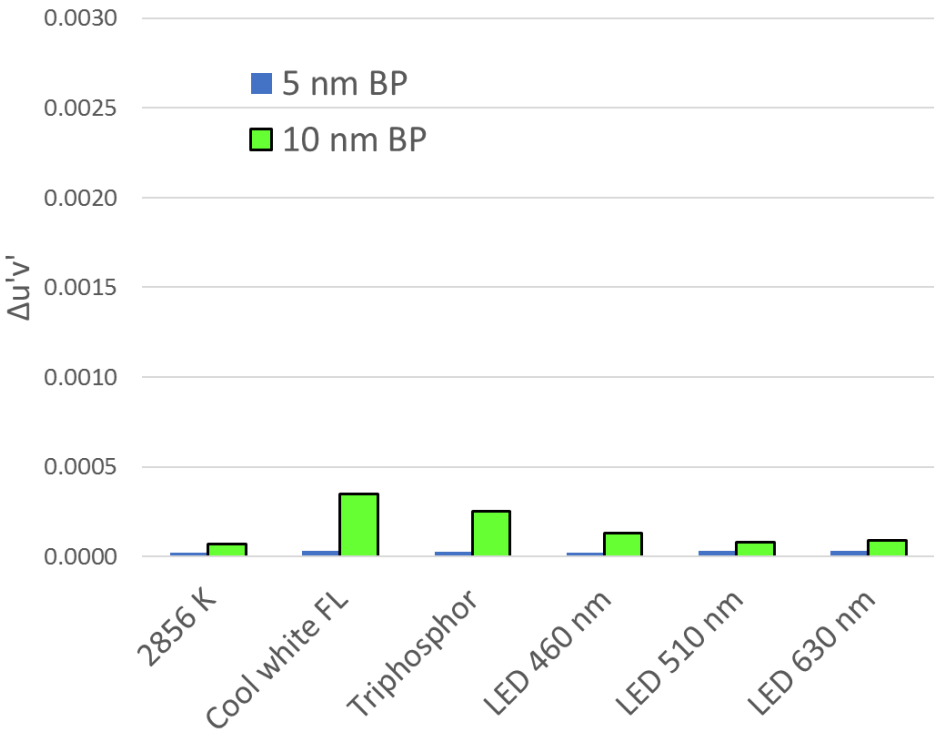
and $X = a_0^{\ 2} - 2a_{-1}a_1.$

Y. Ohno, A Flexible Bandpass Correction Method for Spectrometers, Proc., AIC' 05, Granada, Spain, May 2005

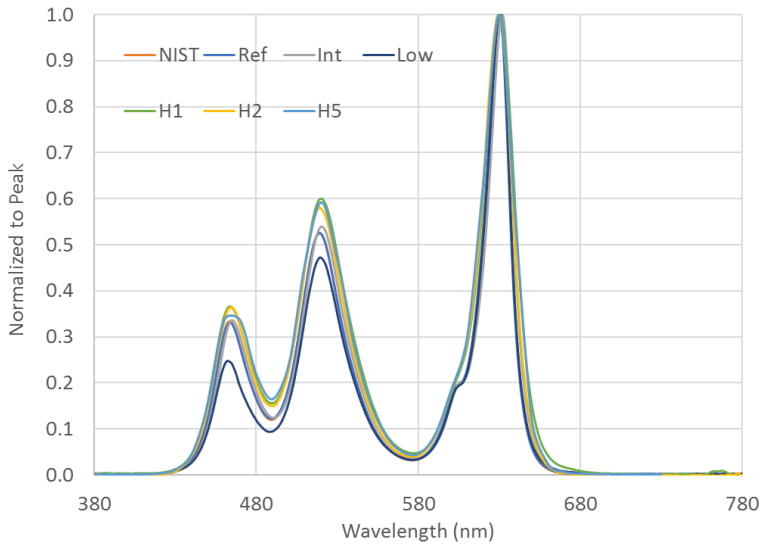
J. Gardner, Bandwidth correction for LED chromaticity, *Color Res. Appl.* 31(5) 374-380

