CORM 2008

CORM Council for Optical Radiation Measurements

Measuring Light for the Human Circadian System

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June 11, 2008

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Acknowledgements

- John Bullough, PhD
- Mariana Figueiro, PhD
- Dennis Guyon
- Mark Rea, PhD
- Program sponsors

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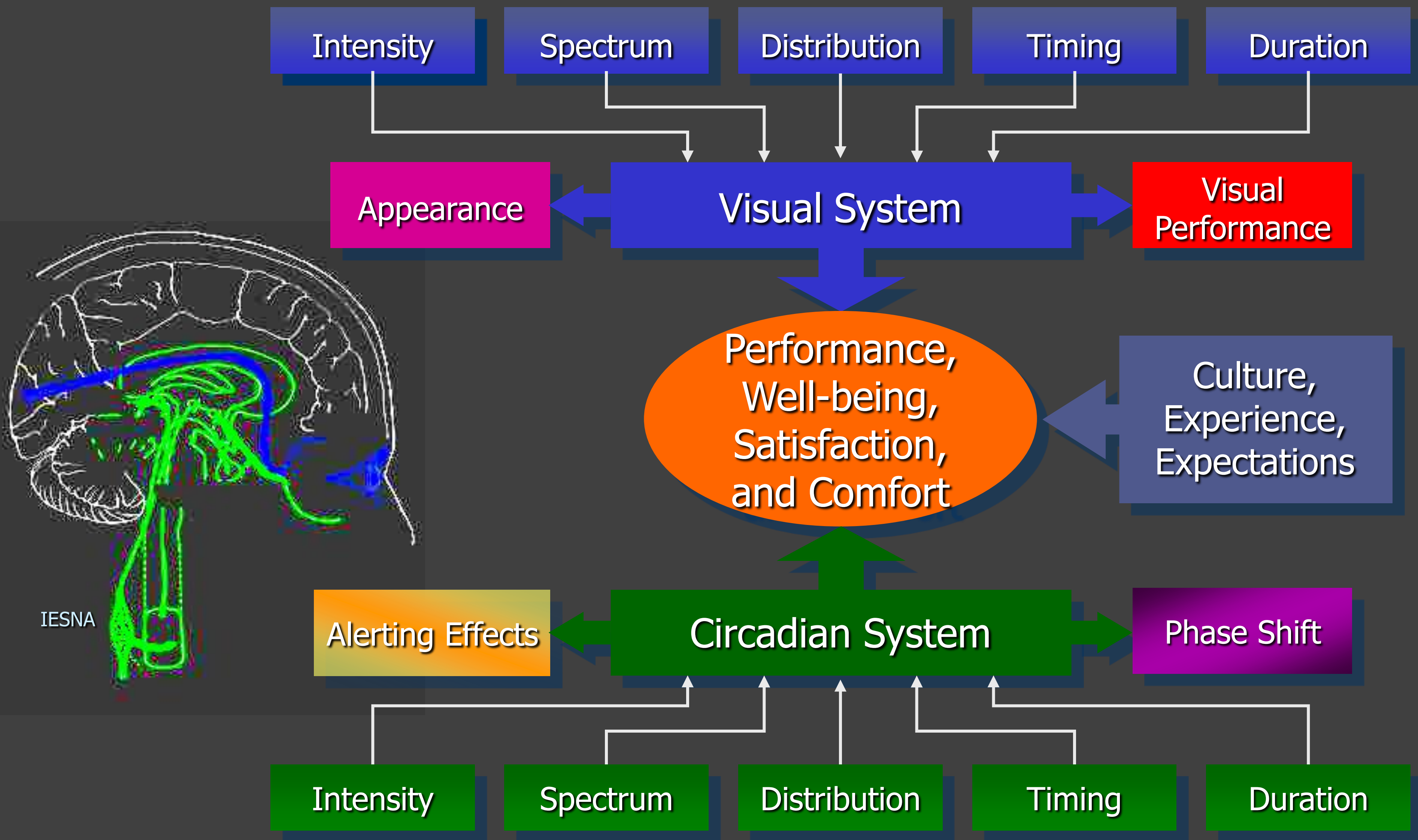
New paradigm for light



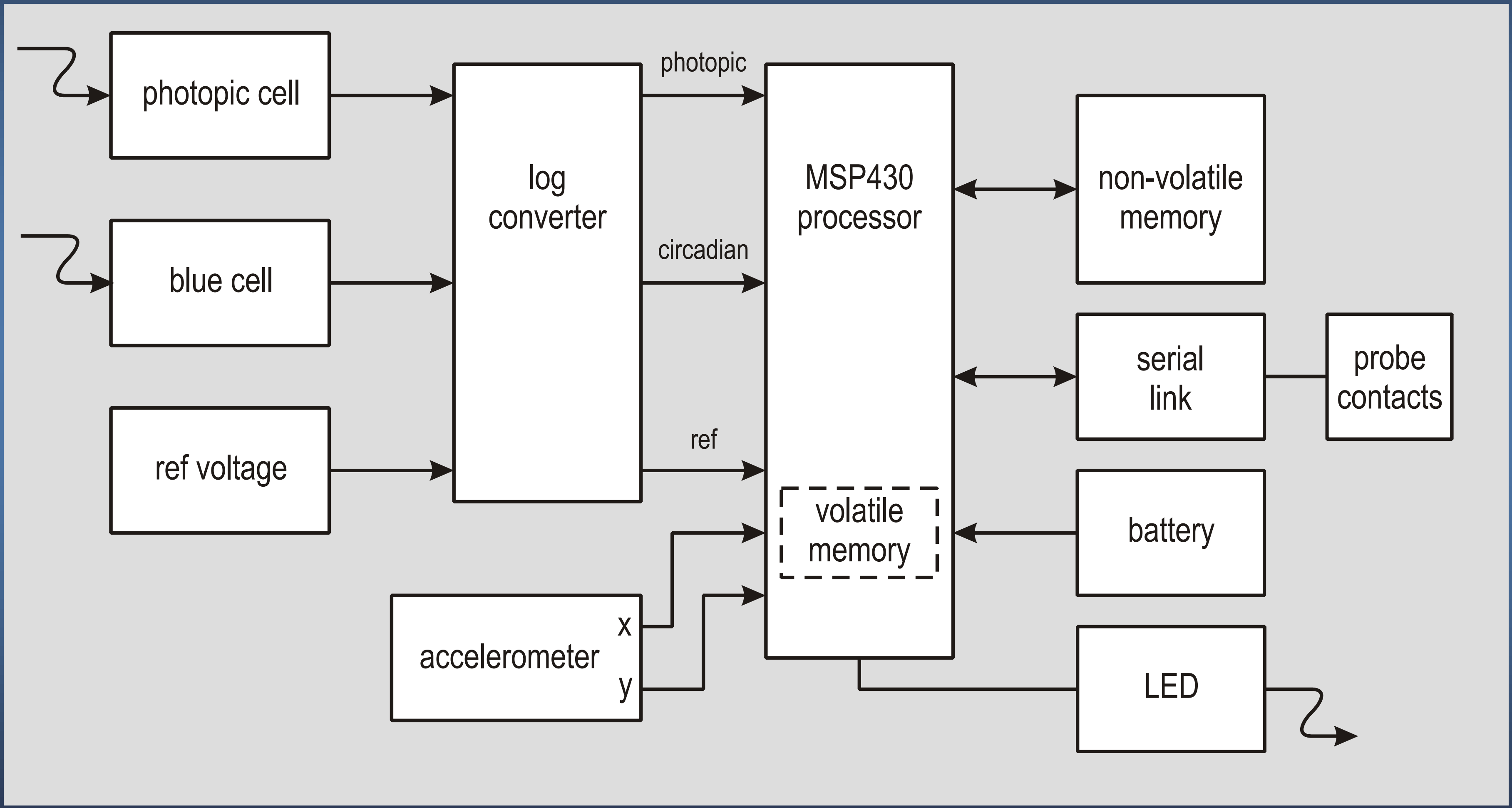
The Daysimeter

- LRC developed an instrument that:
  - Accurately measures retinal light exposures from daylight and electric light as they impact the human circadian system
  - Measures activity
- Instrument's characteristics
  - Lightweight
  - Portable, headset instrument
  - Unobtrusive

