CORM 2011 NIST Measurement Uncertainty Workshop
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Case Study: Measurement protocols for optically active pigmented coatings – luminance ratio

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NIST

U.S. DOD Corrosion Control

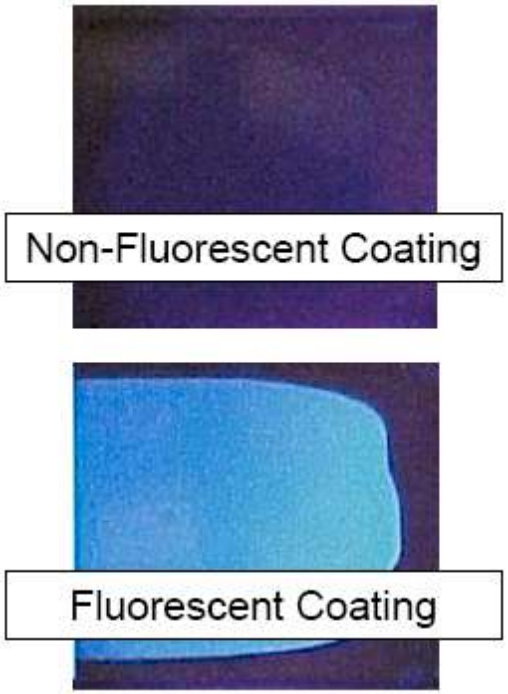
- U.S. Dept. of Defense
  cost of corrosion control $20B/yr
- U.S. Navy corrosion control
  costs $2.4B/yr
- Preservation of tanks
  #1 Fleet maintenance cost

Potential 20 year tank coatings

- Holiday free application
- Rigorous QA/QC required

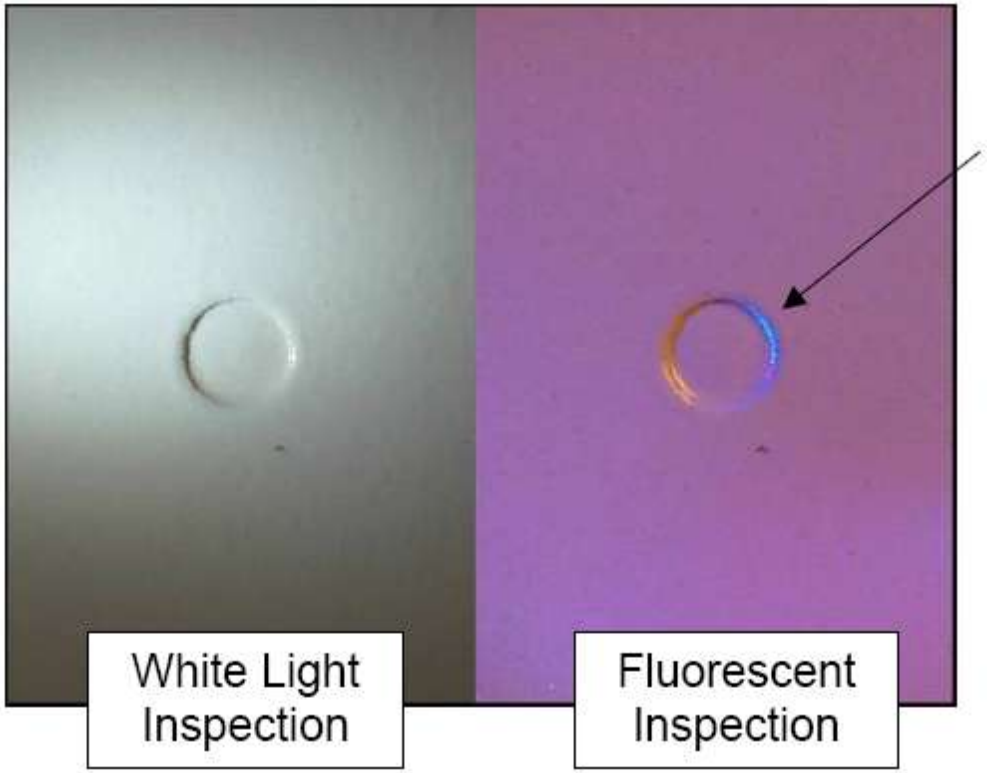
NIST National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Enhanced Visual Inspection with Fluorescent Coatings



Simple coating change to enhance defect contrast

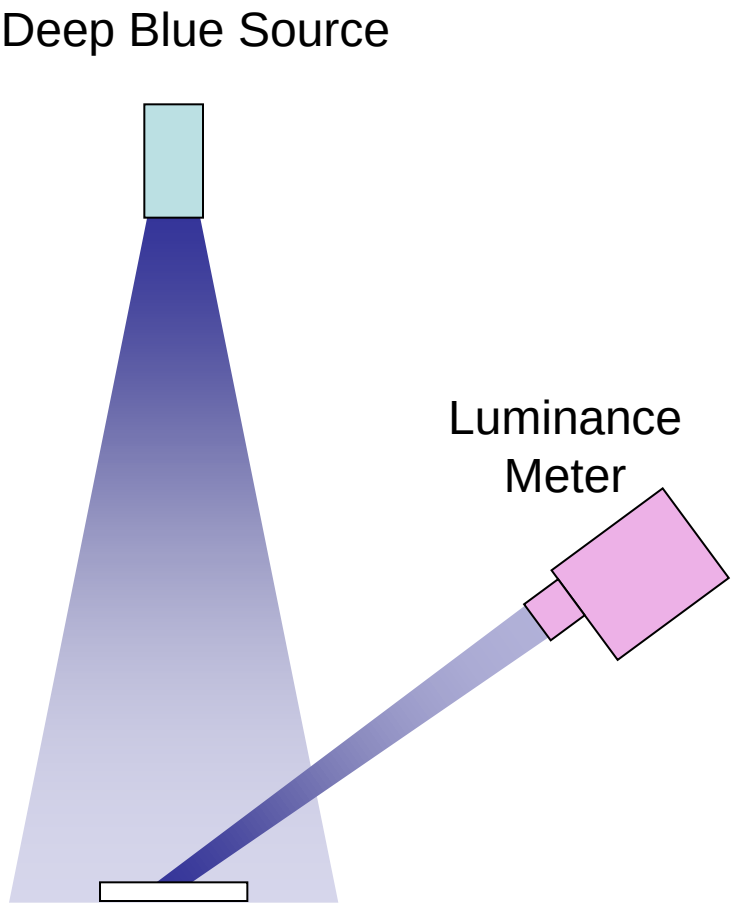
- Add fluorescent pigment
- Illuminate with Deep Blue light
- Emit intense color



Measurement Equation

$$R_L^B = \frac{L^B}{L_P^B}$$

Luminance ratio = luminance of the sample divided by the luminance of a 25 % reflecting Lambertian diffuser under a given deep blue illuminant



Calibrated reference plaque (non-fluorescent) or Test sample (fluorescent)

Measurement Equations

$$L^B = \frac{s - s_d}{r} \cdot F \qquad \frac{V}{V/cd/m^2} = cd/m^2$$

Sample Luminance = luminance meter signal divided by responsivity of the luminance meter for the spectrum of light emitted from the sample, which is different than the deep blue illuminant

$$L_P^B = \frac{s_P - s_d}{r} \cdot F_P \cdot \frac{0.25}{\rho^B} \qquad \frac{V}{V/cd/m^2} = cd/m^2$$

Reference Luminance = luminance meter signal divided by responsivity of the luminance meter for the deep blue illuminant multiplied by the 25 % reflecting Lambertian diffuser divided by the calibrated reflectance of the standard under the deep blue illuminant

Uncertainty Components

$$R_L^B = \frac{\frac{s - s_d \cdot F}{r}}{\frac{s_P - s_{P,d} \cdot F_P}{r} \cdot \frac{0.25}{\rho^B}} \rightarrow \frac{s - s_d}{s_P - s_{P,d}} \frac{F}{F_P} \cdot \frac{\rho^B}{0.25} \cdot C_f$$

s_P – reference signal
$s_{P,d}$ – reference dark signal
s – sample signal
s_d – sample dark signal
F_P – spectral mismatch correction of reference signal
F – spectral mismatch correction of sample signal
ρ^B – luminance reflectance of calibrated reference standard

Uncertainty Components

$$R_L^B = \frac{\bar{s} - s_d}{\bar{s}_P - s_{P,d}} \frac{F}{F_P} \cdot \frac{\rho^B}{0.25} \cdot C_f$$

λ_B – wavelength dependence
$\Delta\lambda_B$ – illumination bandwidth dependence
λ_S – spectral out-of-band light (fluorescence from source)
S – out-of-band stray light (inside detector)
L – linearity of the detector
O – Out-of-field sensitivity of the luminance meter
c_s – voltmeter calibration
ϕ_P – incident angle of light on reference
ϕ – incident angle of light on sample
θ_P – viewing angle of light from reference
θ – viewing angle of light from sample

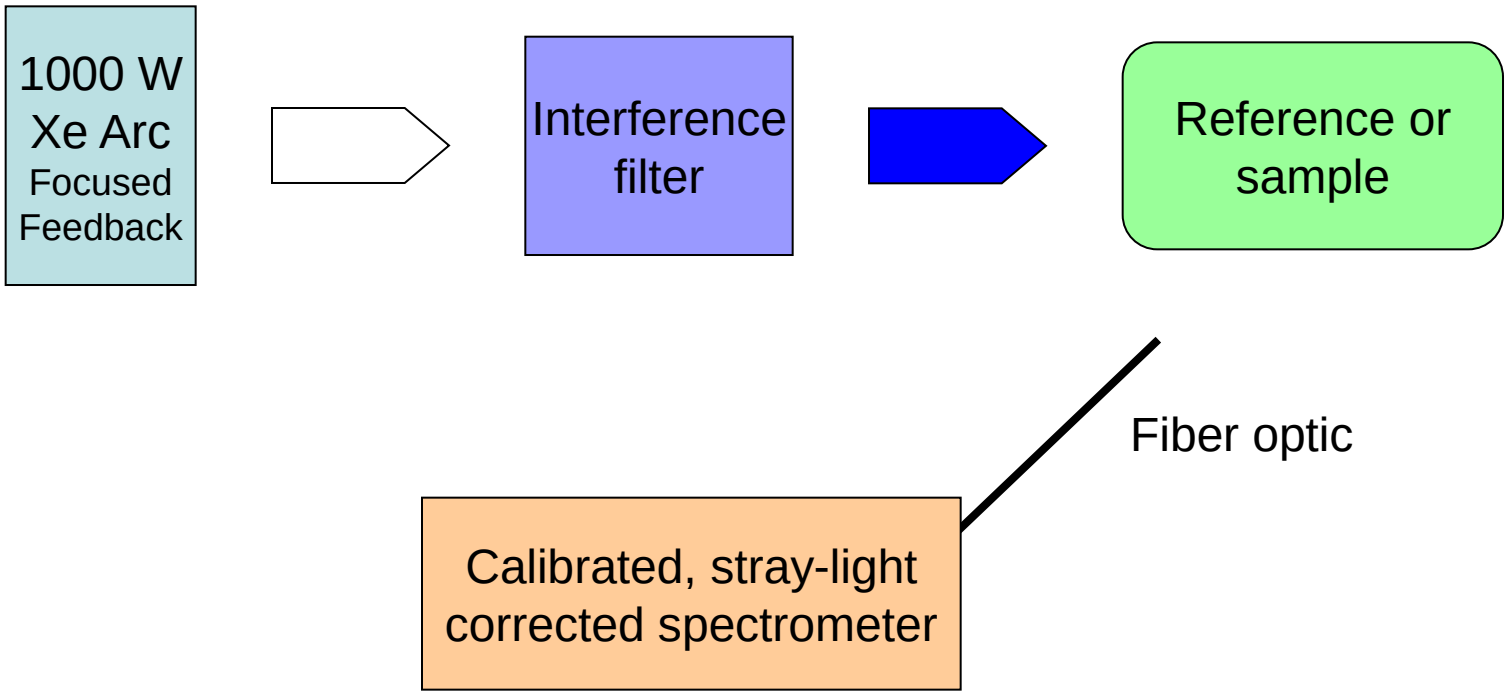
Uncertainty Components

$$R_L^B = \frac{\left(s - s_d\right)}{\left(s_P - s_{P,d}\right)} \frac{F}{F_P} \cdot \frac{\rho^B}{0.25} \cdot C_f$$