Bandpass - correction



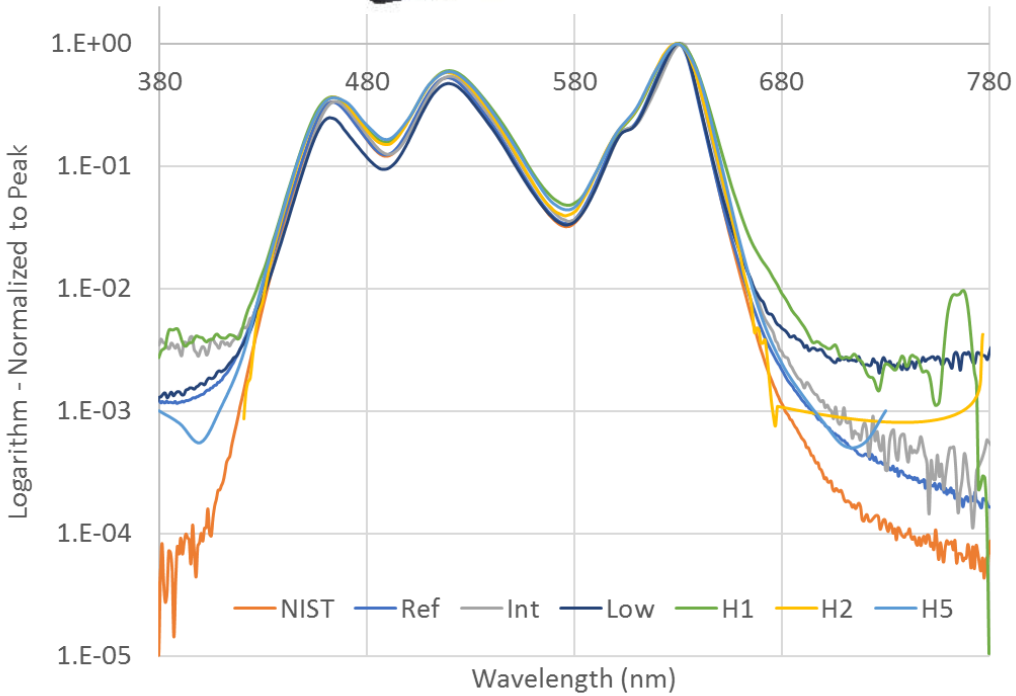


Out-of-band scattered stray light

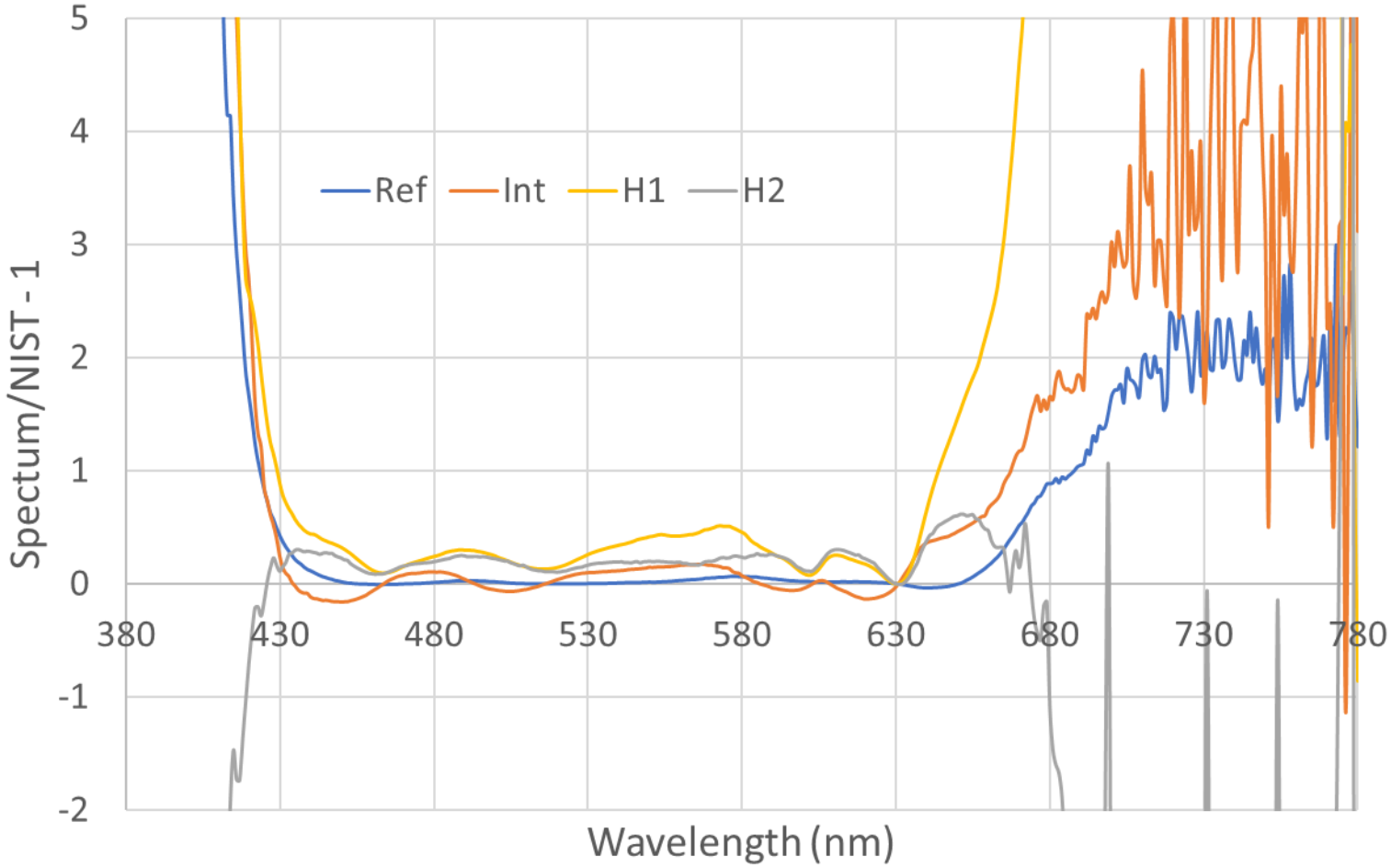


NIST	4304 K	H1	4397 K
Ref	4305 K	H2	4273 K
Int	4409 K	H3	4357 K
Low	4732 K	H4	4296 K
		H5	4342 K