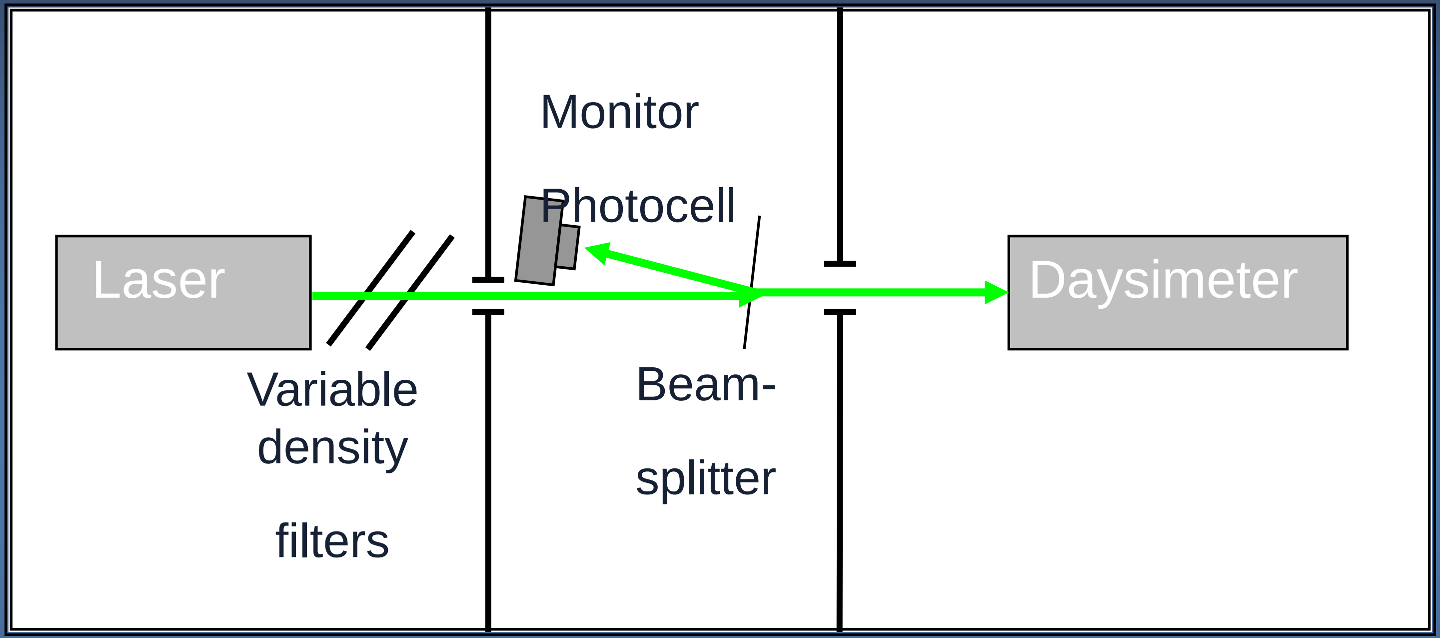
Daysimeter Characteristics

- Two light channels: Photopic and Blue
  - Sensitivity: 1 lux to 100,000 lux
    - Down to < 0.1 lux with degraded accuracy
- 2-axis accelerometer to measure activity
  - Sensitivity ~0.005 g (0.05 m/s^2) to ~5 g (50 m/s^2)
- Sampling rate
  - Samples at 1 Hz
  - For light
    - Logs the mean value over each 30-second period
  - For Activity
    - Logs the squared deviation from the mean over each 30-second period
- Quartz crystal clock keeps track of elapsed time from initial time-stamp
- Sampling size
  - 1 Mb non-volatile memory permits 72 days of continuous data logging at 30-second logging interval (battery life = 30 days)
- Output
  - Serial data interface to PC

