

Spectral calibration of HDR Photography



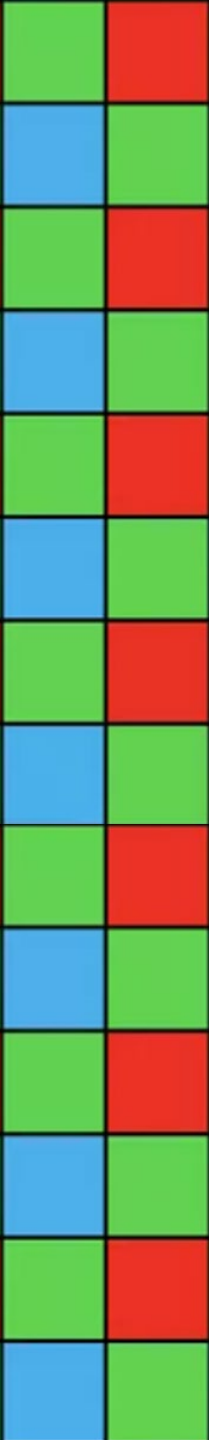
Mehlika Inanici¹ and Martine Knoop²

¹University of Washington, Department of Architecture

²Technische Universität Berlin, Faculty of Electrical Engineering and Computer Science

¹inanici@uw.edu ²martine.knoop@tu-berlin.de





Outline

1. HDR Workflow for luminance measurements
2. Previous work on color measurements with HDR photography
3. Color calibration and testing setups
4. HDR generation methods tested
5. Results
6. Concluding remarks

HDR Photography workflow for luminance measurements

Field measurements:

- Aperture size: f/11
- Shutter speed: varies
- White balance: daylight
- ISO: 100
- Luminance meter to measure a grey card in the scene
- Illuminance meter to measure the illuminance at the lens

Photosphere: Released by Greg Ward in 2004

- Camera response curve is generated with a sample scene and used for all subsequent merges
- Images are saved in .hdr format

Post-processing:

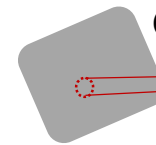
- Vignetting Correction
- Geometric Correction
- Luminance calibration with luminance measurement
- Luminous overflow correction with illuminance measurement (Multi-exposure sequence with f/11 captures approximately 1,000,000 cd/m² as max)