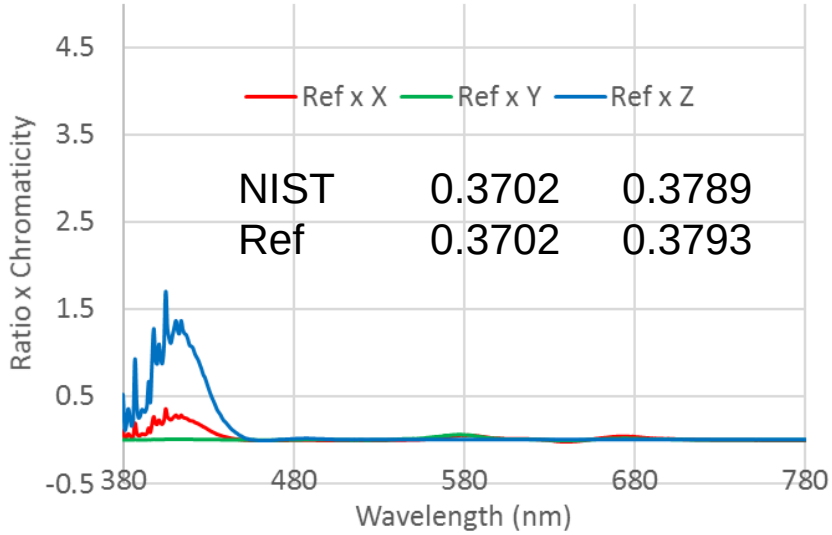
JND ΔCCT = 48 K

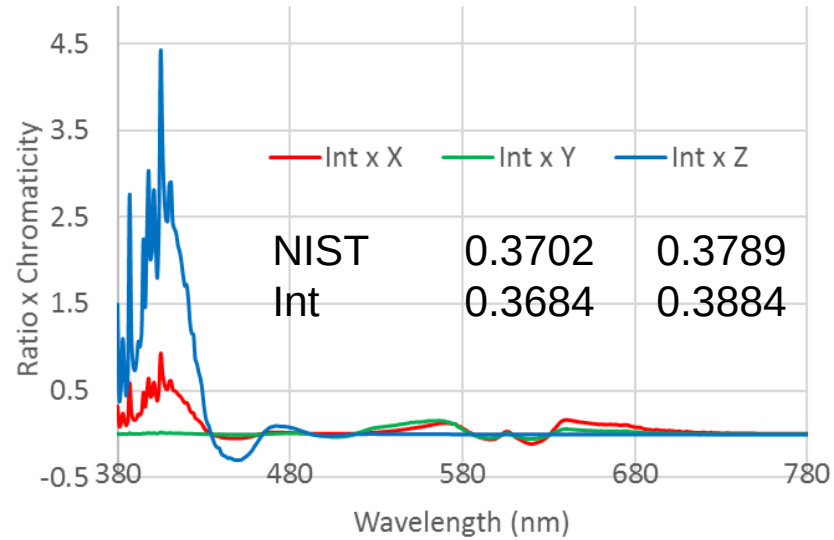


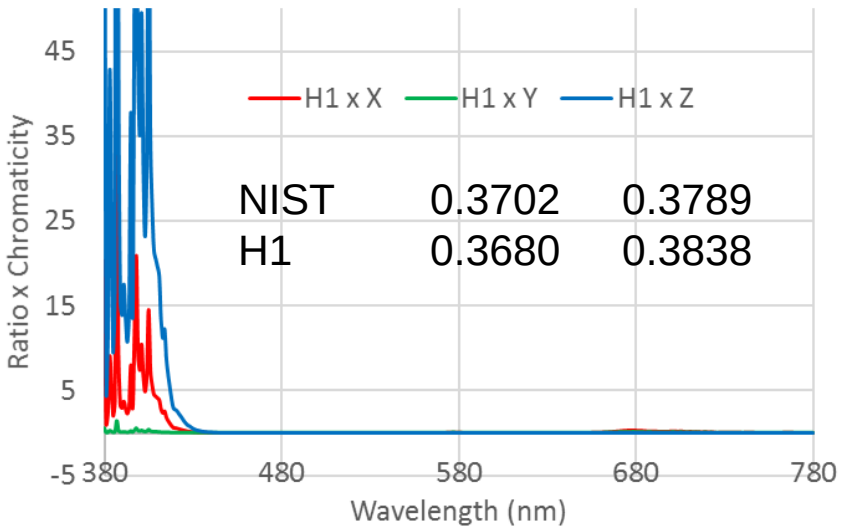
Spectrum ratios