U_L – uniformity of the light source
U_P – uniformity of the reference material
U – uniformity of the sample material
U_r – uniformity of the detector responsivity
T_P – temperature dependence of the reference material
T – temperature dependence of the sample material
T_r – temperature dependence of the luminance meter responsivity
P_P – polarization dependencies of the reference material
P – polarization dependencies of the sample material
P_r – polarization dependencies of the luminance meter
I – deviation from the inverse square law

Wavelength Dependence

Goal: Determine sensitivity coefficient between excitation wavelength and R_L^B



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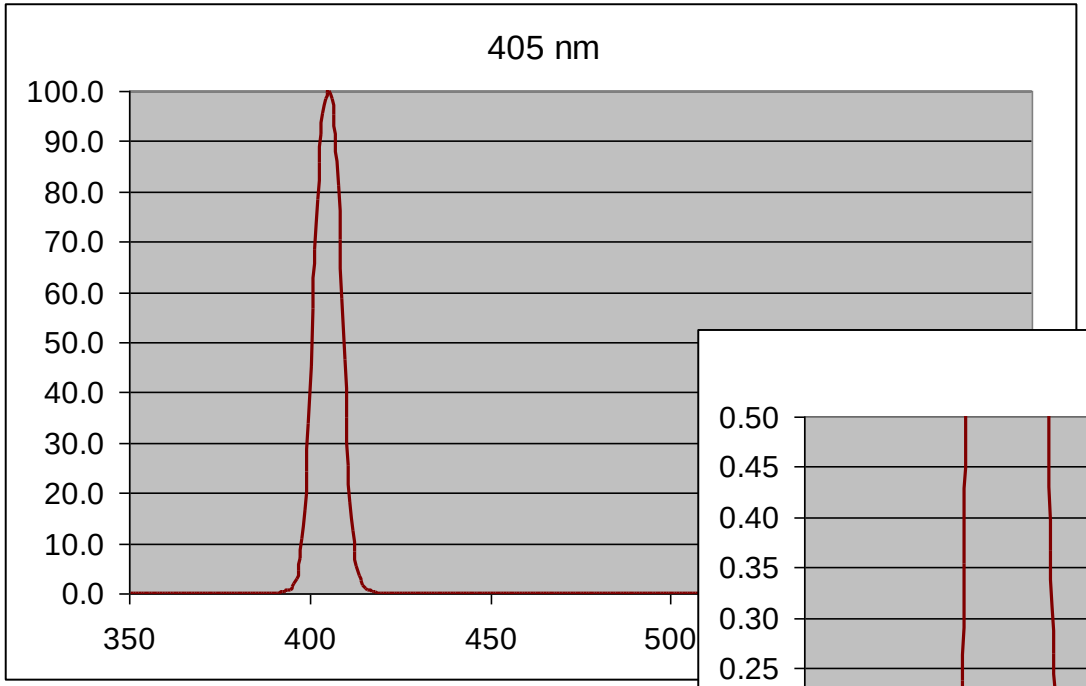

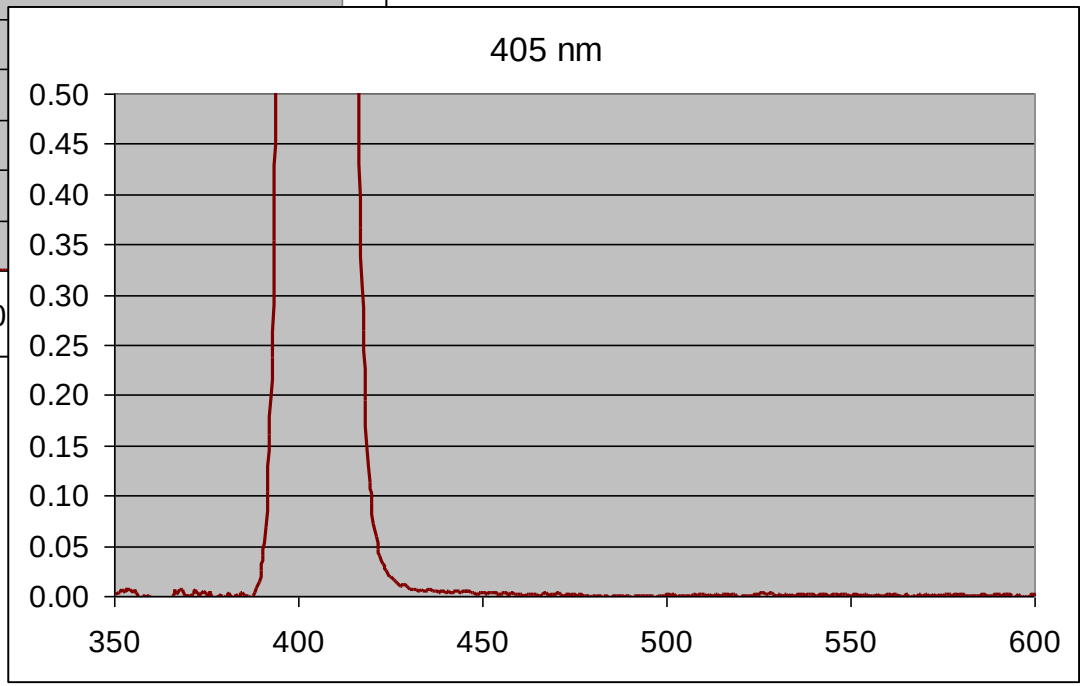

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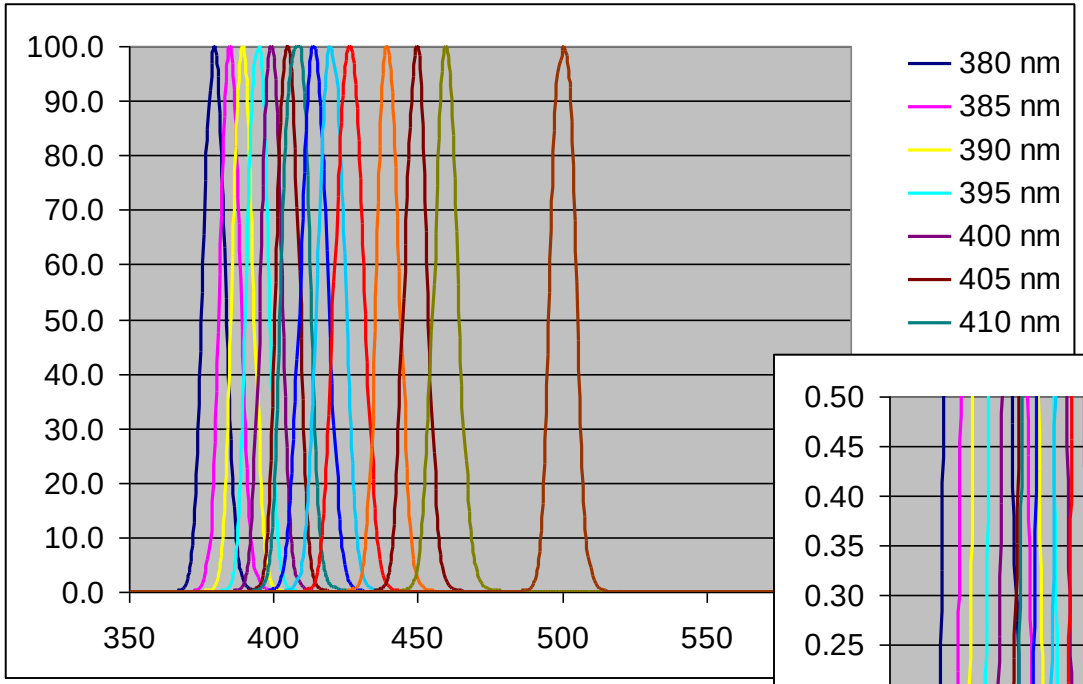
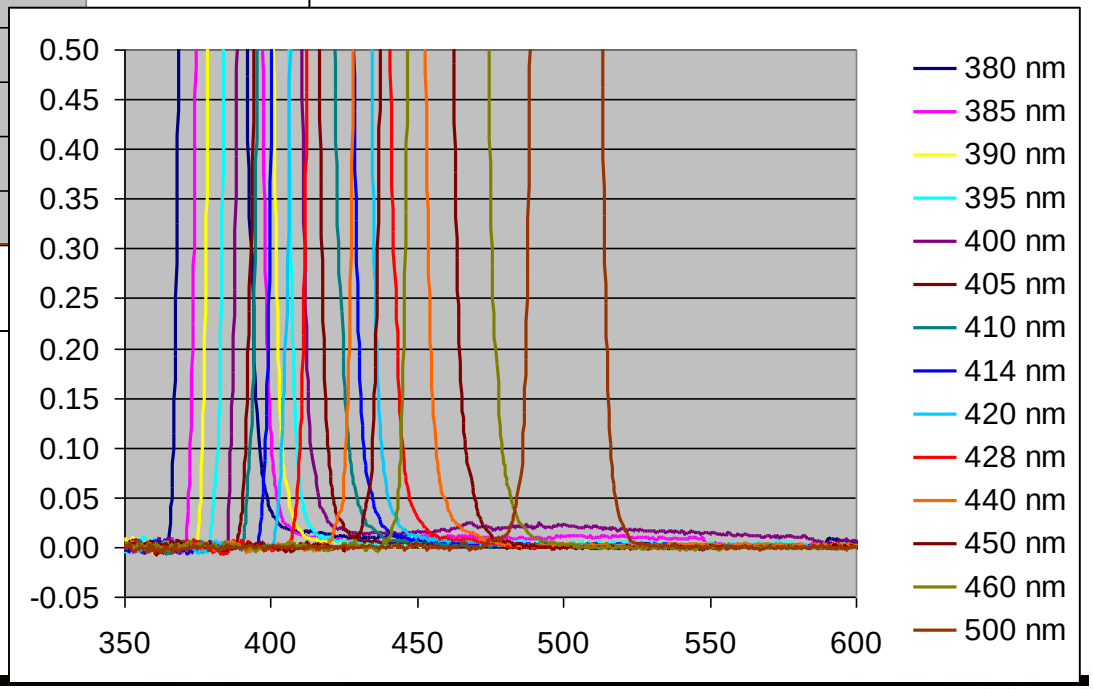