Functional Block Diagram

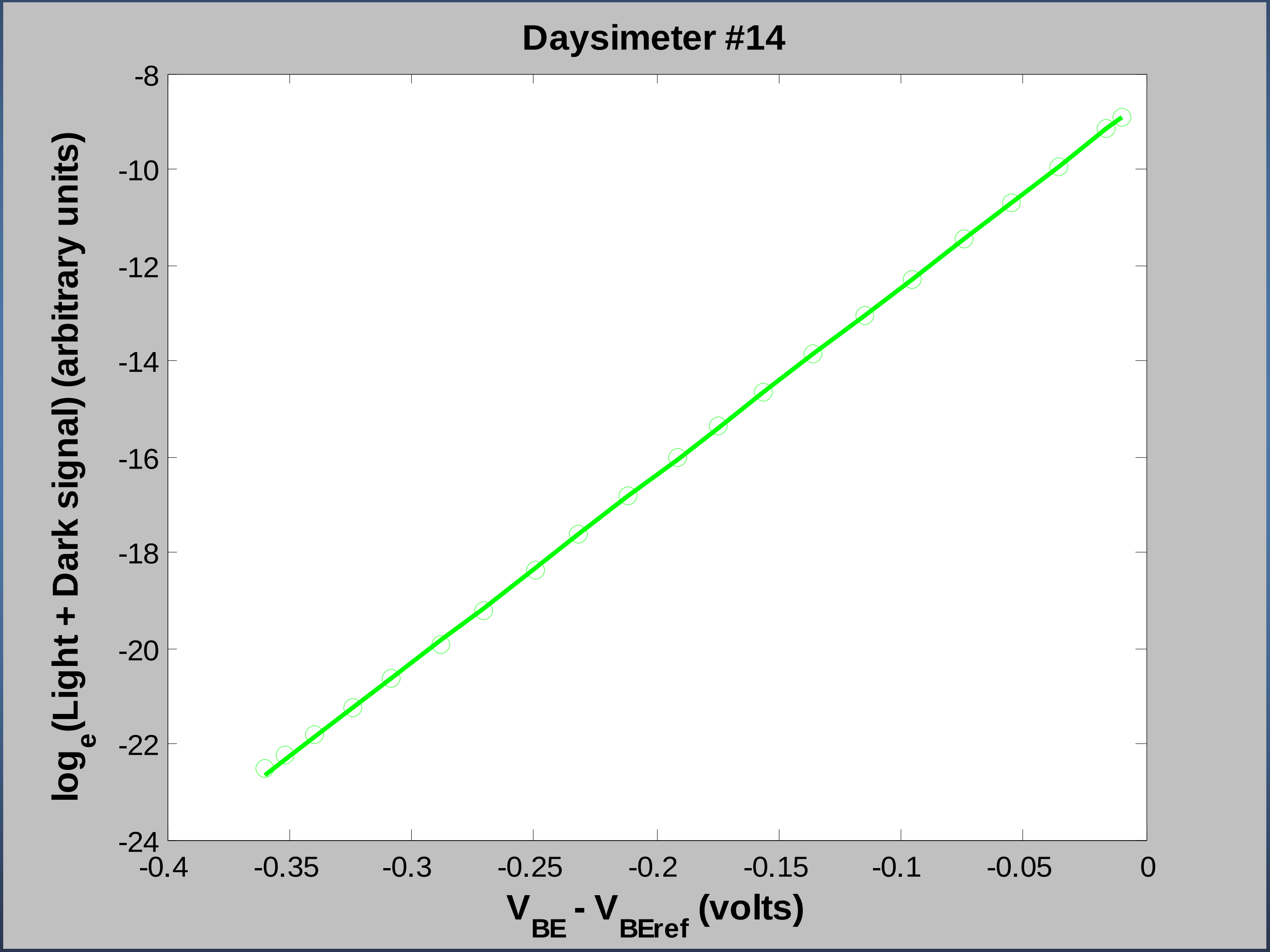


Verifying accuracy over several decades



- Laser illumination isolates intensity response from spectral and spatial changes
- 35 mW laser provides intensity matching direct sunlight

Linearity testing



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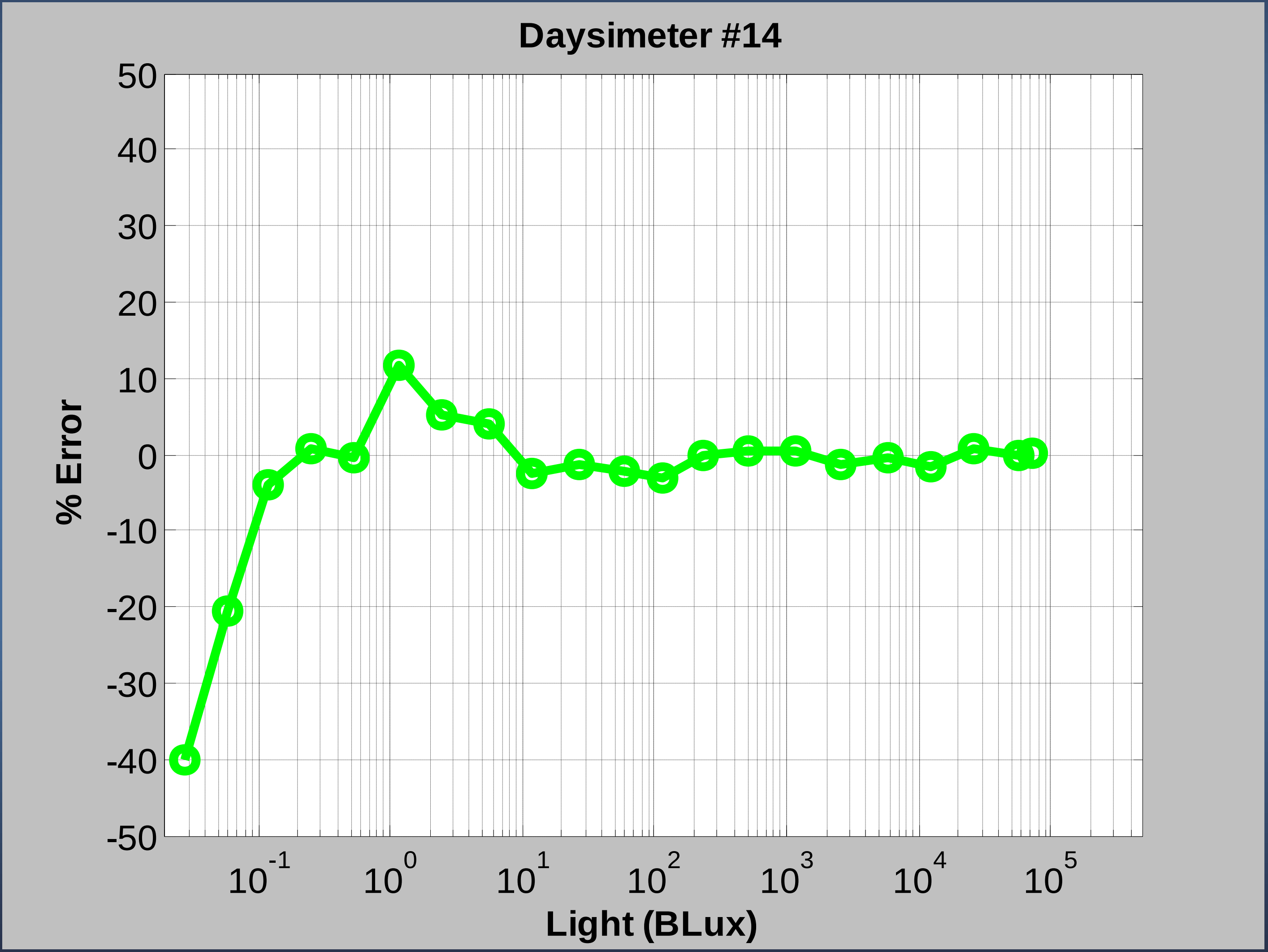
Linearity testing