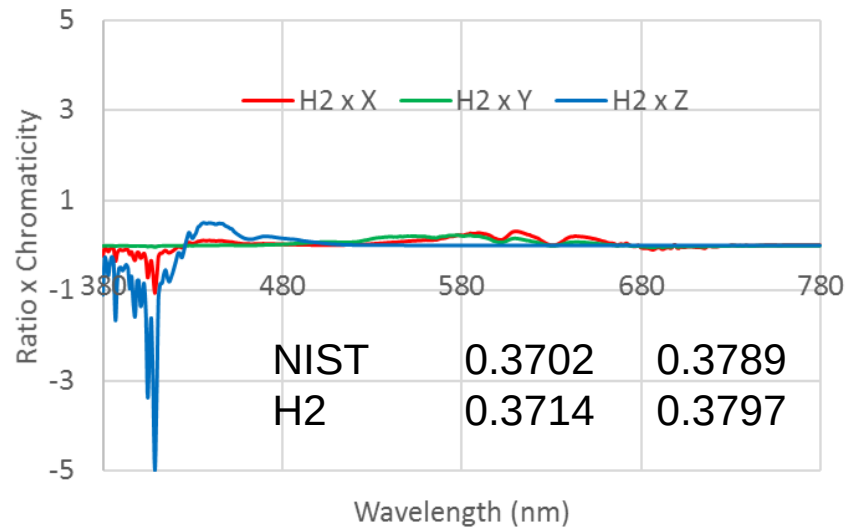


Spectrum ratios x chromaticity matching functions

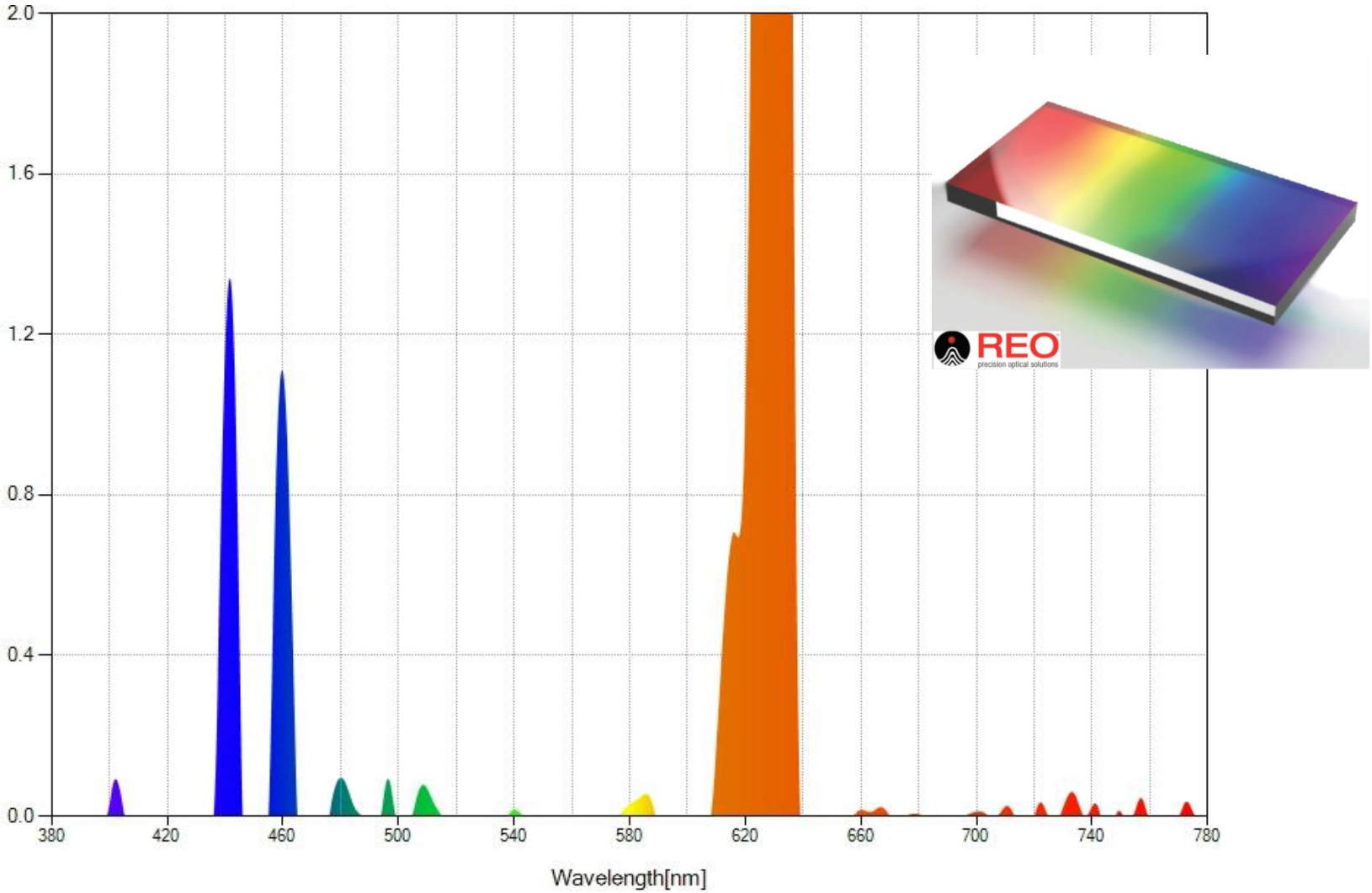