Camera mounted on a sturdy tripod



fisheye lens



Grey card



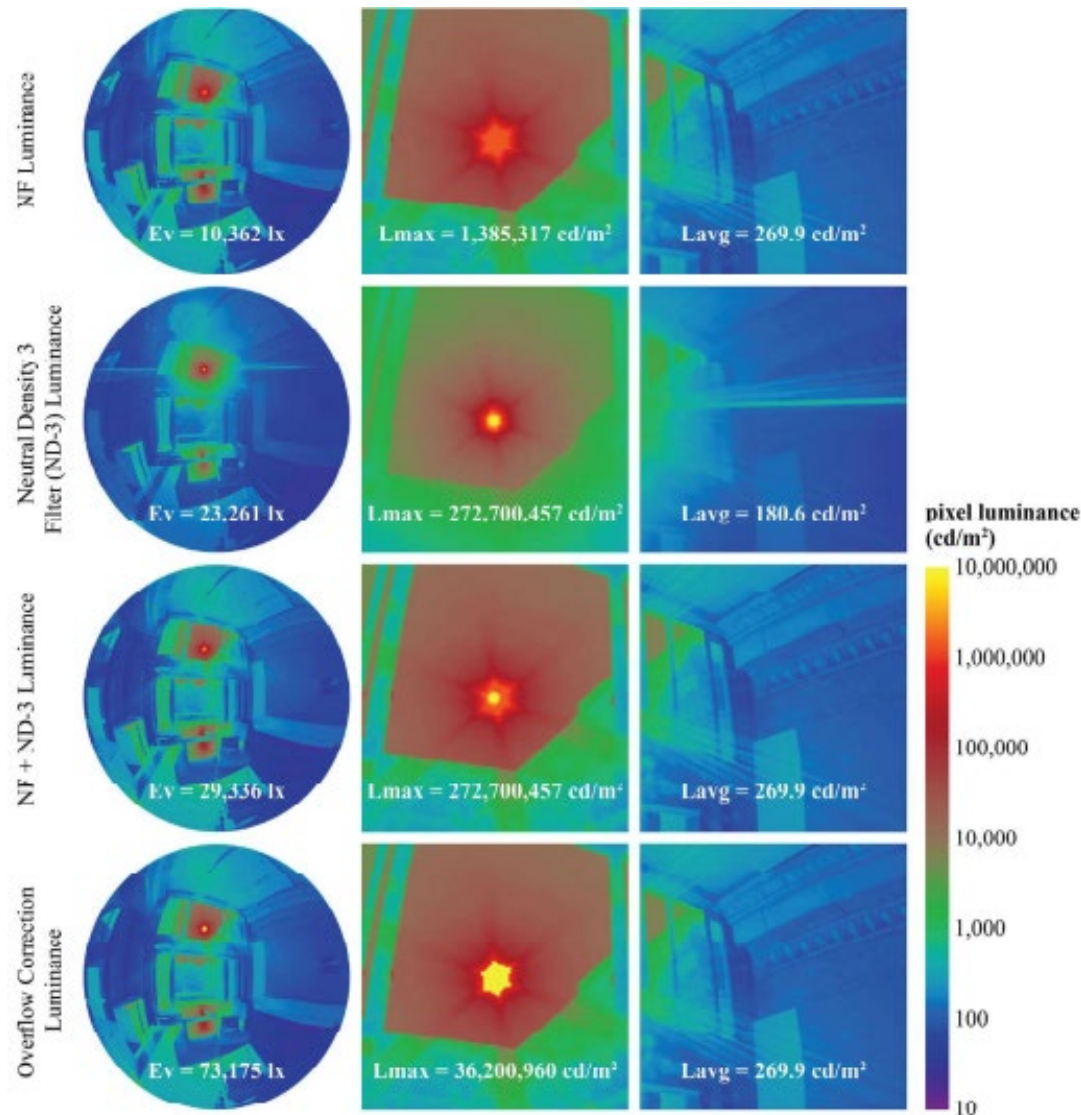
Luminance Meter



Illuminance meter

Measured illuminance at the camera lens: 73,175 Lx

No filter f/11



ND3 with f/11

Partial combinations of
no filter and ND3 with f/11

Luminous overflow correction

References:

Inanici M. "Evaluation of High Dynamic Range Photography as a Luminance Measurement Technique", *Journal of Lighting Research and Technology*, 38(2), 2006, 123-136.

Jakubiec A, Inanici M, van den Wymelenberg K, Mahic A. "Improving the Accuracy of Measurements in Daylit Interior Scenes using High Dynamic Range Photography," *Passive and Low Energy Architecture Conference*, Los Angeles, CA, July 11-13, 2016.

Jakubiec A, van den Wymelenberg K, Inanici M, Mahic A. "Accurate Measurement of Daylit Interior Scenes using High Dynamic Range Photography," *CIE Lighting Quality and Energy Efficiency Conference*, Melbourne, Australia, March 3-5, 2016.

Needs for better color accuracy

- Light and health metrics: non-visual effects of lighting spectra
 - Effects of lighting spectra on vision (glare, acuity...)
 - Color appearance
 - Controlled environment agriculture
-
- Can we measure tristimulus color reliably with HDR photography?
 - Can we reconstruct spectra?
-
- Targeted applications: Sky spectra, Indoor lighting spectra, light and health metrics

HDR Photography workflow for COLOR measurements

Previous work:

Jung BY and Inanici M. Measuring Circadian Lighting through High Dynamic Range Photography, *Lighting Research and Technology*, 51(5): 742-763, 2019.