E2501-07	% < 450 nm
390 nm – 100 %	410 nm – 100 %
395 nm – 100 %	414 nm – 100 %
400 nm – 100 %	420 nm – 100 %
405 nm – 100 %	



% Visible	
390 nm – 0.04 %	405 nm – 0.02 %
395 nm – 0.06 %	410 nm – 0.02 %
400 nm – 0.28 %	414 nm – 0.05 %
	420 nm – 0.10 %

Wavelength Dependence

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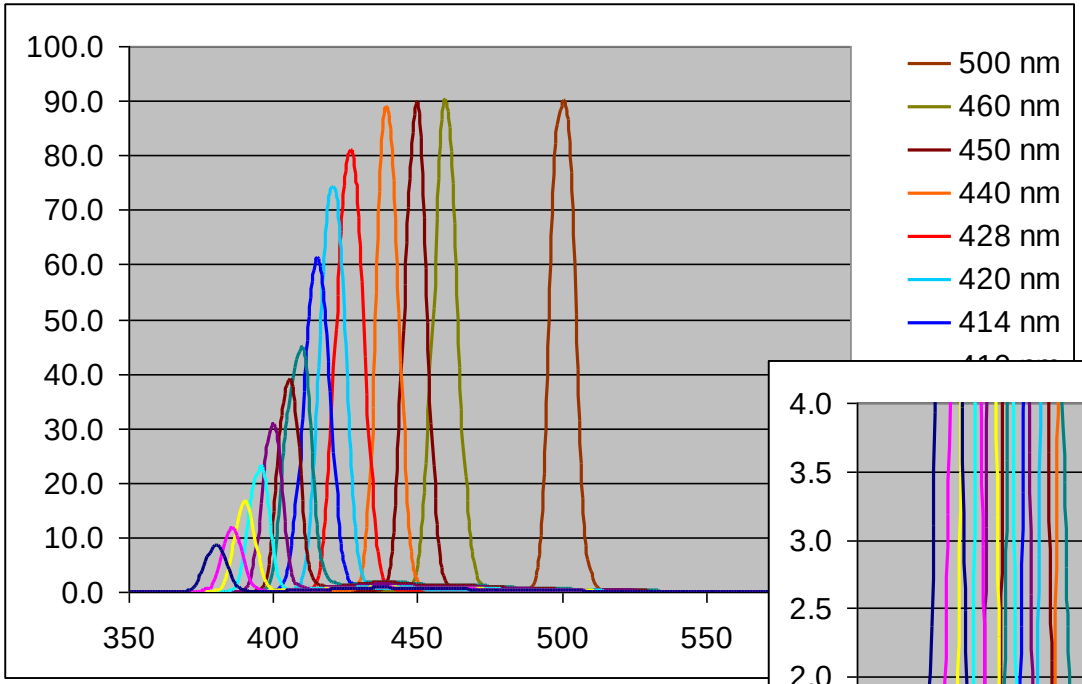
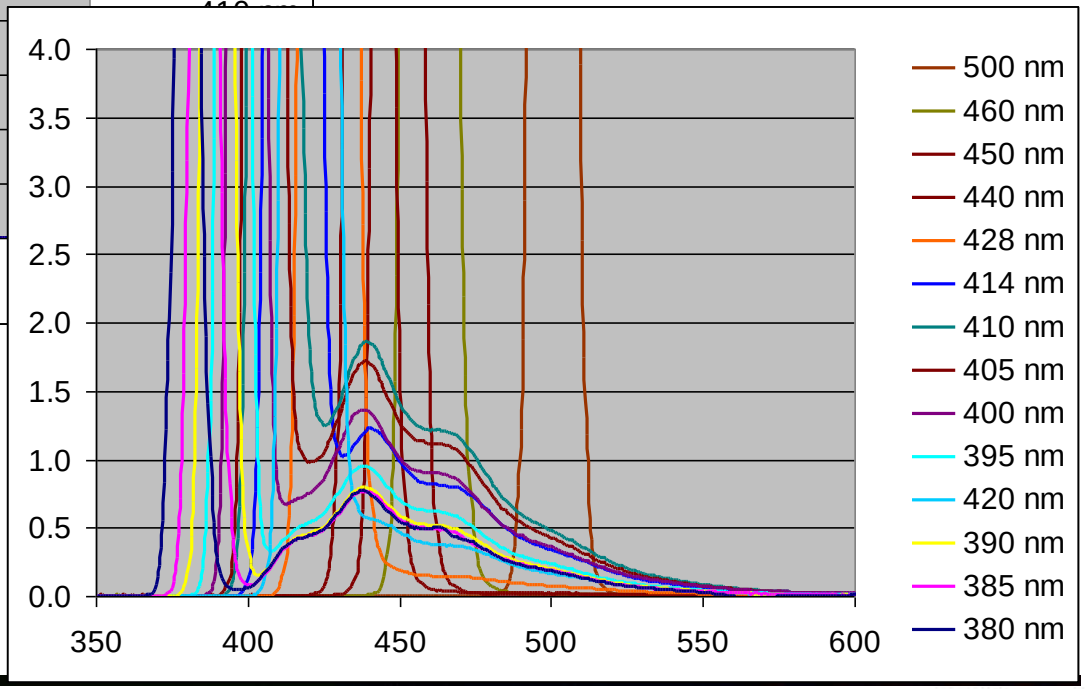


Sample 210



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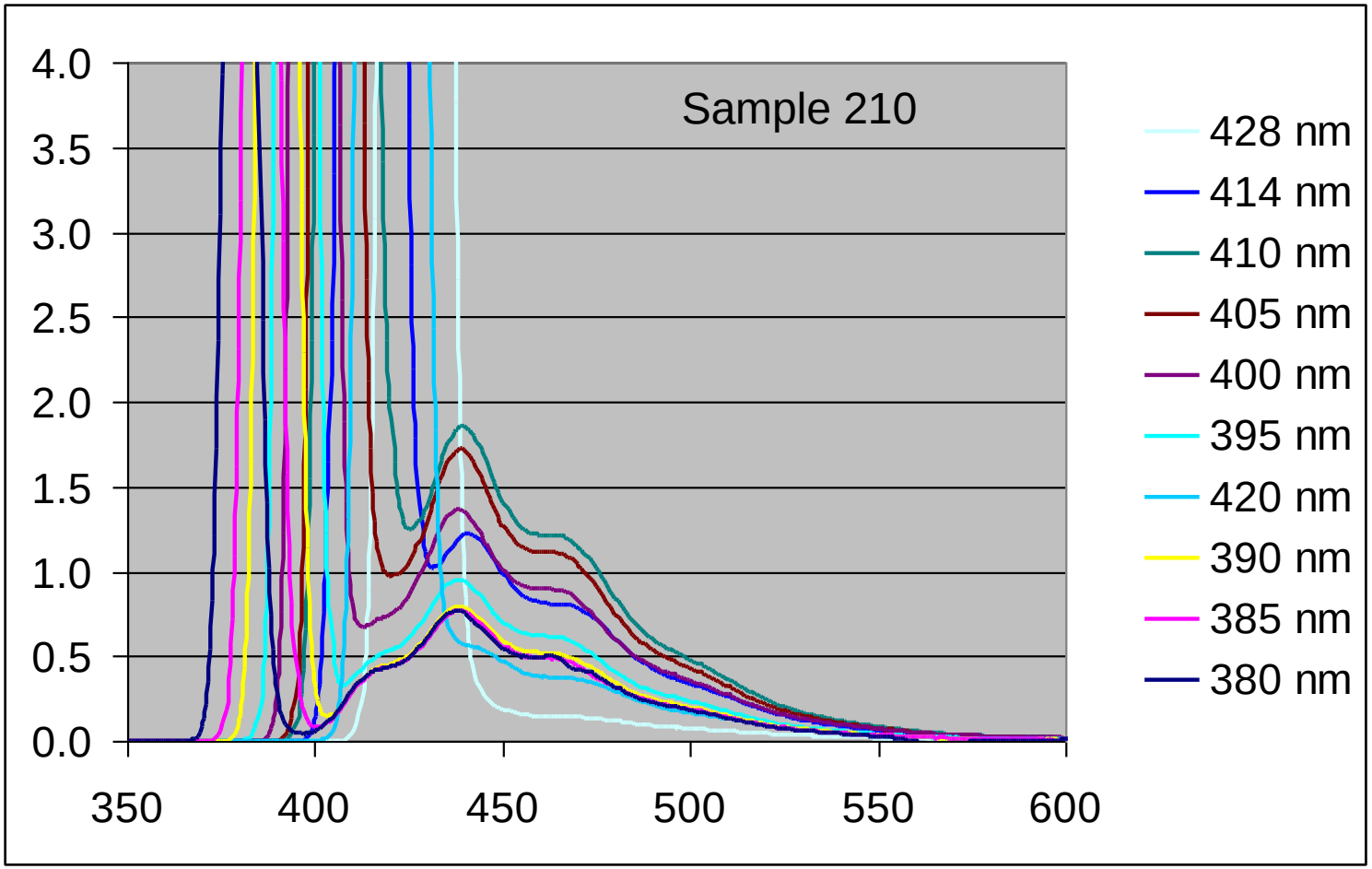