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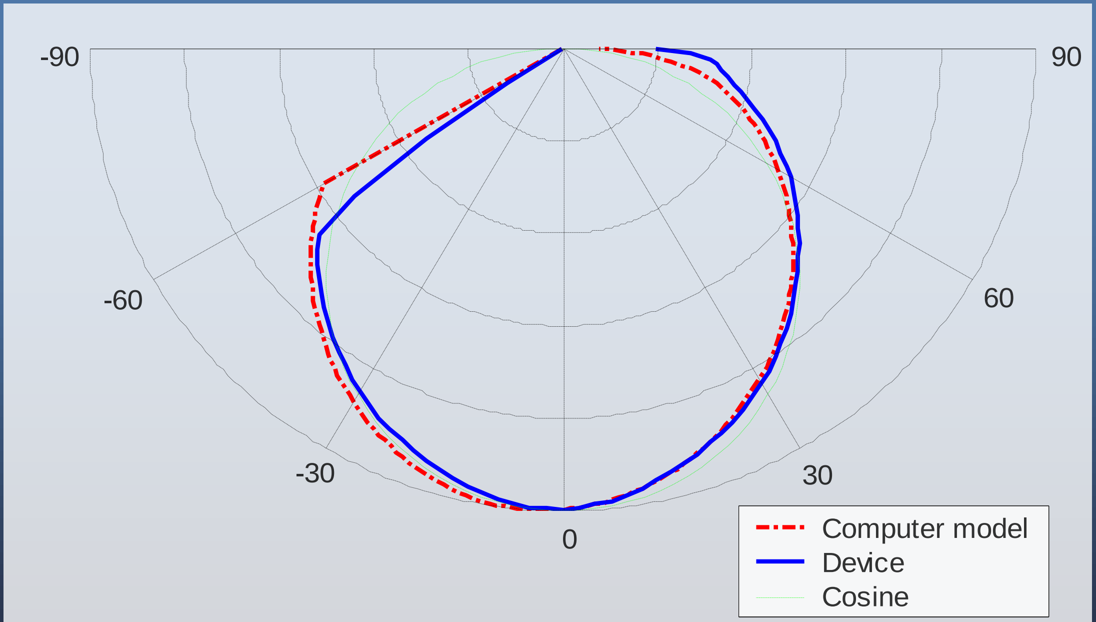
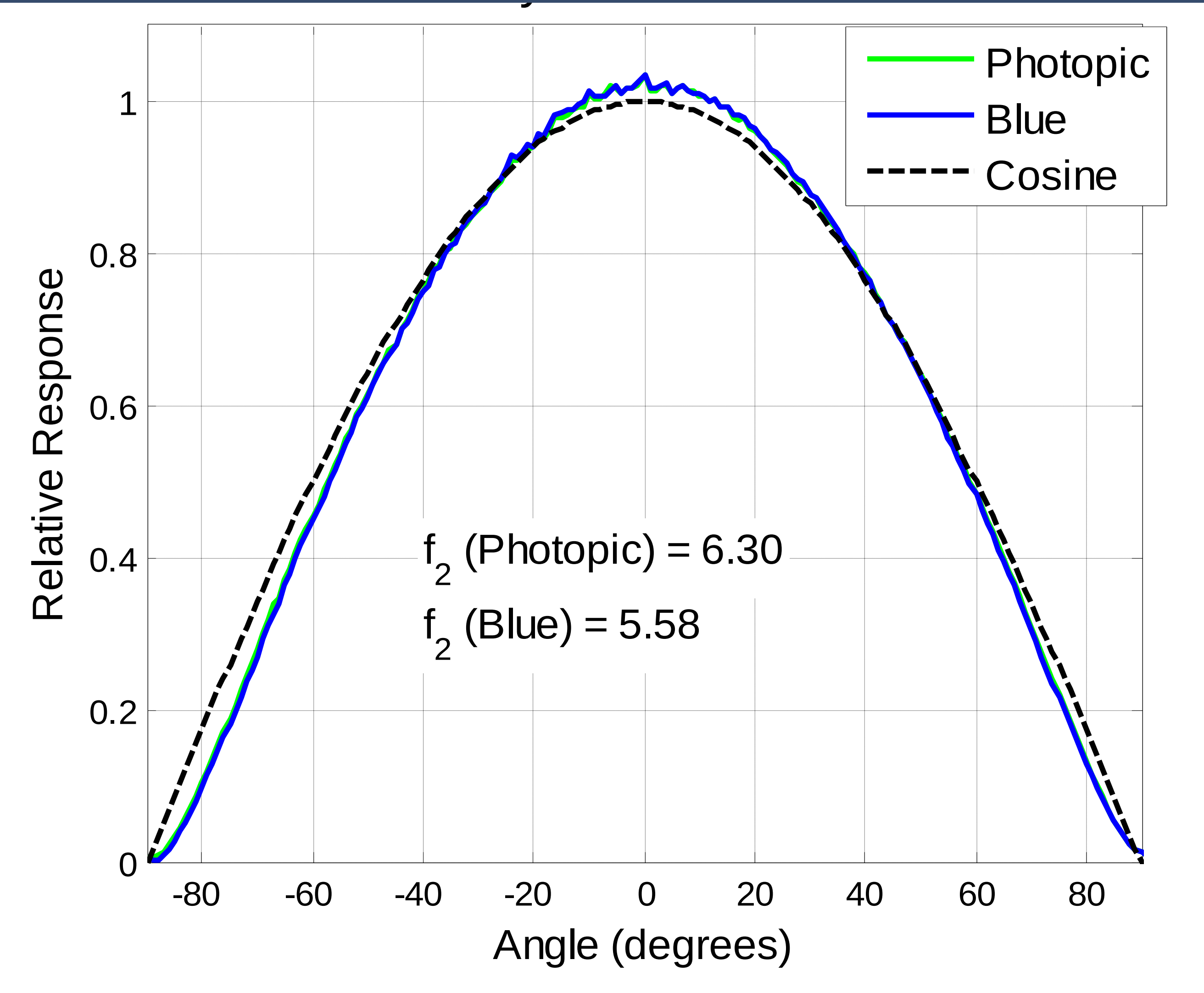
Circadian spatial sensitivity

- ipRGC distributed diffusely throughout retina
- Some evidence for anisotropic retinal sensitivity but, for now assume isotropic
- Retinal flux as a function of viewing angle determined from ray-tracing model of human eye



Daysimeter spatial response

- Flat opal diffuser provides simple solution, yet not ideal



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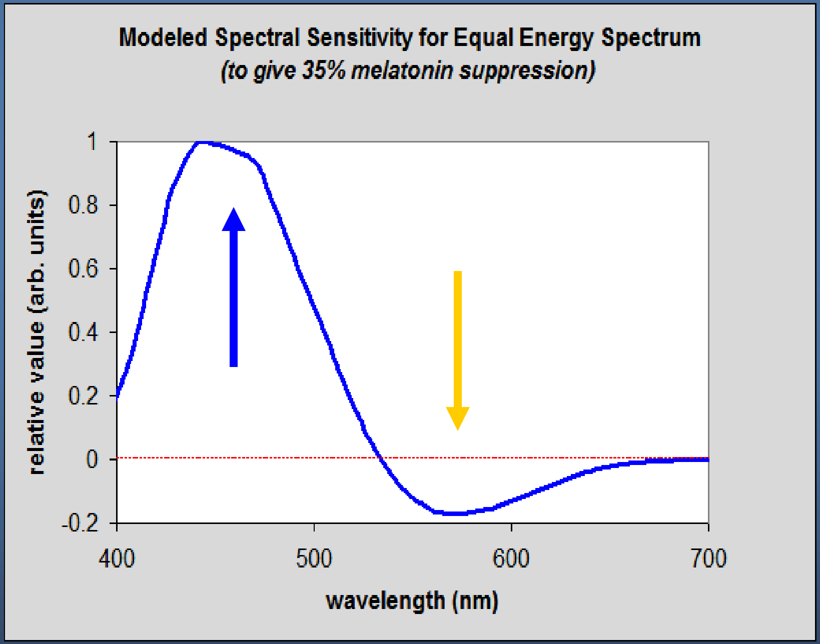
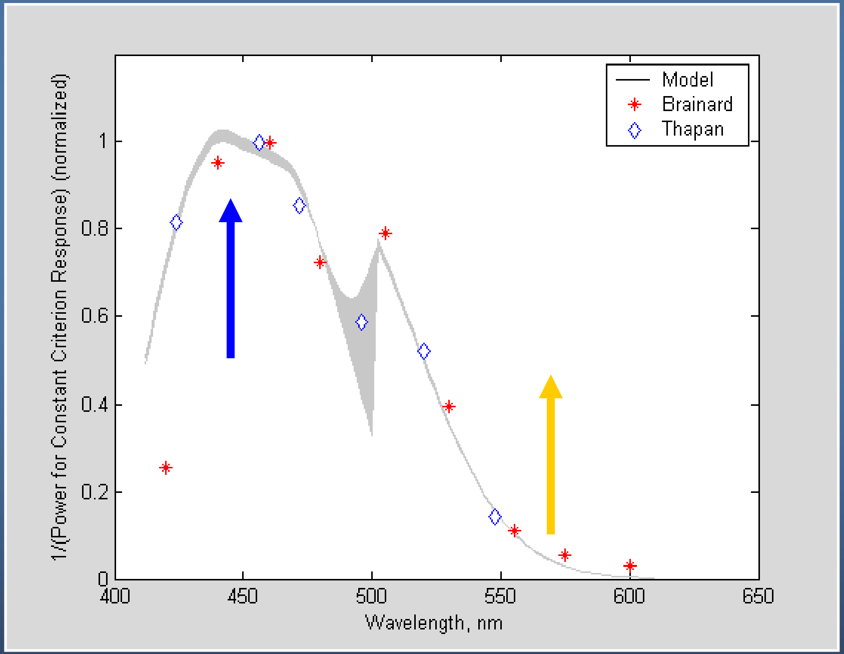
Spectral: the proposed model