- Calibration of camera with XYZ measurements at the camera lens
- Hemispherical calibration, hemispherical testing with EML
- Error % with global calibration of camera < 10%, with every scene < 1%
- Per-pixel accuracy is unknown

Borrino K, De Azambuja FV, Sapat N, and Viggiano JA. Sensitivity analysis applied to ISO recommended camera color calibration methods to determine how much of an advantage, if any, does spectral characterization of the camera offer over the chart-based approach. IS&T International Symposium on Electronic Imaging, 2017.

- LDR image color calibration
- Compares chart-based and spectral responsivity methods under electric light sources in a lab environment
- Color calibration needs to be done with every light source
- Estimated CCTs are error-prone (ΔE^* 4.3 - 9.2): The higher the illuminance, the higher the CCT error.

A. Color Calibration Setup1: Corridor Macbeth scene with skylight

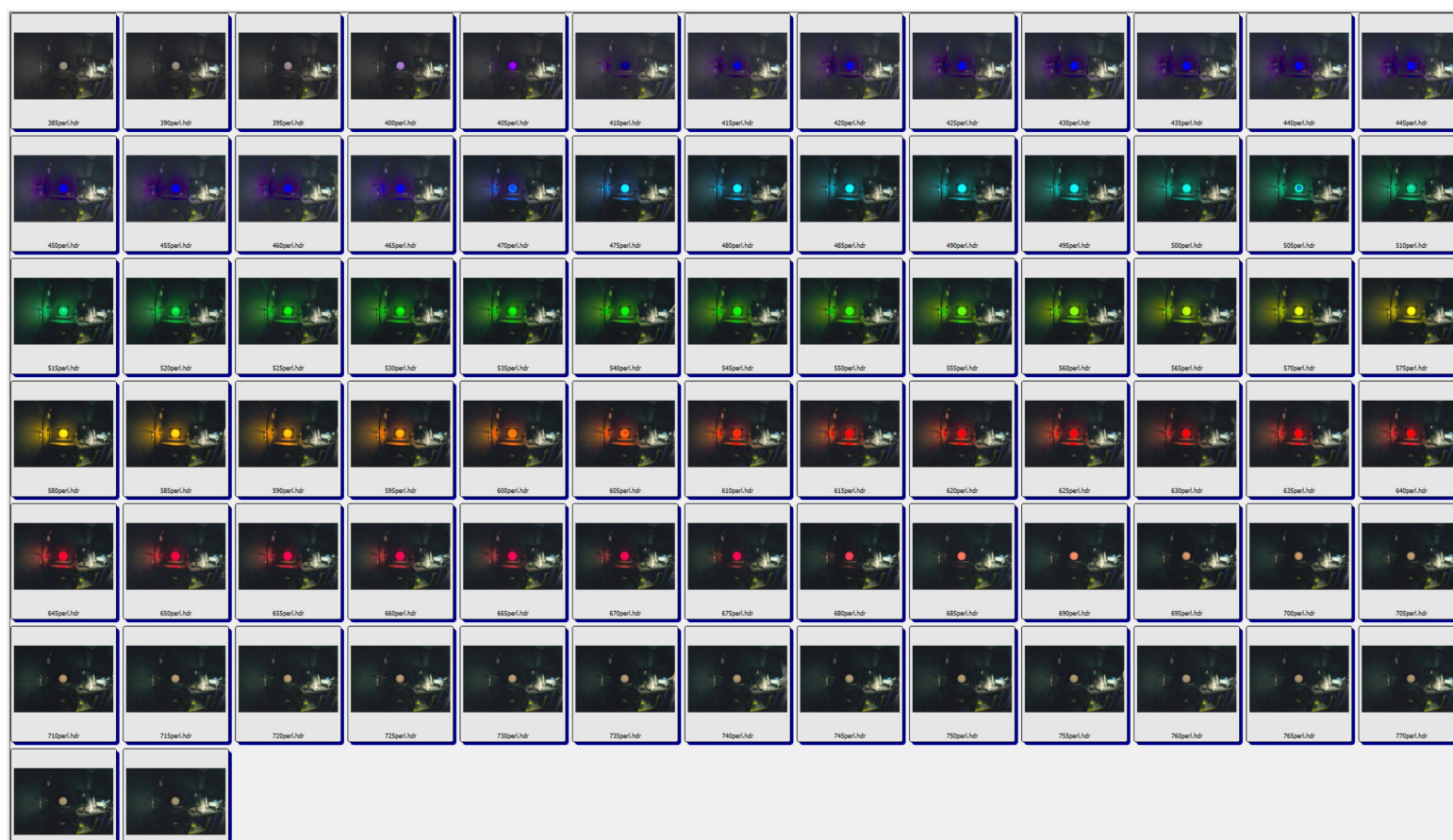


- **24** exposure sequences with Canon EOS R5 with RF7-14 F2.8-3.5 L fisheye lens (190°)
- **24** spectrophotometric measurements with Jeti spectrophotometer (Spectraal 1511) using 2° attachment directed at one patch to measure the spectral luminance of a patch after the exposure sequence



All measurements were taken in TU Berlin, June 2026.

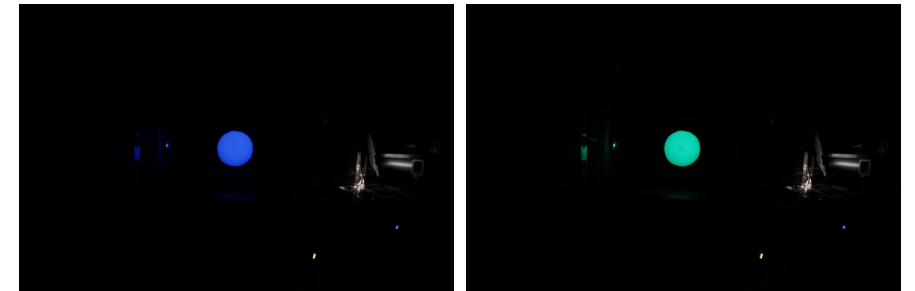
A. Calibration Setup2: Narrow-band Light Source