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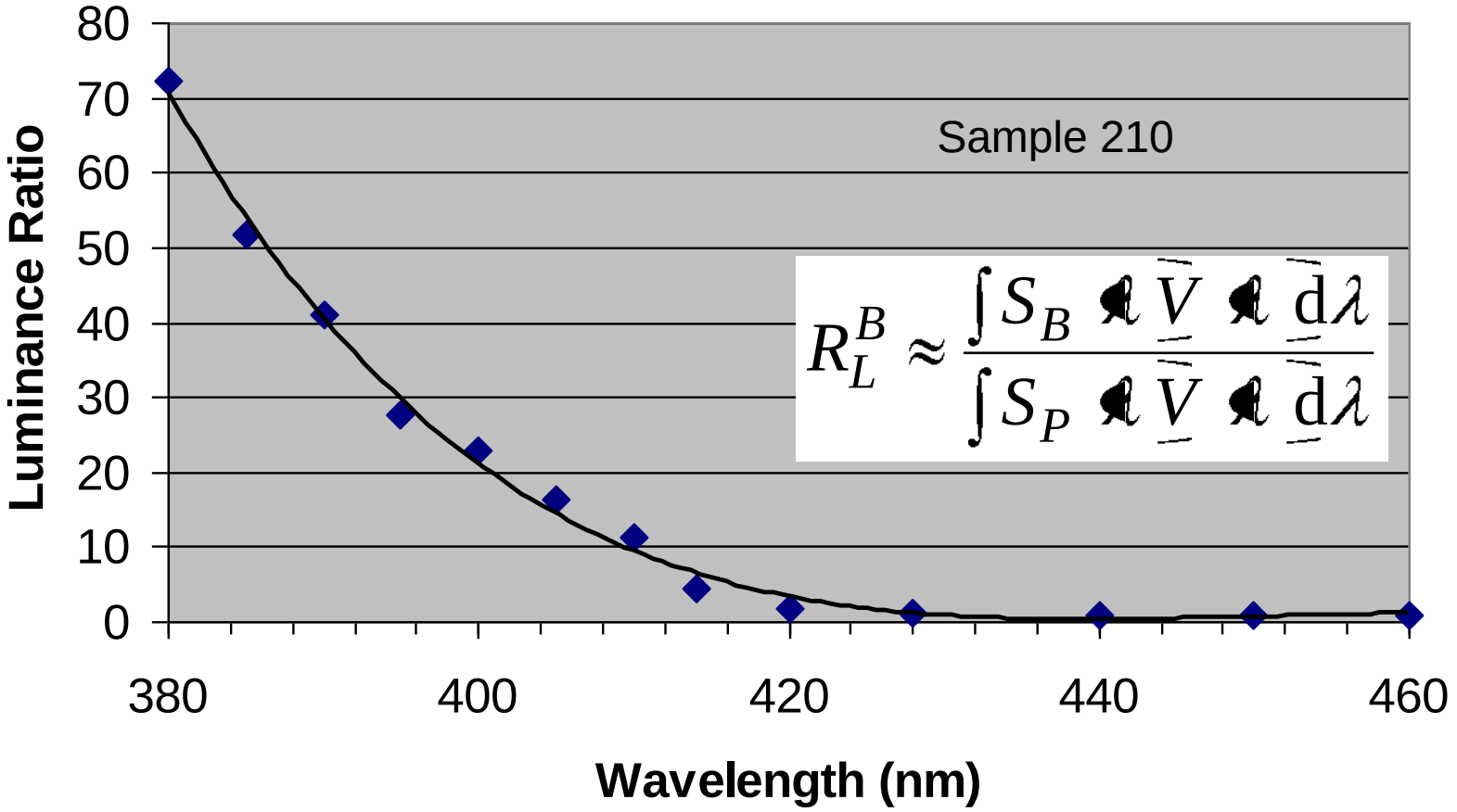


Sensitivity coefficient → -7 % per nanometer

Wavelength Dependence

Goal: Determine sensitivity coefficient between excitation wavelength and R_L^B

$$\frac{\partial R_L^B}{\partial \lambda} = \frac{-10\%}{nm} \quad \text{and} \quad \Delta\lambda = 2\,nm$$

404 nm – 406 nm

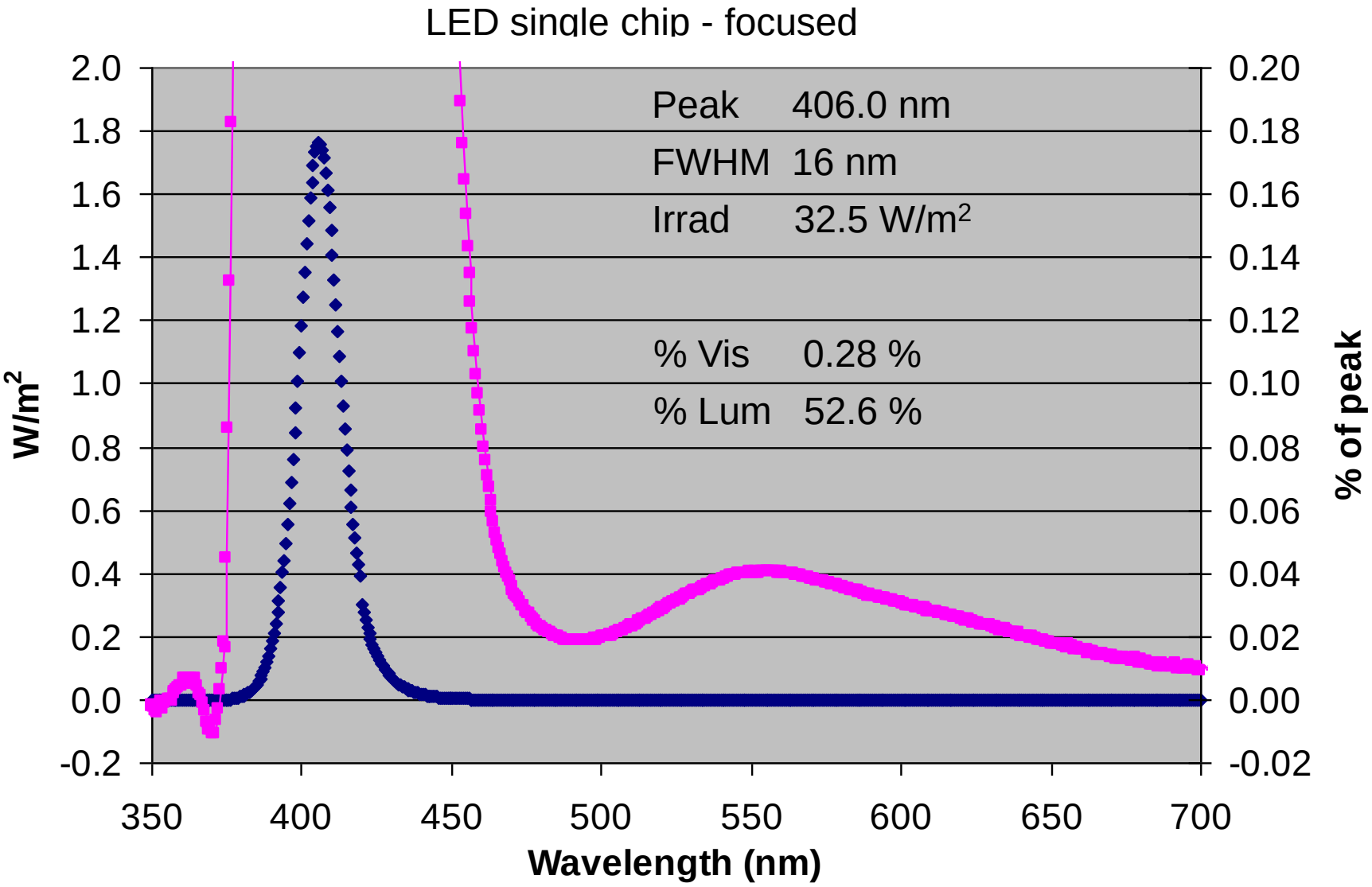
According to ASTM E2630

$$u(\lambda) = 0.58nm \quad \text{and} \quad u_x(R_L^B) = 5.8\%$$

NIST Calibration Service according to ASTM E2630

$$u(\lambda) = 0.05nm \quad \text{and} \quad u_x(R_L^B) = 0.5\%$$

Spectral Out-of-Band Light - Source



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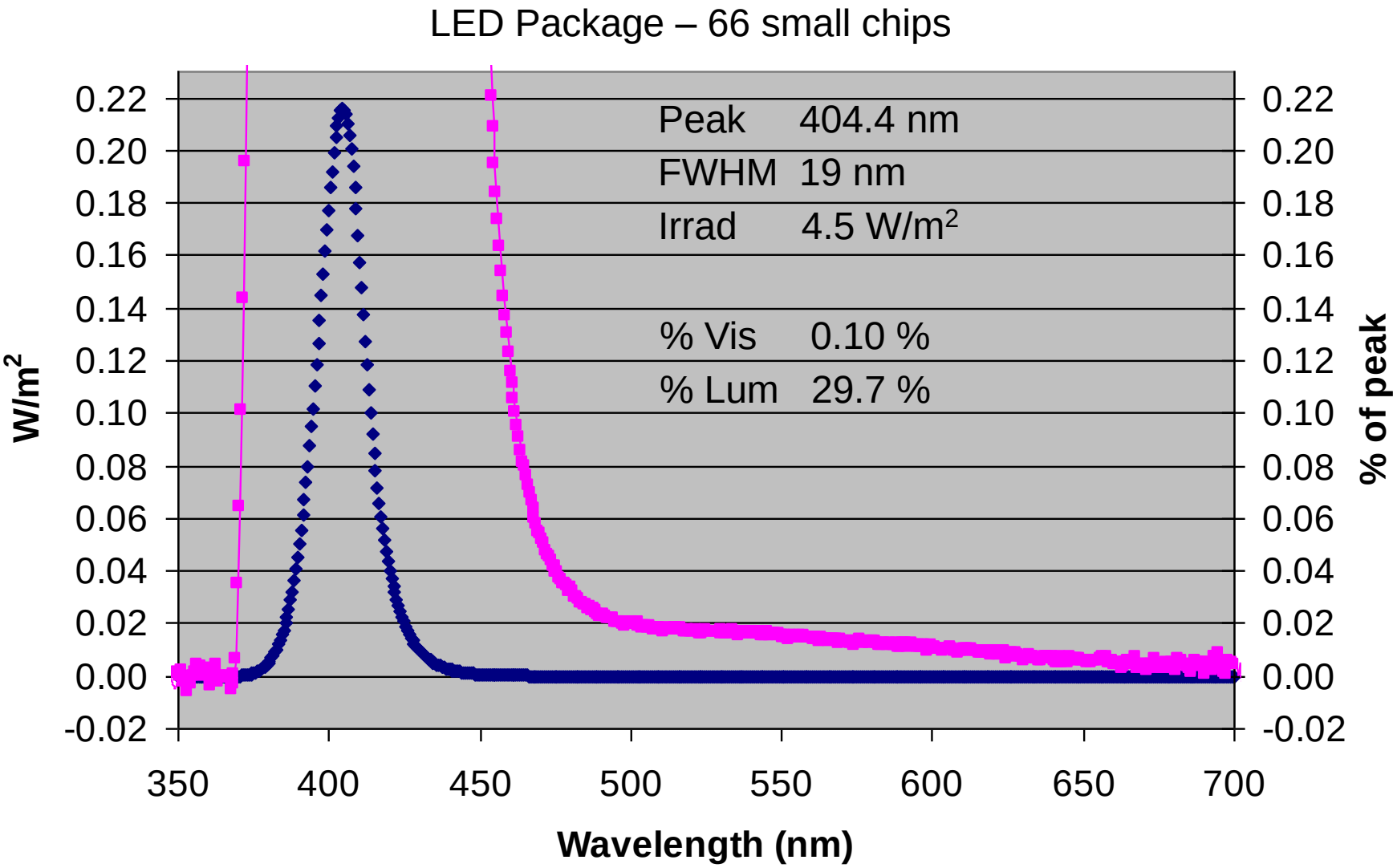