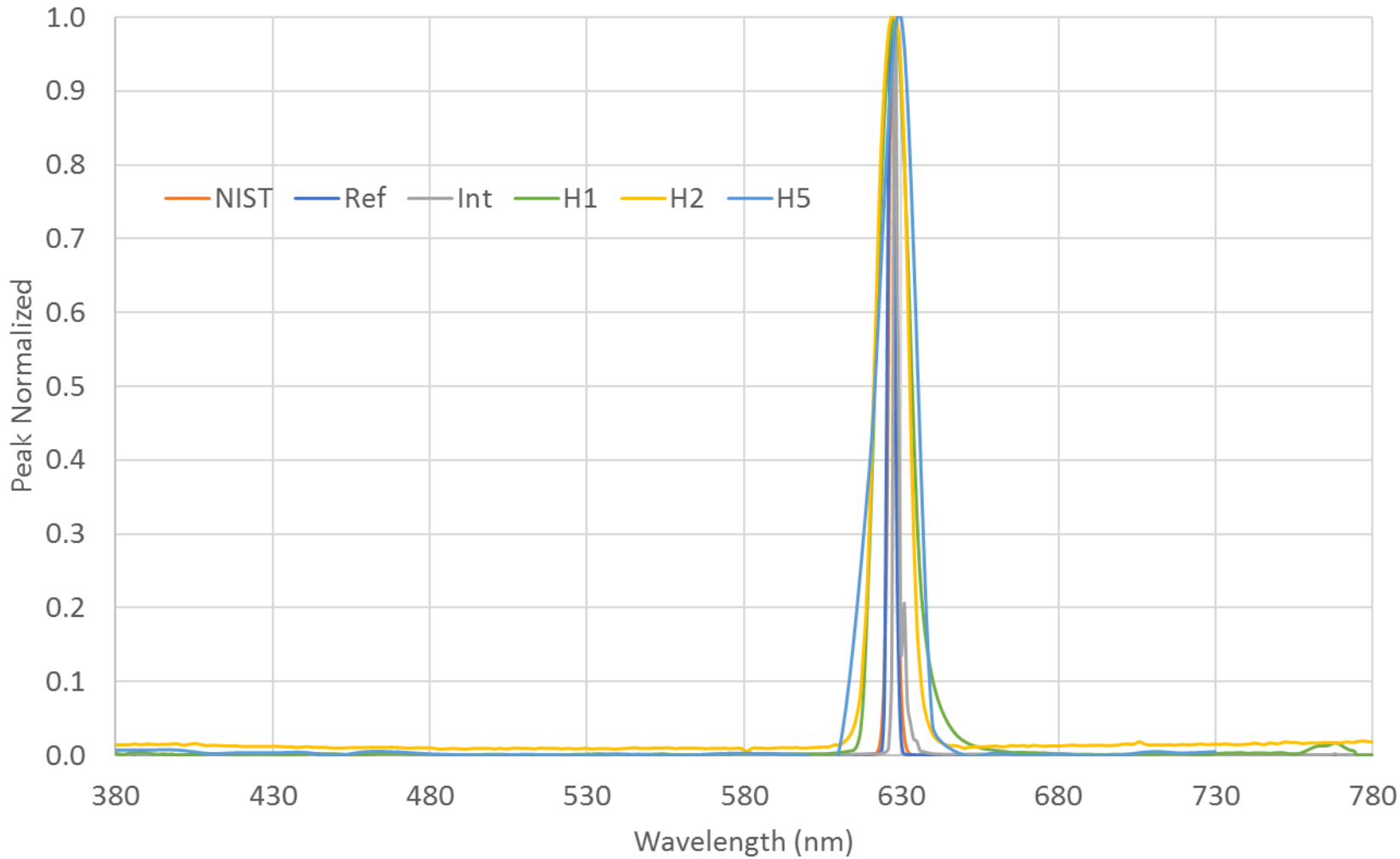




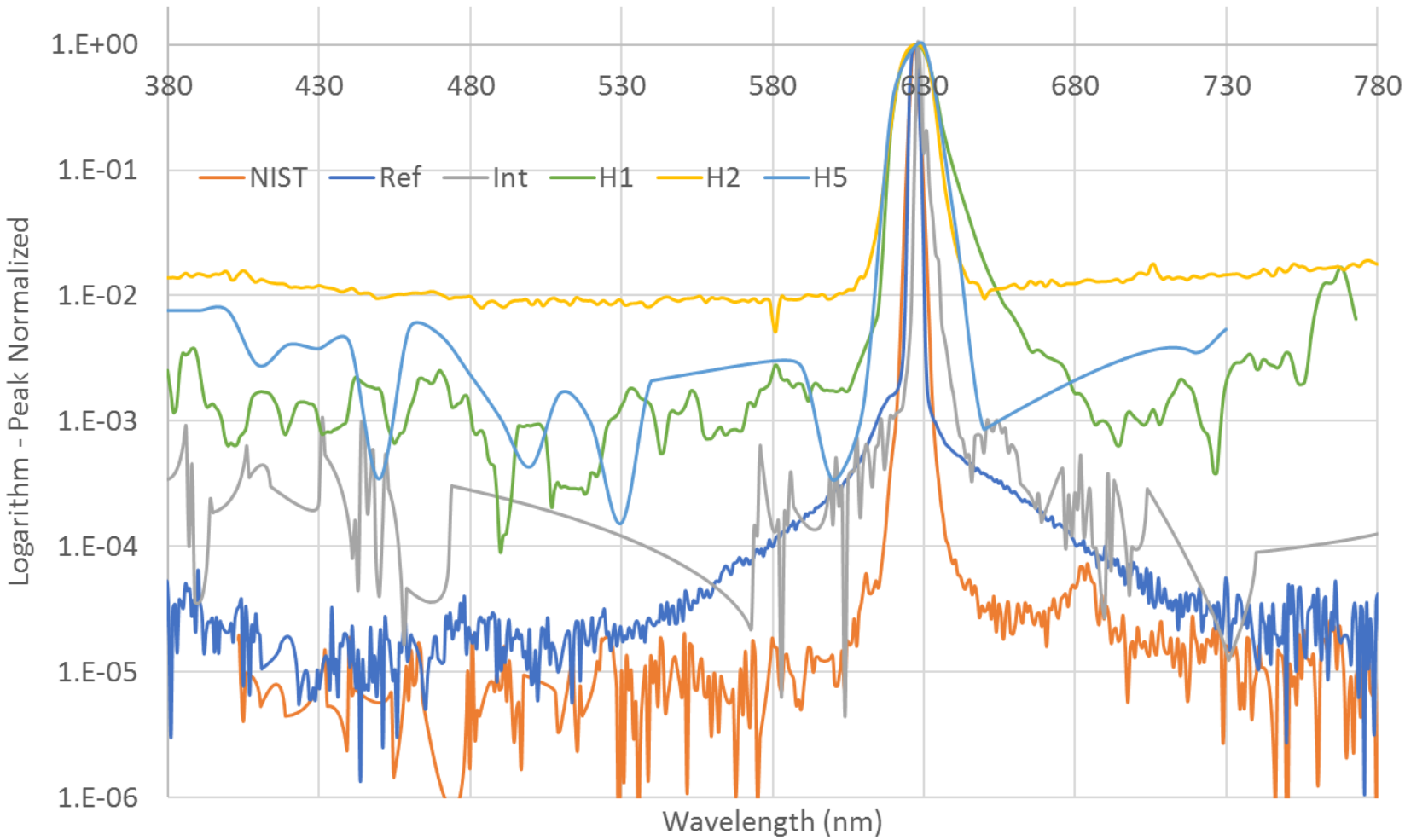
Out-of-band transmittance – H3



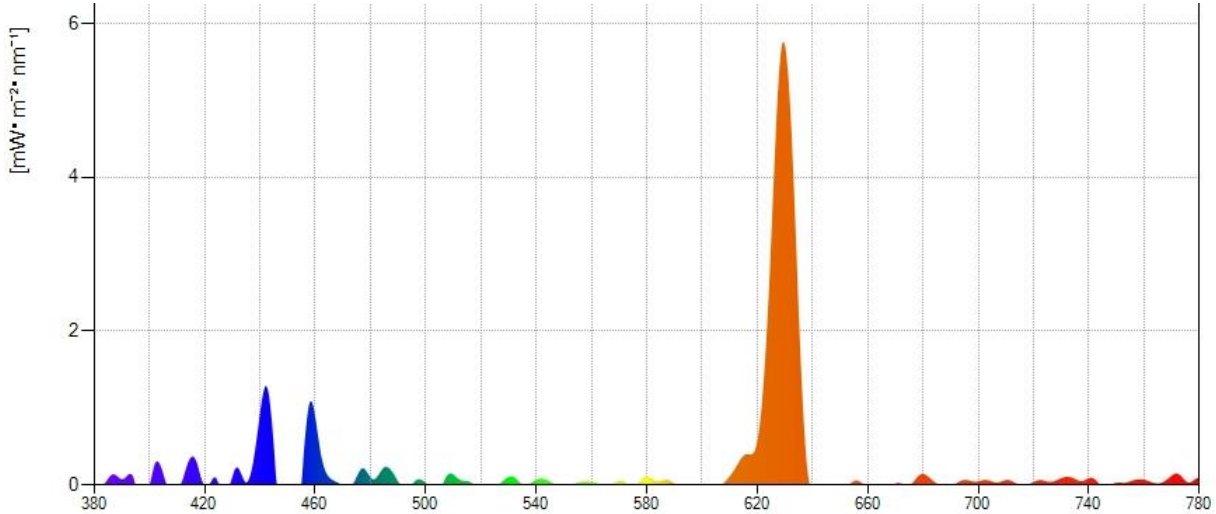