OL490 is an agile light source programmed for **81** narrow wavelength bandwidths (5nms) between 380 and 780nm. It is mounted with a diffuser.

81 exposure sequences with Canon EOS R5 with RF7-14 F2.8-3.5 L fisheye lens (190°)

81 spectrophotometric measurements with Jeti spectrophotometer (Spectraal 1511) using 2° attachment directed at the diffuser to measure its spectral luminance after the exposure sequence



B. Testing Setup1: Corridor scene with blue patches



- 6 exposure sequences with Canon EOS R5 with RF7-14 F2.8-3.5 L fisheye lens (190°)
- 6 spectrophotometric measurements with Jeti spectrophotometer (SpectraVal 1511) using 2° attachment directed at one patch to measure the spectral luminance of a patch after the exposure sequence

B. Testing Setup2: Sky dome with reference patches



Exposure sequences with Canon EOS R5 with RF7-14 F2.8-3.5 L fisheye lens (190°)^{e,f}



4 spectrophotometric measurements:

^a Jeti SpectraVal 1511 spectrophotometer with 2° attachment directed at blue patch^g

^b Jeti specbos 1211-2 spectrophotometer with 2° attachment directed at grey patch^h

^c Jeti specbos 1211-2 spectrophotometer with 180° diffuser to measure global horizontal spectra

^d Custom-built spectral sky scanner automatically measures the spectral and spatial distribution of daylight across 145 different sky directions every two minutes

B. Testing Setup3: Lab Macbeth scene with e.lights*



One set of exposure sequence with Canon EOS R5 with RF7-14 F2.8-3.5 L fisheye lens (190°)