- LRC developed and published a model for human circadian phototransduction





Rea et al., 2005; Figueiro et al., 2004

Potential spectral response functions for
(equal energy) white light and for monochromatic light

Model for circadian stimulus (CS)

$$CS = \left[\underbrace{a_1 \int M_\lambda P_\lambda d\lambda - b_1}_{\text{ipRGC}}\right] + \left[a_2 \left(\underbrace{\int S_\lambda P_\lambda d\lambda}_{\text{S-cone}} - k \underbrace{\int V_{10\lambda} P_\lambda d\lambda}_{\text{Photopic}}\right) - b_2\right] - \underbrace{a_3 \left(1 - e^{-\frac{\int V'_\lambda P_\lambda d\lambda}{rodSat}}\right)}_{\text{Rod}}$$

for

$$\underbrace{\int S_\lambda P_\lambda d\lambda}_{\text{S-cone}} - k \underbrace{\int V_{10\lambda} P_\lambda d\lambda}_{\text{Photopic}} \geq 0$$

S-cone - Photopic ≥ 0

$$CS = \underbrace{a_1 \int M_\lambda P_\lambda d\lambda - b_1}_{\text{ipRGC}}$$

for

$$\underbrace{\int S_\lambda P_\lambda d\lambda}_{\text{S-cone}} - k \underbrace{\int V_{10\lambda} P_\lambda d\lambda}_{\text{Photopic}} < 0$$

S-cone - Photopic < 0

CS_A – Scaled for a sense of scale

- $CS_A = 5831 \times CS$
- Scaled to equal 1000 units for 1000 lux CIE Illuminant A (2856 K)
- Generally
  - Higher CCT: CS_A/lux >1
  - Lower CCT: CS_A/lux < 1

Spectrum	CS	CS_A	Illuminance (lux)
Incandescent (A)	0.172	1000	1000
Daylight (D65)	0.344	2004	1000
3500 K RE Fluorescent	0.176	1026	1000
HPS	.0643	375	1000

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CS_A is not linear with irradiance

	Illuminance (lux)			
Spectrum	10	100	1 000	10 000
Incandescent (A)	0	47	1 000	10 500
Daylight (D65)	0	134	2 004	25 240
3500 K RE Fluorescent	0	50	1 026	10 790
HPS	0	0	375	4 273

- Rod inhibition is reduced at higher irradiance levels
- Photoreceptor thresholds affect lower ranges
- Amount of reduction depends on spectrum
  - Varying amounts of spectral opponency

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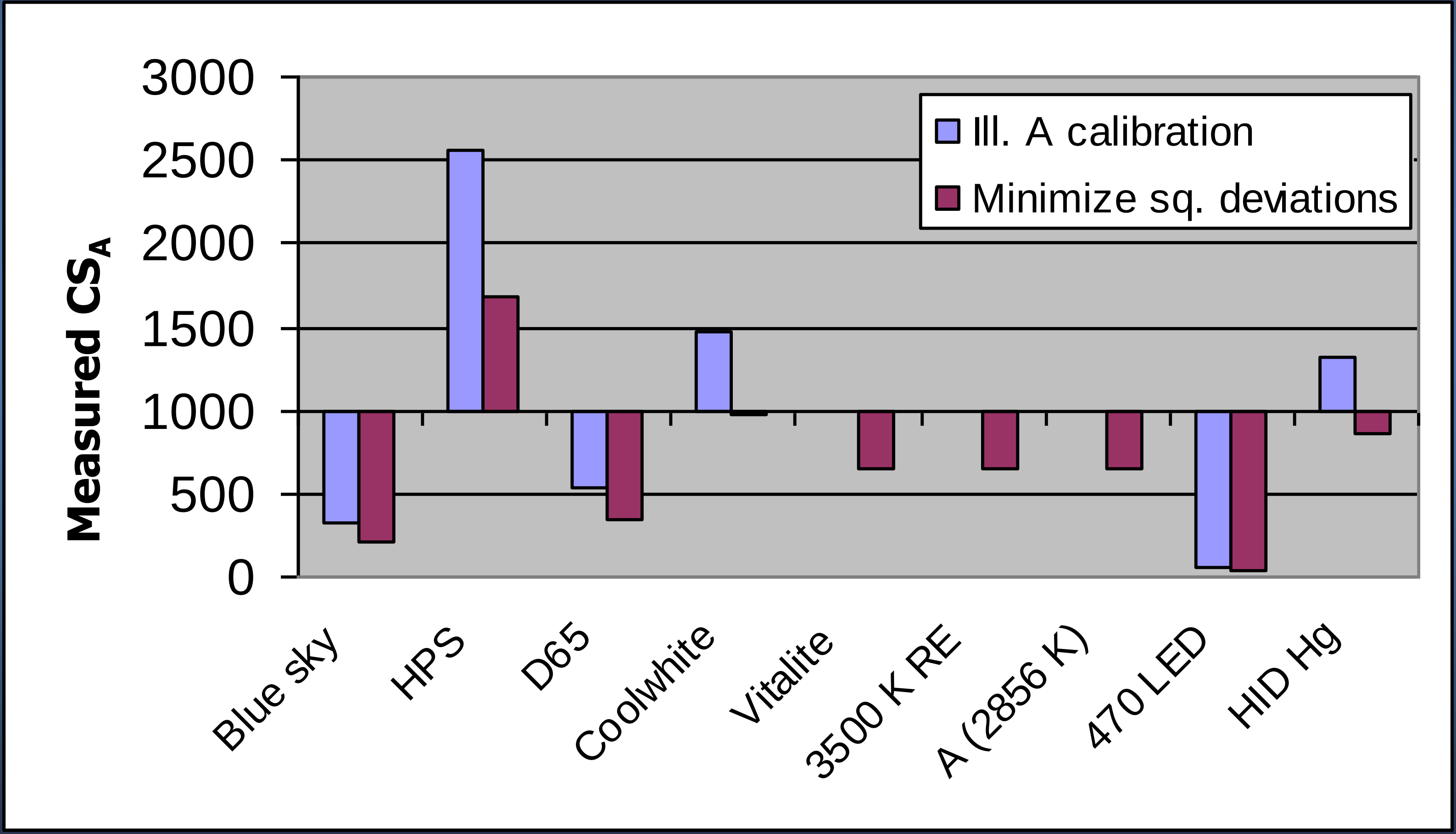
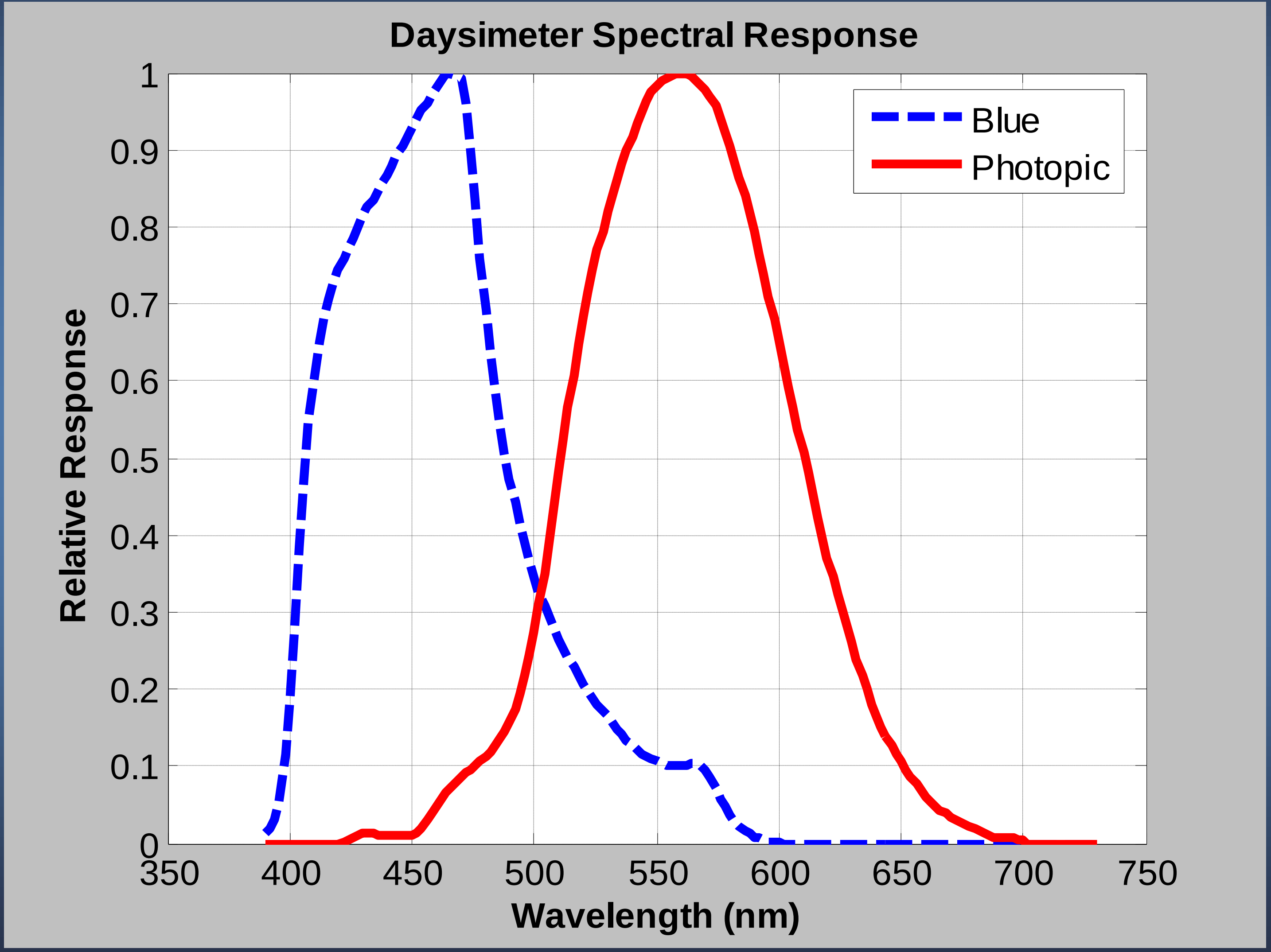
Measuring CS_A with a 1-sensor system