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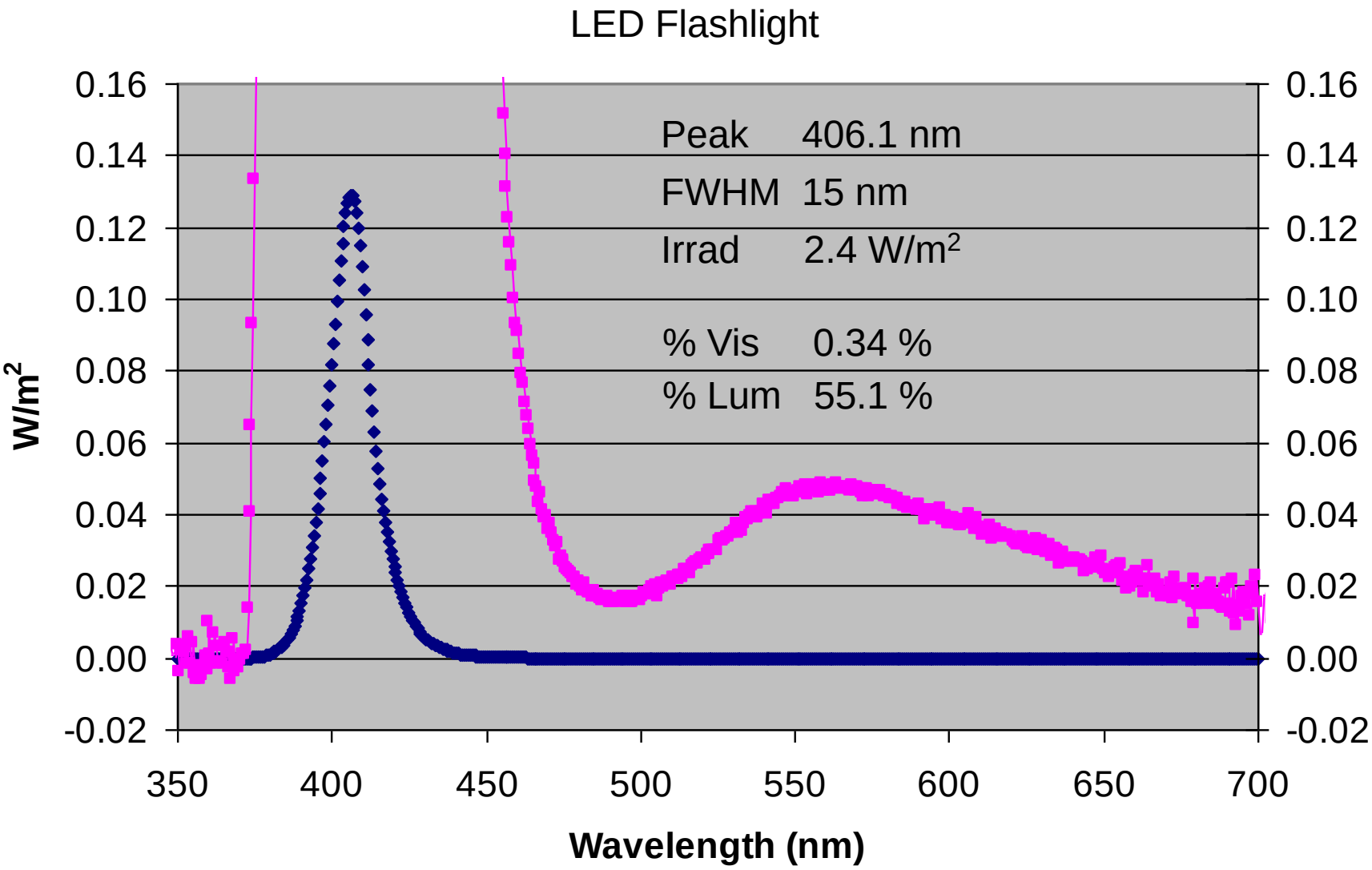

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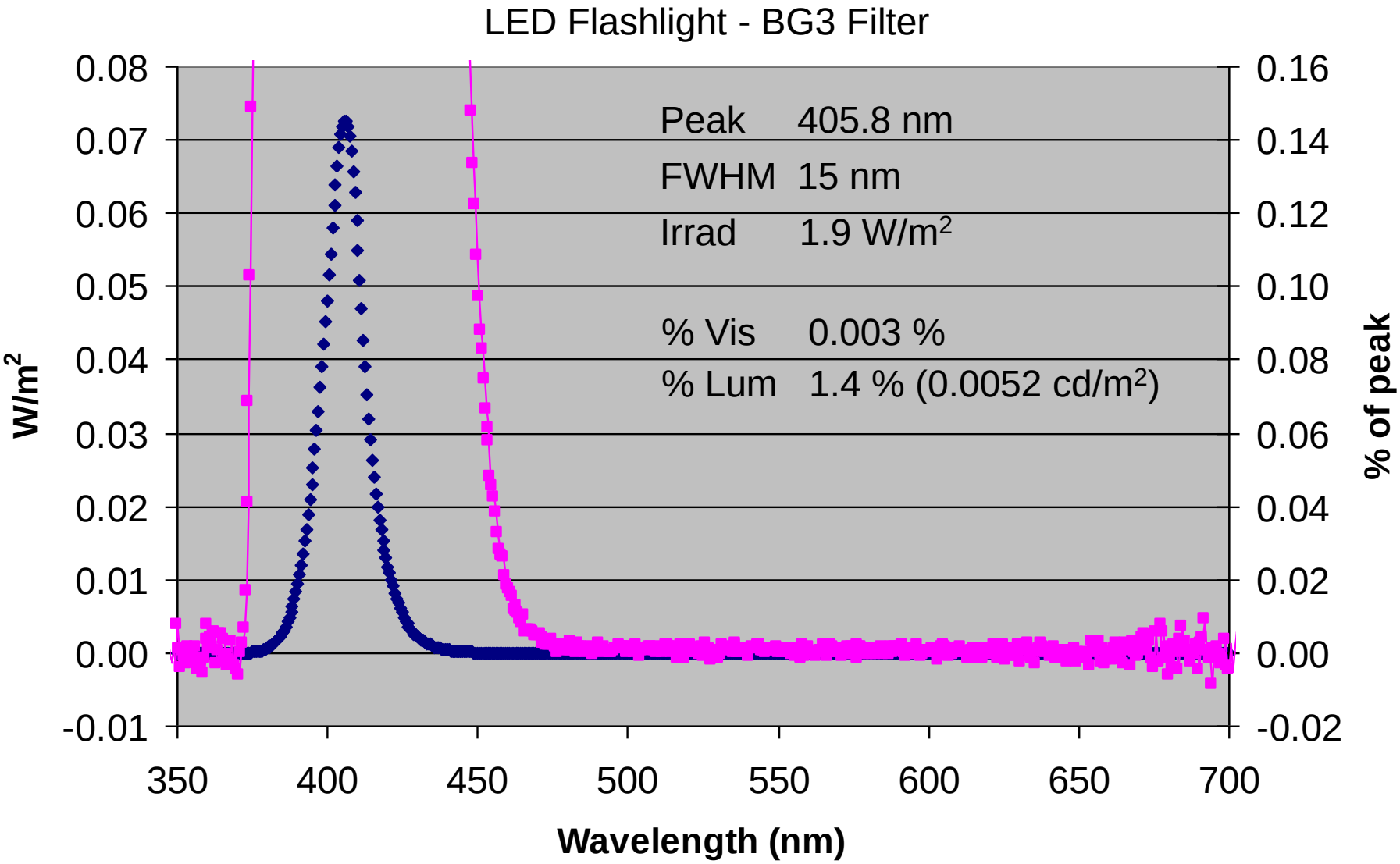

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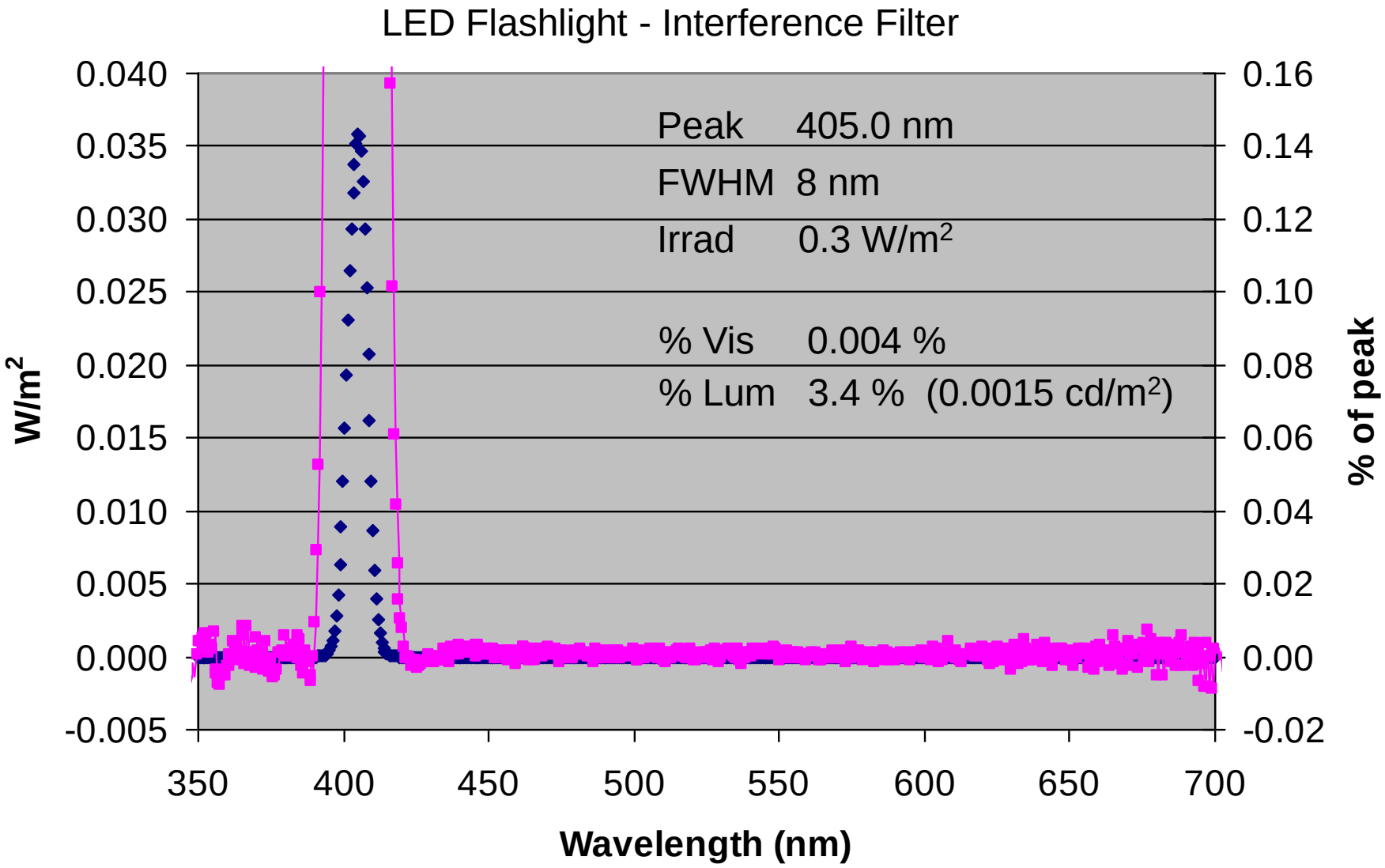