24 spectrophotometric measurements with Jeti spectrophotometer (SpectraVal 1511) using 2° attachment directed at one patch to measure the spectral luminance of a patch after the exposure sequence

*fluorescent lights

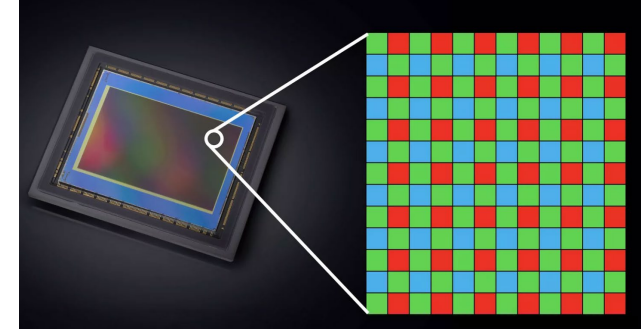
HDR generation methods

Each exposure is saved as RAW (CR3) and JPG.

- Method 1: Photosphere (Windows)
 - Exposures saved as JPEG (sRGB) – merged in Photosphere
- Method 2: hdrgen (Ubuntu)
 - Exposures saved as RAW (CR3) – converted to 8-bit TIF with Canon Digital Photo Professional 4 with *Wide Gamut RGB*– merged in hdrgen (2025 version)
`hdrgen -m 400 -a -e -r tifbasecam6.rsp -c XYZ -o image2.hdr *.TIF`
- Method 3: raw2hdr Perl script with dcraw and exiftool (Ubuntu)
 - Exposures saved as RAW (CR3) – converted to Adobe Digital Negative Converter (DNG) – converted to TIF with dcraw – merged in hdrgen (2025)
`perl raw2hdr.pl -c XYZ -o image3.hdr *.dng`
- Method 4: Spectral reconstruction with the narrow band setup from RAW files