Out-of-band scatter & transmittance

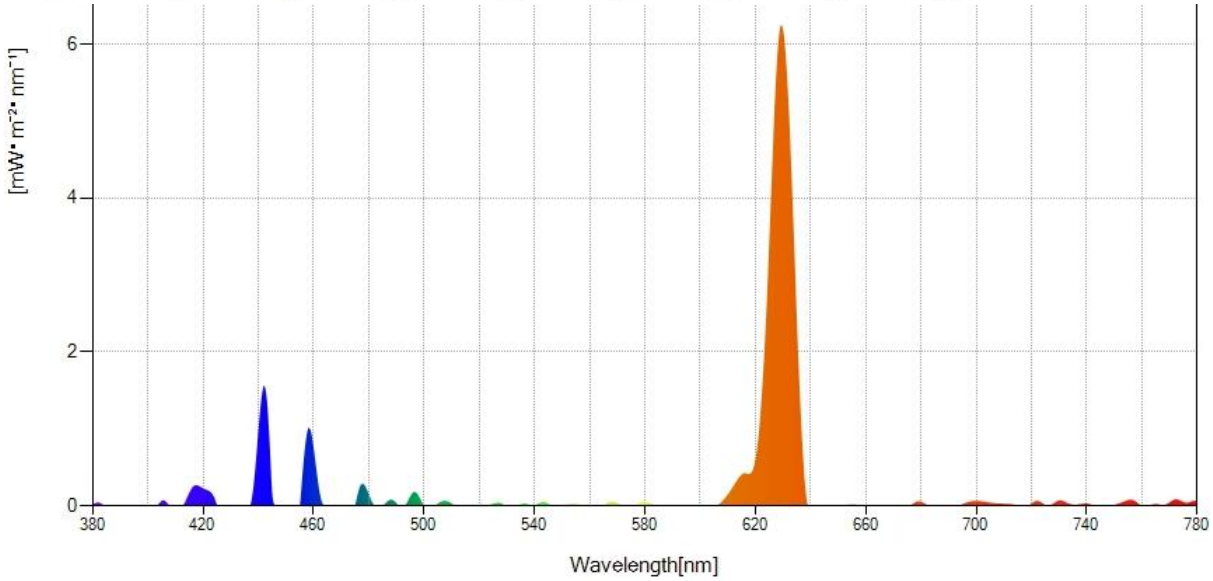


Out-of-band scatter & transmittance



Surrounding effects & geometry