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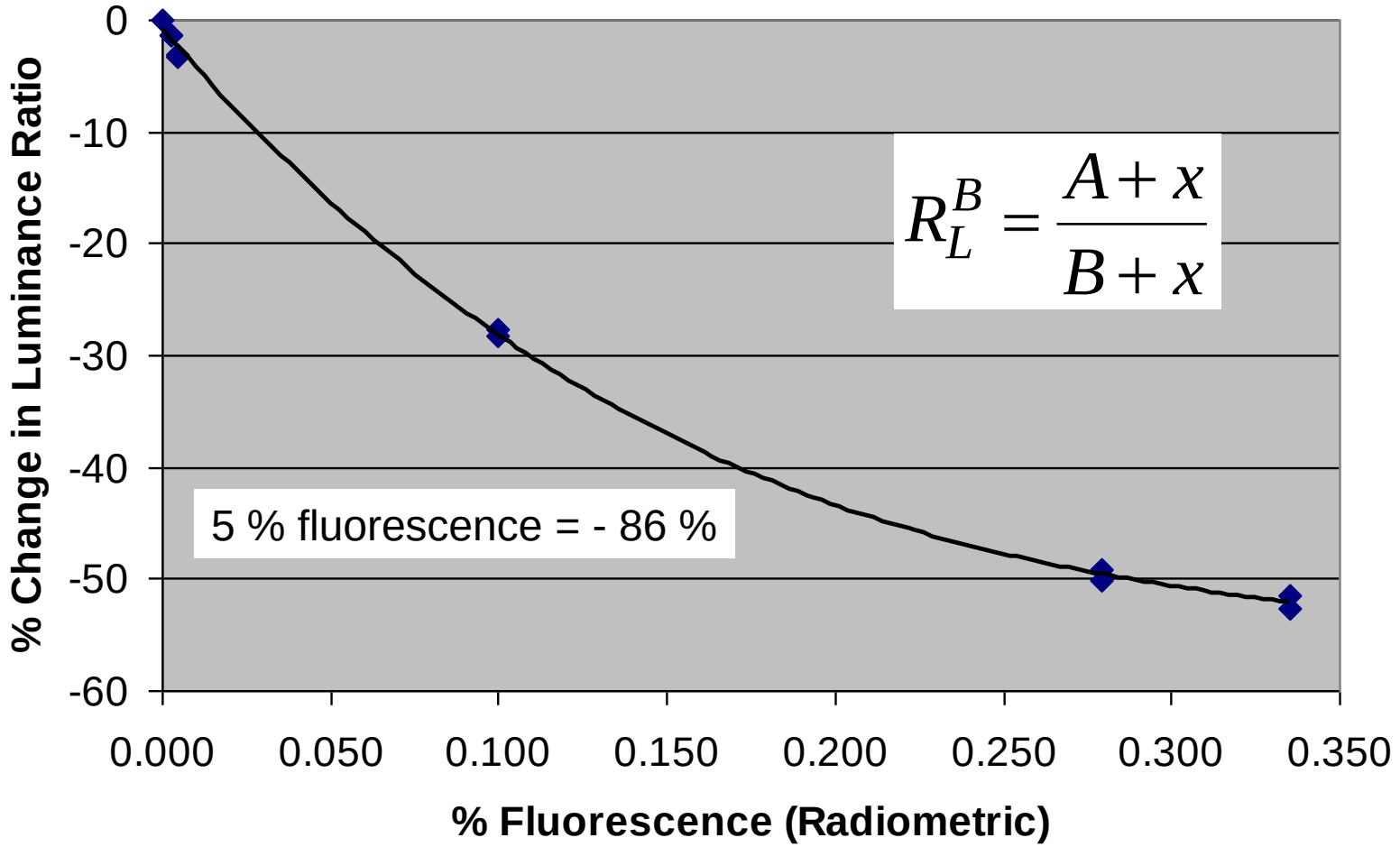
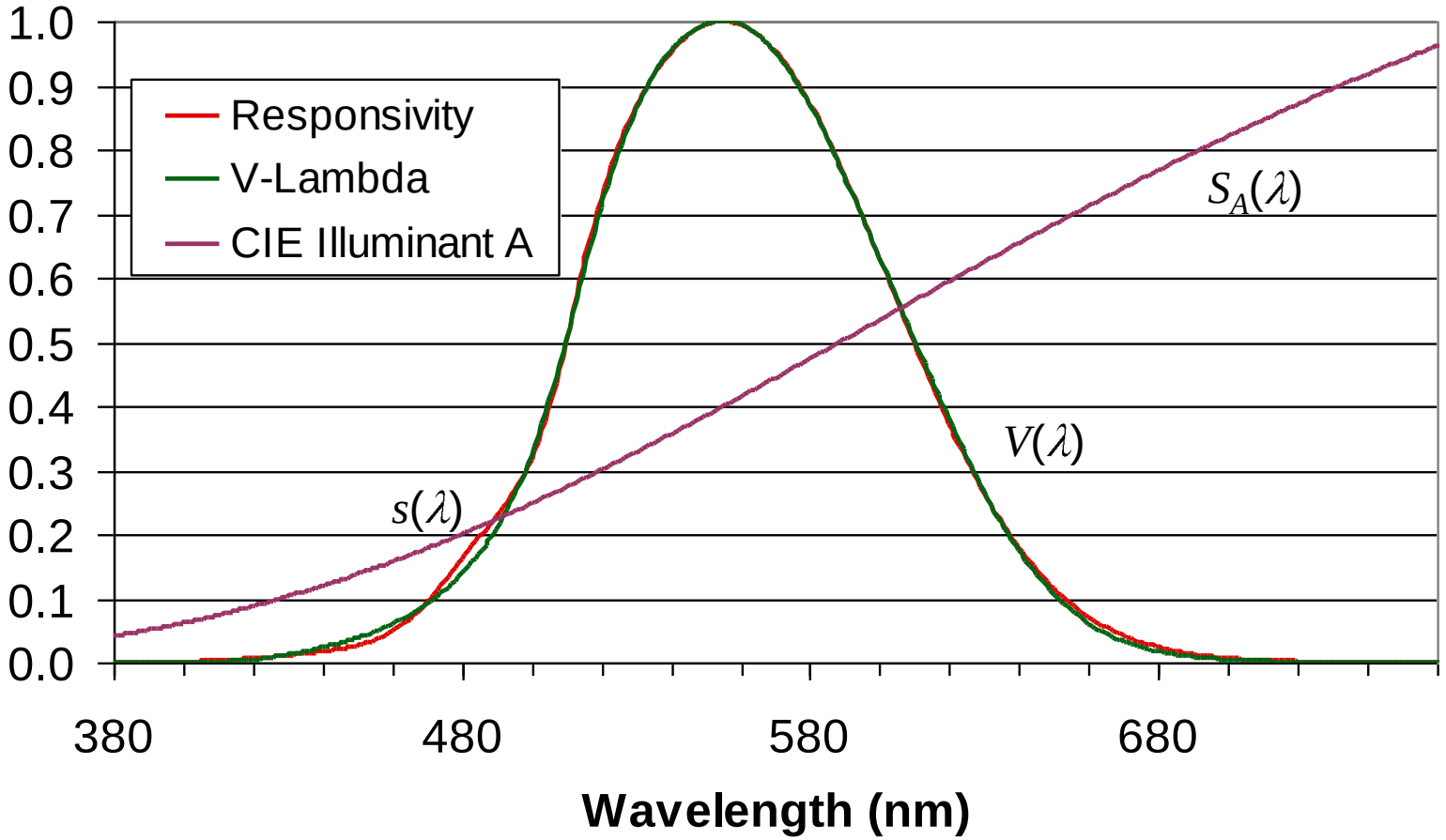