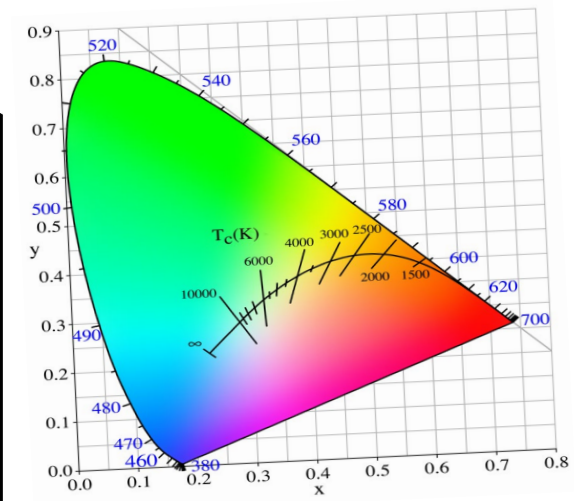
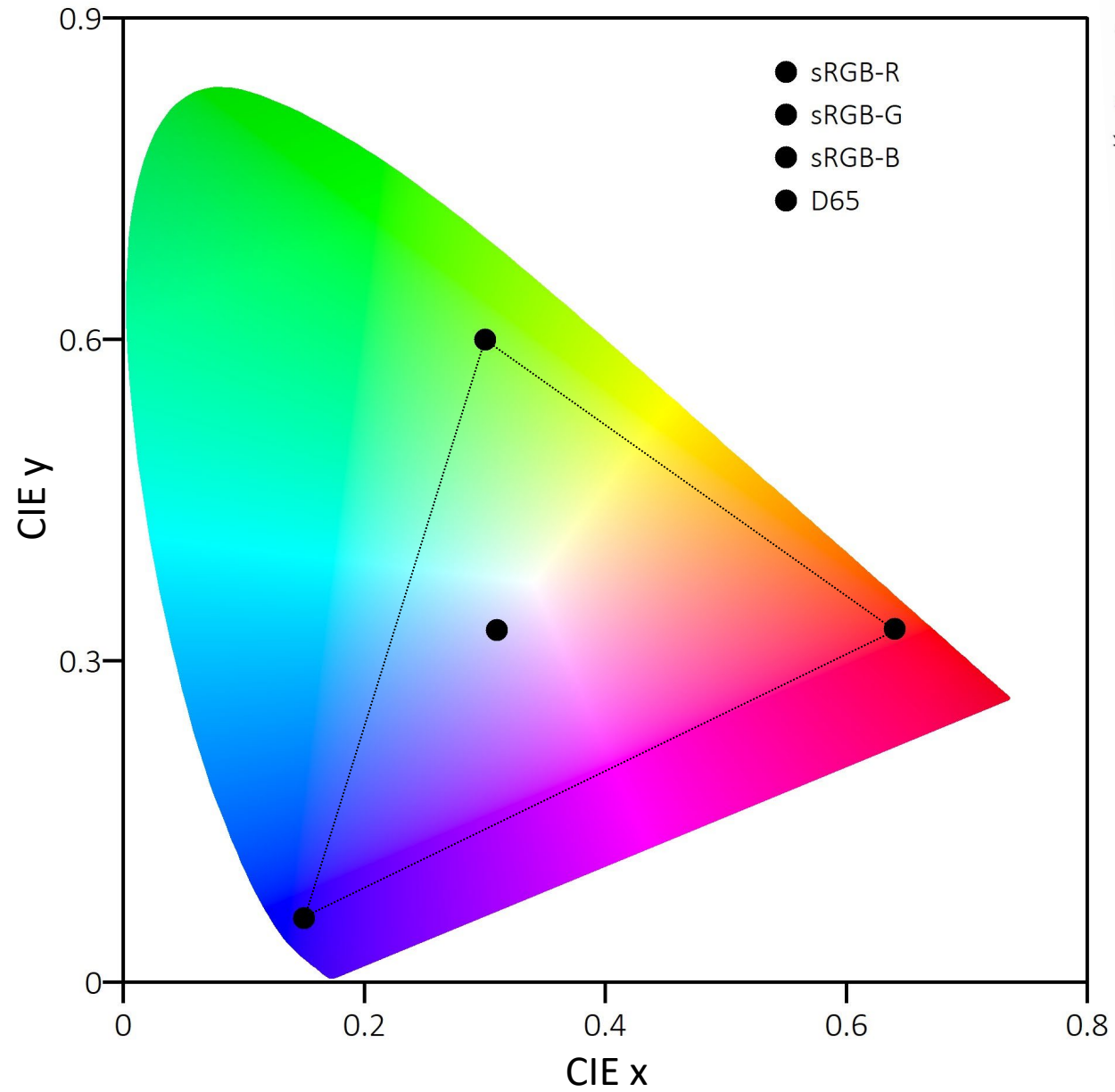
* Camera response curve is generated for each method using the same scene exposures.