Photopic sensor: measuring sources at 1000 CS_A units



Daysimeter spectral response



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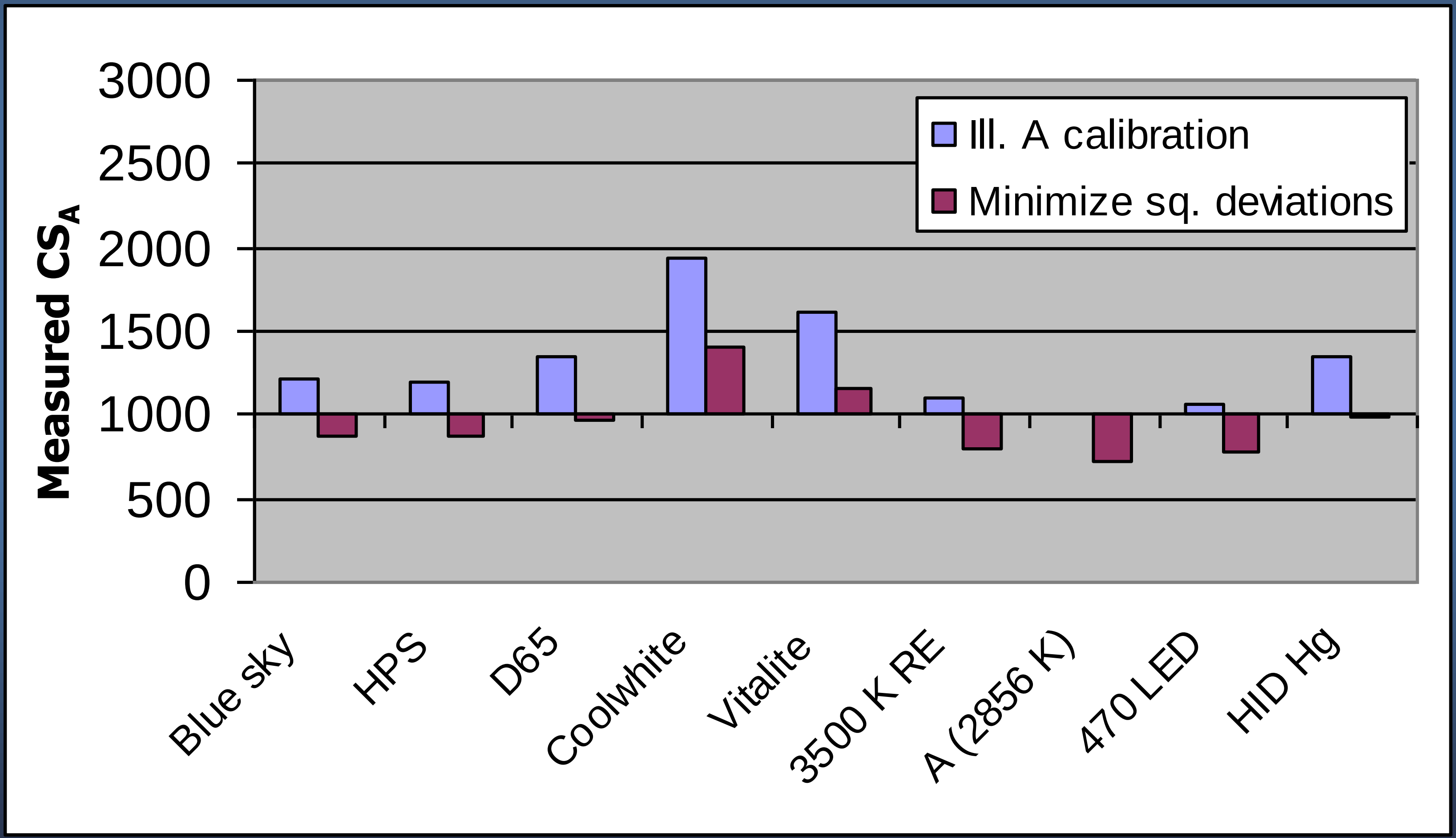
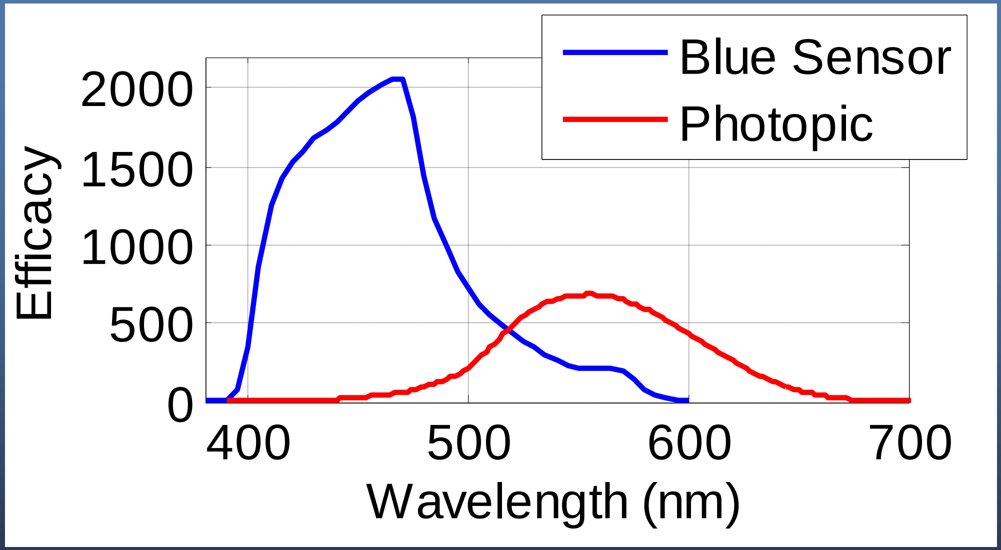
Measuring CS_A with a 1-sensor system