Illumination geometry

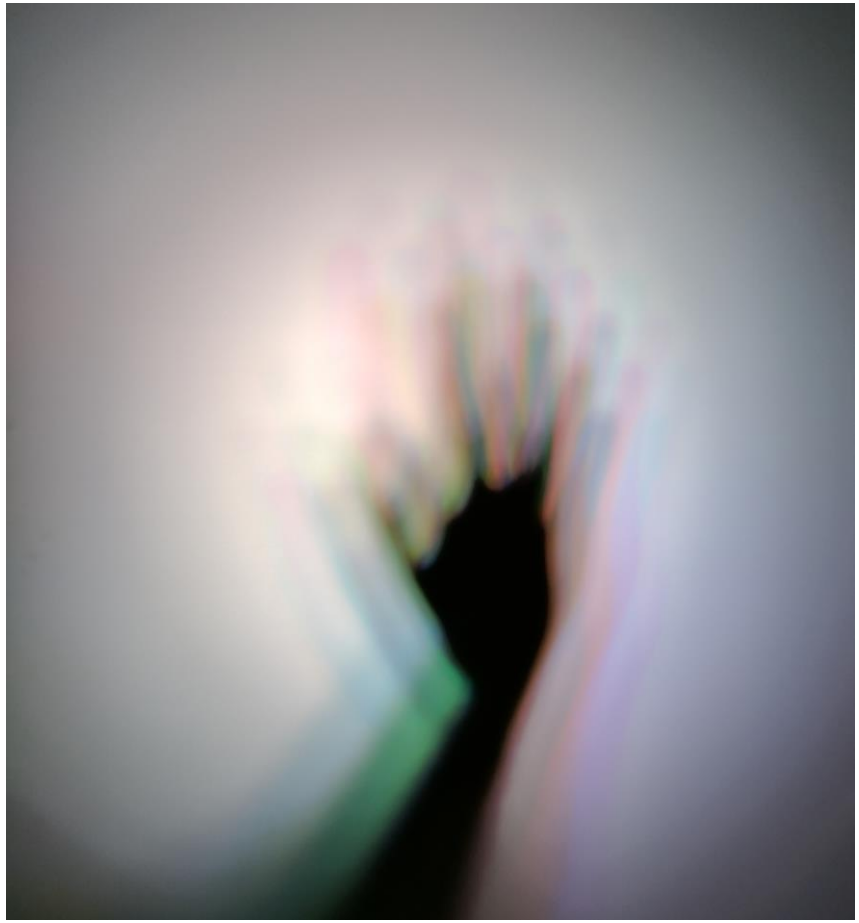
- Direct
- Diffuse

Surrounding effects & geometry

Wall reflectance

Secondary sources of light

Source nonuniformity



Color shadows

Summary

- What we found
- What that means

- Anecdotal evidence warrants further investigation
- Next steps

- Until then?