CR3, DNG, TIF, JPG

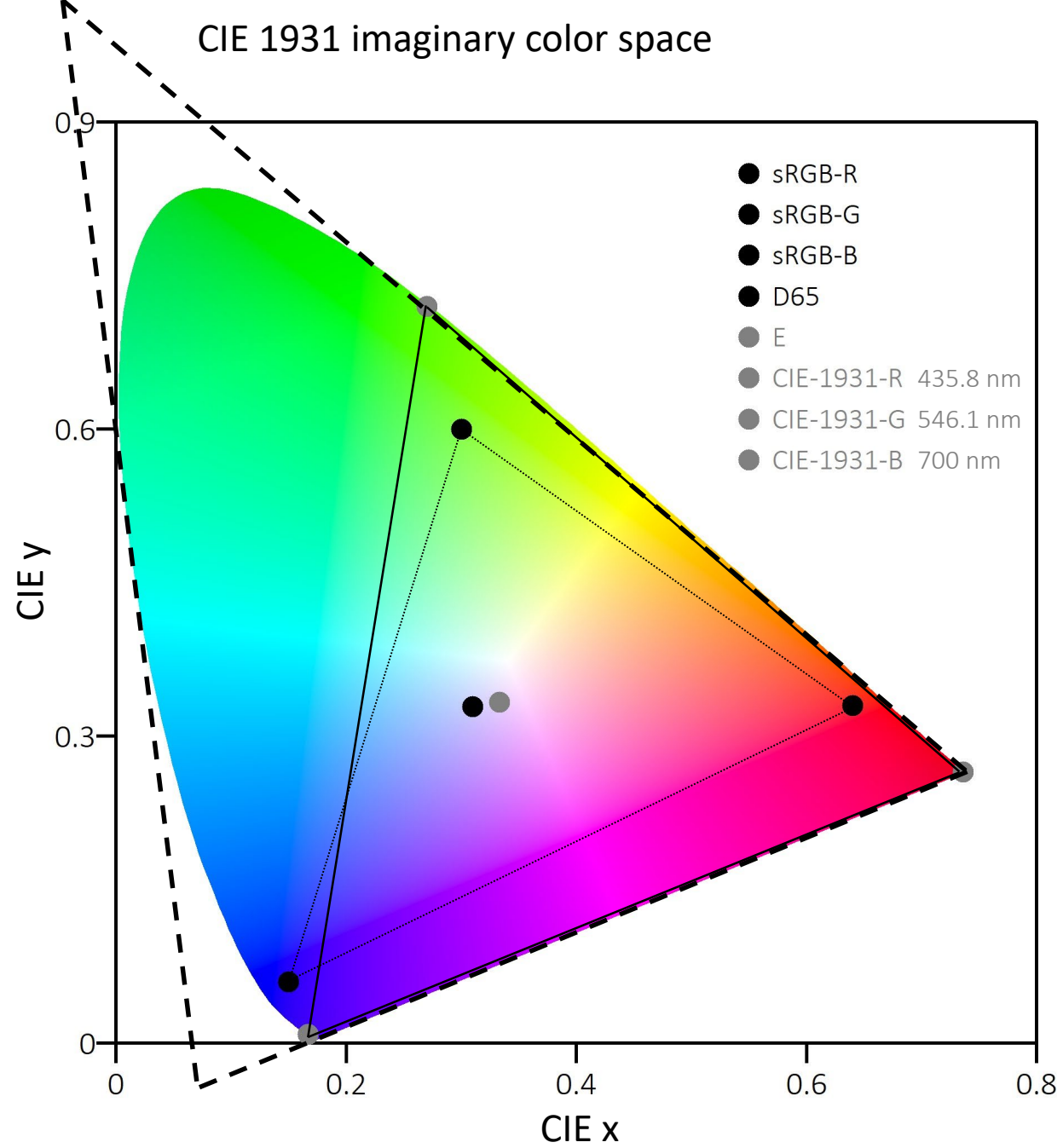


- JPG files store 8-bit data in sRGB space. *Method1*
- CR3 files store unprocessed 14-bit data
- “RAW image processing is actually one of the most proprietary, tightly-guarded aspects of modern digital camera design”
(Canon Raw Image Fundamentals)
- “RAW image processing will not be identical, using a camera maker’s software vs. that of a third-party software maker”
(Canon Raw Image Fundamentals)
- Canon Digital Photo Professional 4 converts CR3 to TIFF, the color space selected is wide gamut RGB *Method2*
- Adobe DNG (Digital Negative) files do not have a fixed color space. Standard DNG files contain raw, camera-native sensor data tied to the scene and use embedded metadata color matrices. It converts CR3 to DNG, dcraw converts DNG to TIF.
Method3
- TIFF files do not have a fixed color space.