"Blue" sensor (GaAsP cell with 400 nm long-pass filter)



How to measure "Blue" response?

- The blue sensor is not precisely matched to any efficiency function
- The blue sensor signal is only an intermediate response used to calculate the circadian stimulus
- Create a unit equal to lux for CIE Illuminant A (2856 K) irradiance: "Blux"



$$\int A_\lambda V_\lambda d\lambda = \int A_\lambda B_\lambda d\lambda$$

CS_A from 2-sensor Daysimeter

Calculation approximating circadian stimulus

if Blue > (x0)Photopic

CS = (x1)Blue – (x2)Photopic;

else

CS = (x3)Blue + (x4)Photopic;

x0	x1	x2	x3	x4
1.184	0.9866	0.6155	1.020	-0.085

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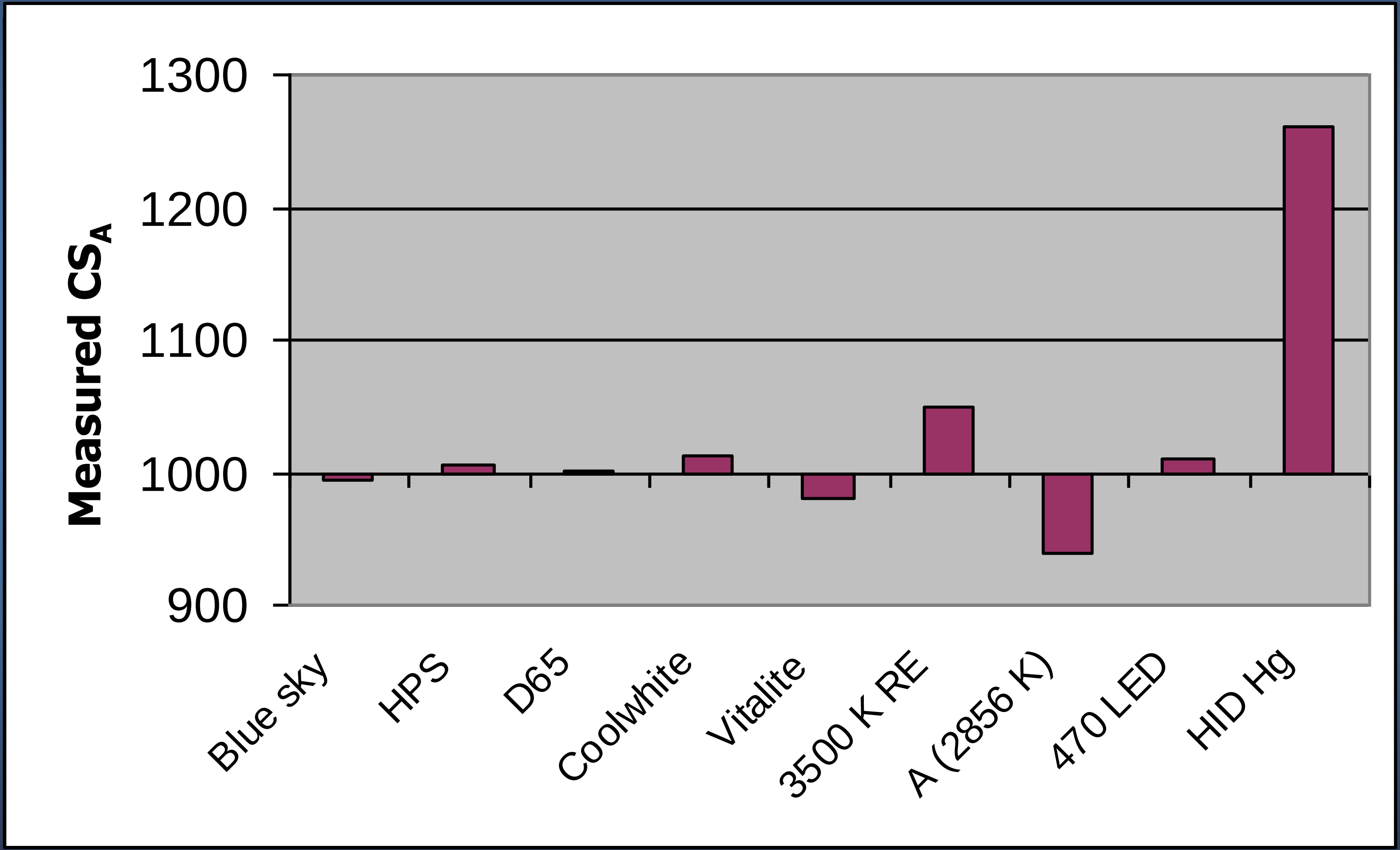
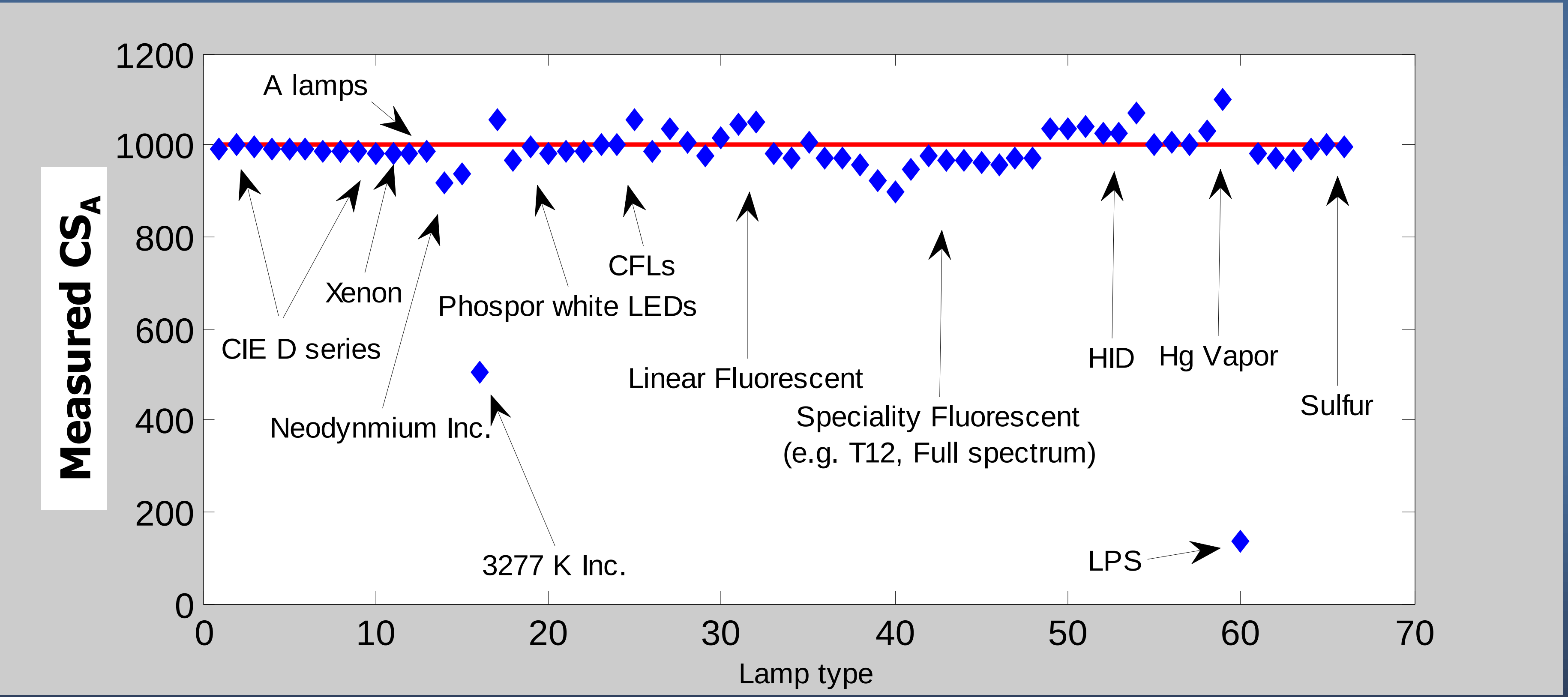
Measuring CS_A with a 2-sensor system