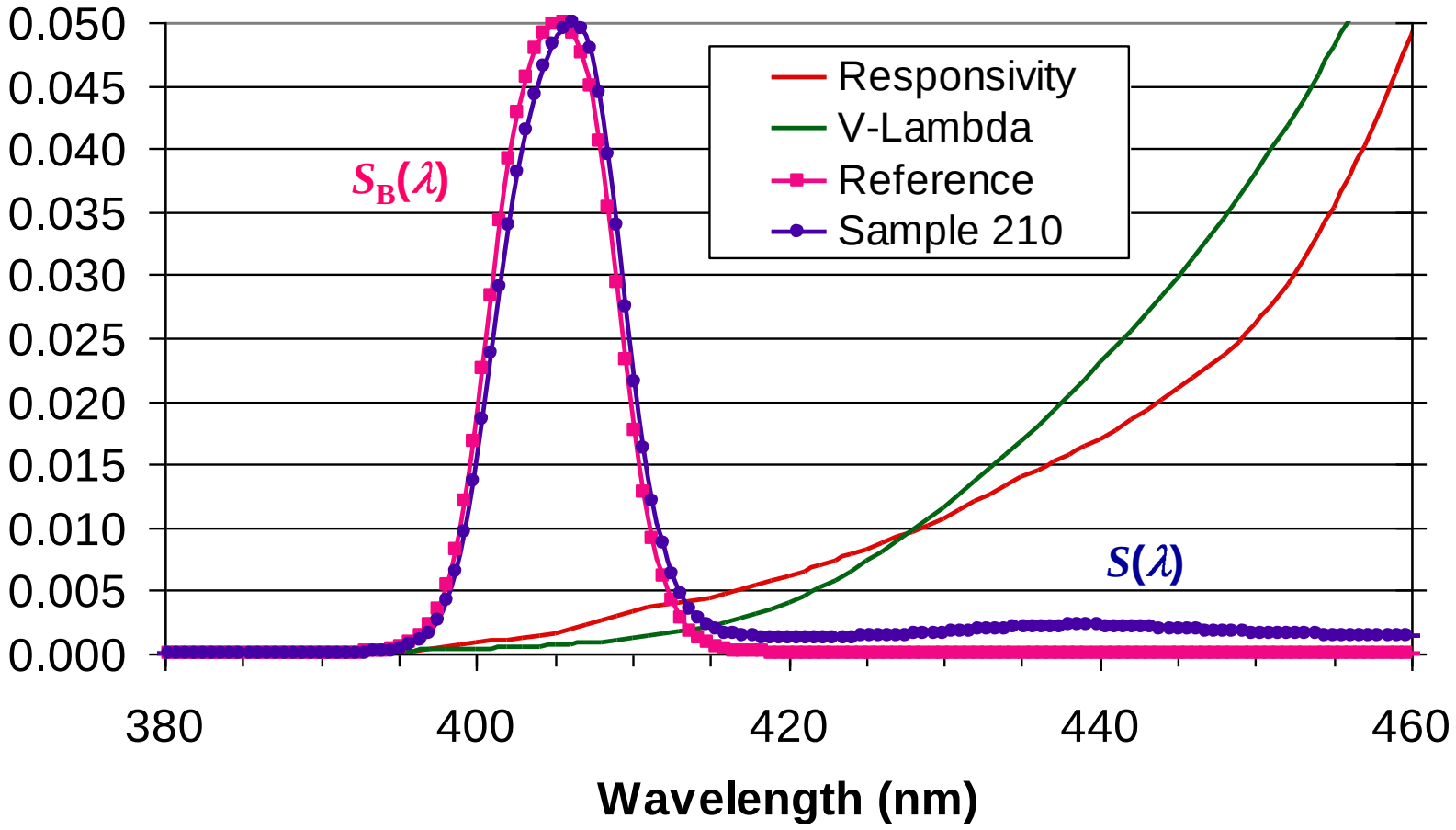
$$\frac{\partial R_L^B}{\partial \lambda_s} = \frac{-340.8\%}{\%\, f} \quad \text{at } 0.005\% \qquad u(\lambda_s) = 0.005\% \quad u_x(R_L^B) = 0.017\%$$

Spectral Mismatch Correction, *F*



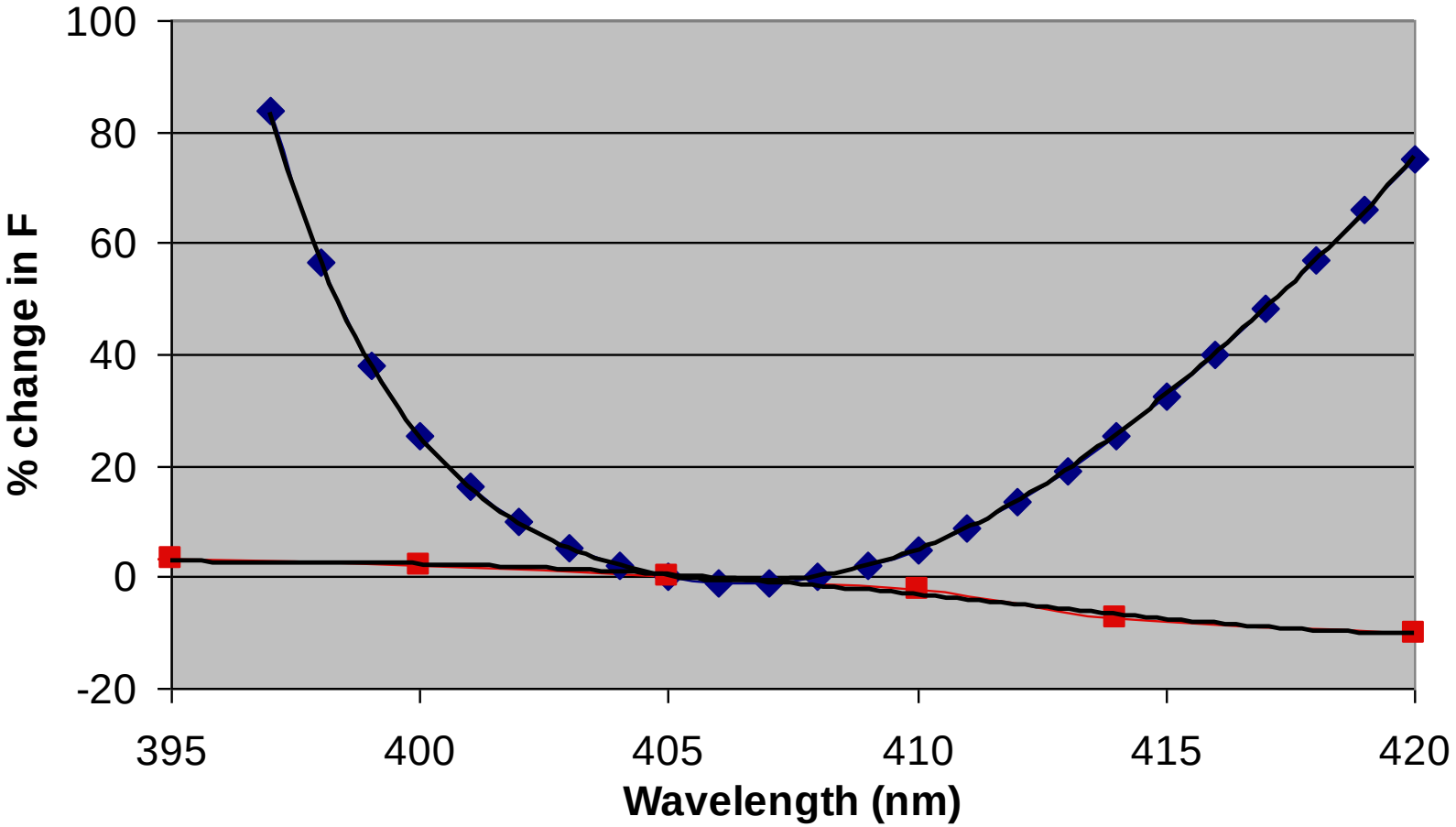
$$F_P = \frac{\int_\lambda S_A \, \underline{s} \, \underline{\mathrm{d}\lambda}}{\int_\lambda S_A \, \underline{V} \, \underline{\mathrm{d}\lambda}} \cdot \frac{\int_\lambda S_B \, \underline{V} \, \underline{\mathrm{d}\lambda}}{\int_\lambda S_B \, \underline{s} \, \underline{\mathrm{d}\lambda}}$$

Spectral Mismatch Correction, *F*



$$F_P = 0.321 \quad F = 0.984$$

Spectral Mismatch Correction



$$\frac{\partial F_P}{\partial \lambda} = \frac{-2.4\%}{nm} \quad \text{and} \quad \frac{\partial F}{\partial \lambda} = \frac{-0.6\%}{nm}$$

Spectral Mismatch Correction

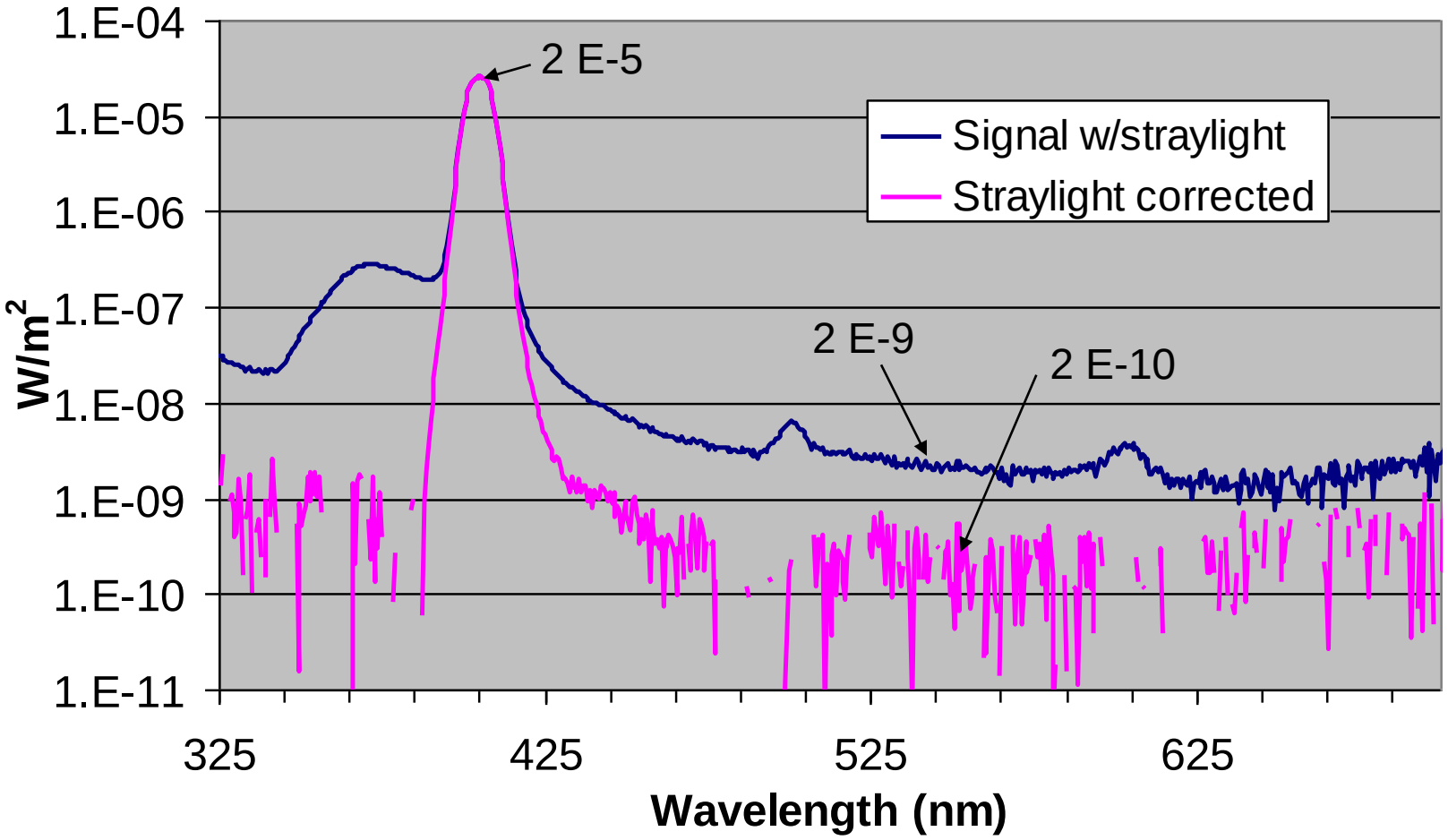
$$\frac{\partial F_P}{\partial \lambda} = \frac{-2.4\%}{nm} \quad \text{and} \quad \frac{\partial F}{\partial \lambda} = \frac{-0.6\%}{nm} \qquad \Delta\lambda = 2\,nm$$

$$u(\lambda) = 0.58nm \quad \text{and} \quad u(F_P) = -1.39\%, u(F) = 0.35\%$$

NIST Calibration Service according to ASTM E2630

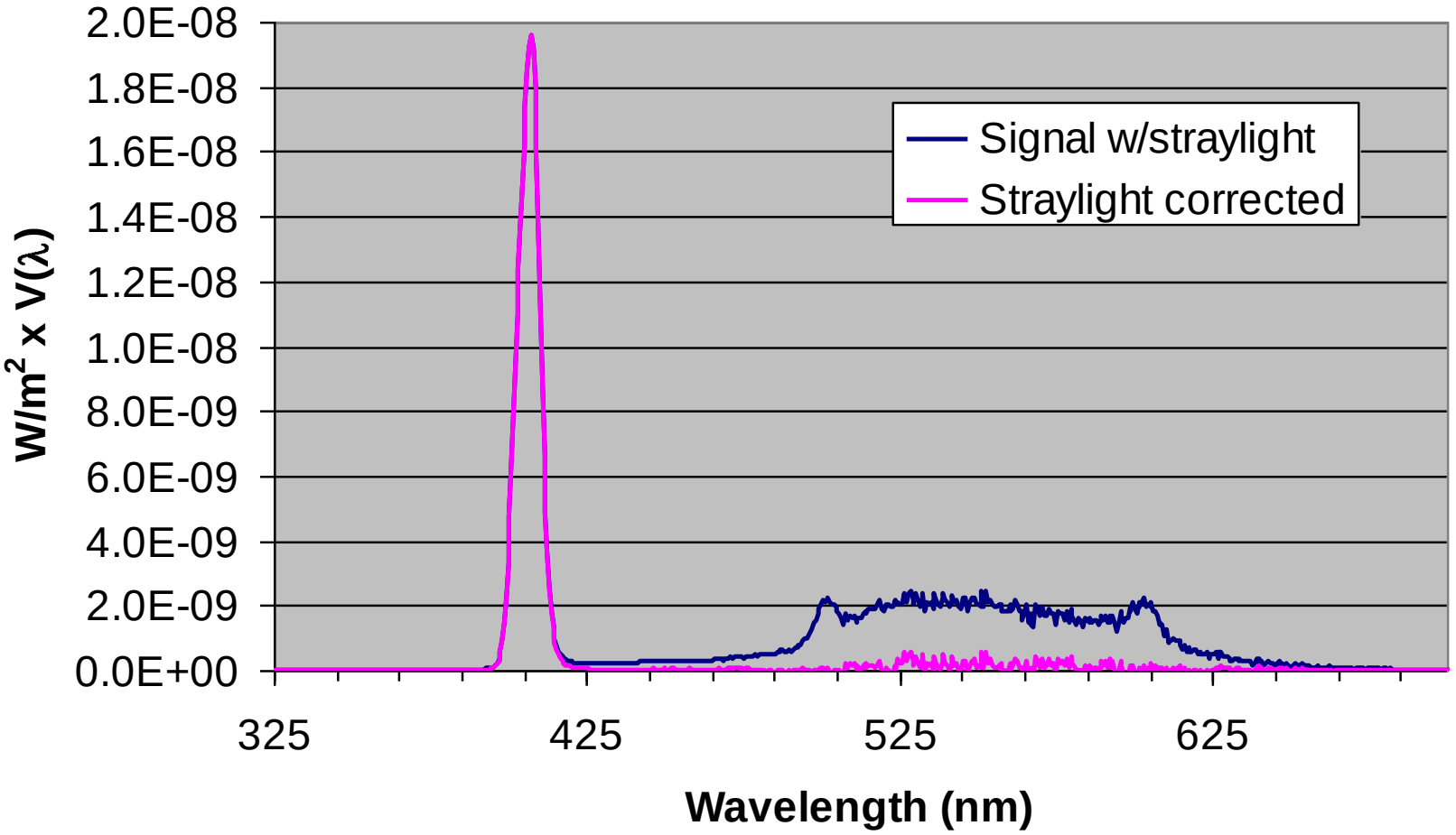
$$u(\lambda) = 0.05nm \quad \text{and} \quad u(F_P) = -0.12\%, u(F) = 0.03\%$$

Out-of-band Stray Light - Detector



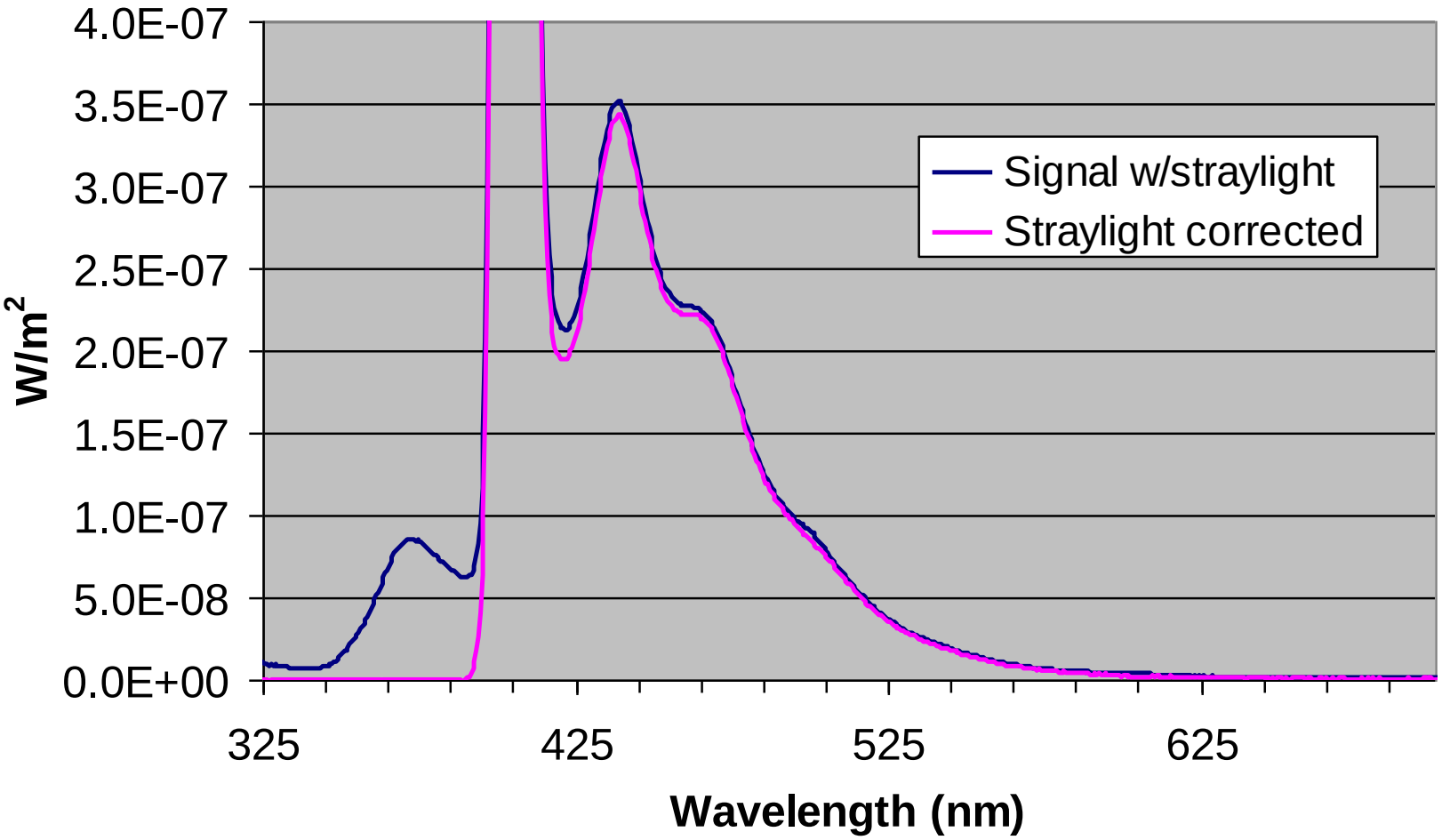
Stray light 0.423 % Corrected 0.036 %

Out-of-band Stray Light - Detector



Straylight $R_L^B = 6.88$ Corrected $R_L^B = 15.23$ 45 %

Out-of-band Stray Light - Detector



$$\frac{\partial R_L^B}{\partial S} = \frac{-511007\%}{\text{Stray Rejection}} \quad \text{at Stray Rejection} = 10^{-5}$$

NIST Uncertainty Budget

Component	Symbol	Value	$u(x_i)$	$\partial R_L{}^B/\partial x_i$	Contribution	%
Sample signal	s	4.2120 V	0.0005 V	3.62 V^{-1}	0.000003	0.01
Sample dark signal	s_d	0.0001 V	0.0005 V	-3.62 V^{-1}	0.000003	0.01
Reference signal	s_P	0.3500 V	0.0001 V	-43.52 V^{-1}	0.000019	0.03
Reference dark signal	$s_{P,d}$	0.0000 V	0.0001 V	43.52 V^{-1}	0.000019	0.03
Spectral mismatch C_f sample	F	0.984	0.001	-15.48	0.000240	0.10
Spectral mismatch C_f reference	F_P	0.321	0.001	47.45	0.002252	0.31
Standard luminance reflectance	ρ_B	0.9700	0.0025	15.70	0.001541	0.26
Excitation wavelength	λ_B	1.0	0.05 nm	-1.52 nm^{-1}	0.005800	0.50
Wavelength correction	C_λ	1.0	0.05 nm	-1.52 nm^{-1}	0.005800	0.50
Illumination bandwidth	$\Delta\lambda_B$	1.0	0.05 nm	0.37 nm^{-1}	0.000334	0.12
Spectral out-of-band light	λ_s	1.0	0.0003	-51.91	0.000002	0.01
Linearity of detector	L	1.0	0.0005	15.23	0.000058	0.05
Out-of-field sensitivity	O	1.0	0.0005	15.23	0.000058	0.05
Voltmeter calibration	c_S	1.0	0.00005	15.23	0.000001	0.01
Illumination angle	ϕ	0.0	0.1	-0.033 /	0.000011	0.02
Viewing angle	θ	45.0	0.1	0.02 /	0.000006	0.02
Luminance Ratio	$R_L{}^B$	**15.23**	**Combined unc.**		**0.13**	
Relative expanded uncertainty		**1.7 %**	**Rel. combined unc.**		**0.8 %**	