- Photopic + Blue sensor: measuring sources at 1000 CS_A units



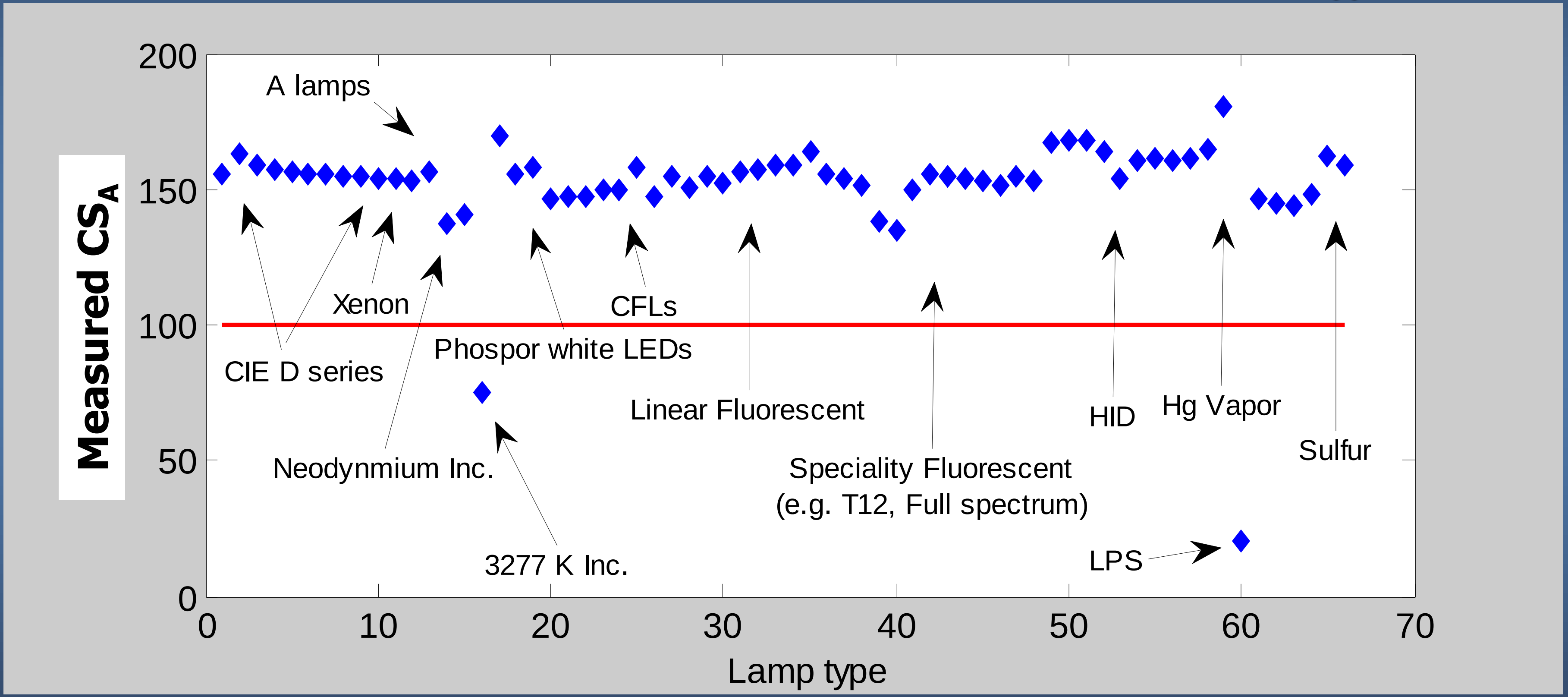
Measuring CS_A with a 2-sensor system

Photopic + Blue sensor: measuring sources at 1000 CS_A units



Measuring CS_A with a 2-sensor system

Photopic + Blue sensor: measuring sources at 100 CS_A units



Need to modify CS_A for non-linear response, e.g. $CS_A = \left(1 - e^{-\alpha CS_A}\right) CS_A$

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Summary

- Ecological studies on people's circadian-effective light exposure require a small, wearable measurement device
  - Temporal
    - Time information needed to calculate dose
    - Collection of measurements over relatively long periods (days) is necessary for entrainment/rhythm studies
  - Intensity
    - Measurement range from 1 to 100 000 lux
  - Spatial
    - Measure light available to the retina: cosine approximation
  - Spectral
    - A two-sensor device can well approximate the 4-photoreceptor spectral model for most light sources

Thank you!

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