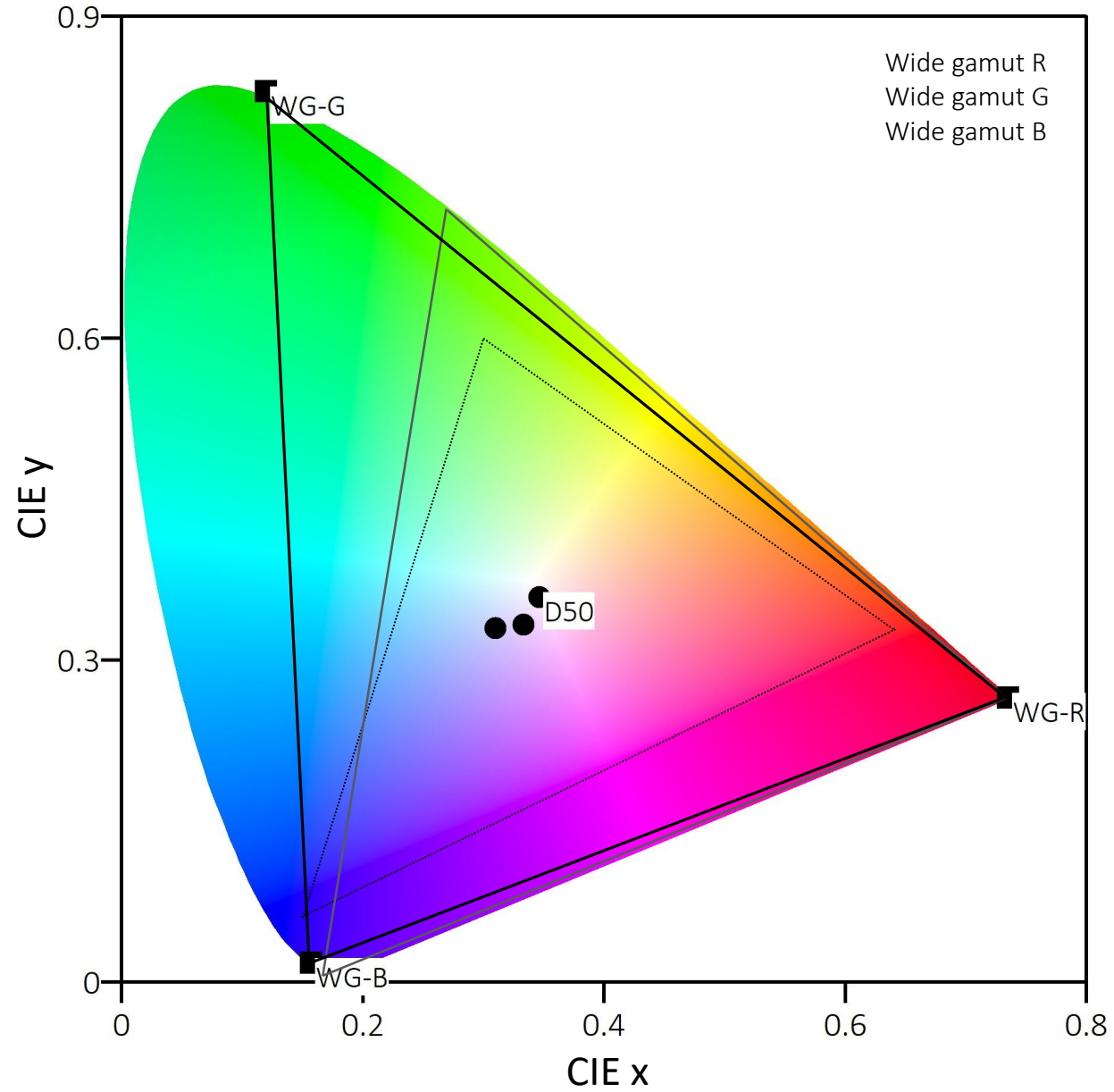
Chromaticity Diagram



Chromaticity Diagram

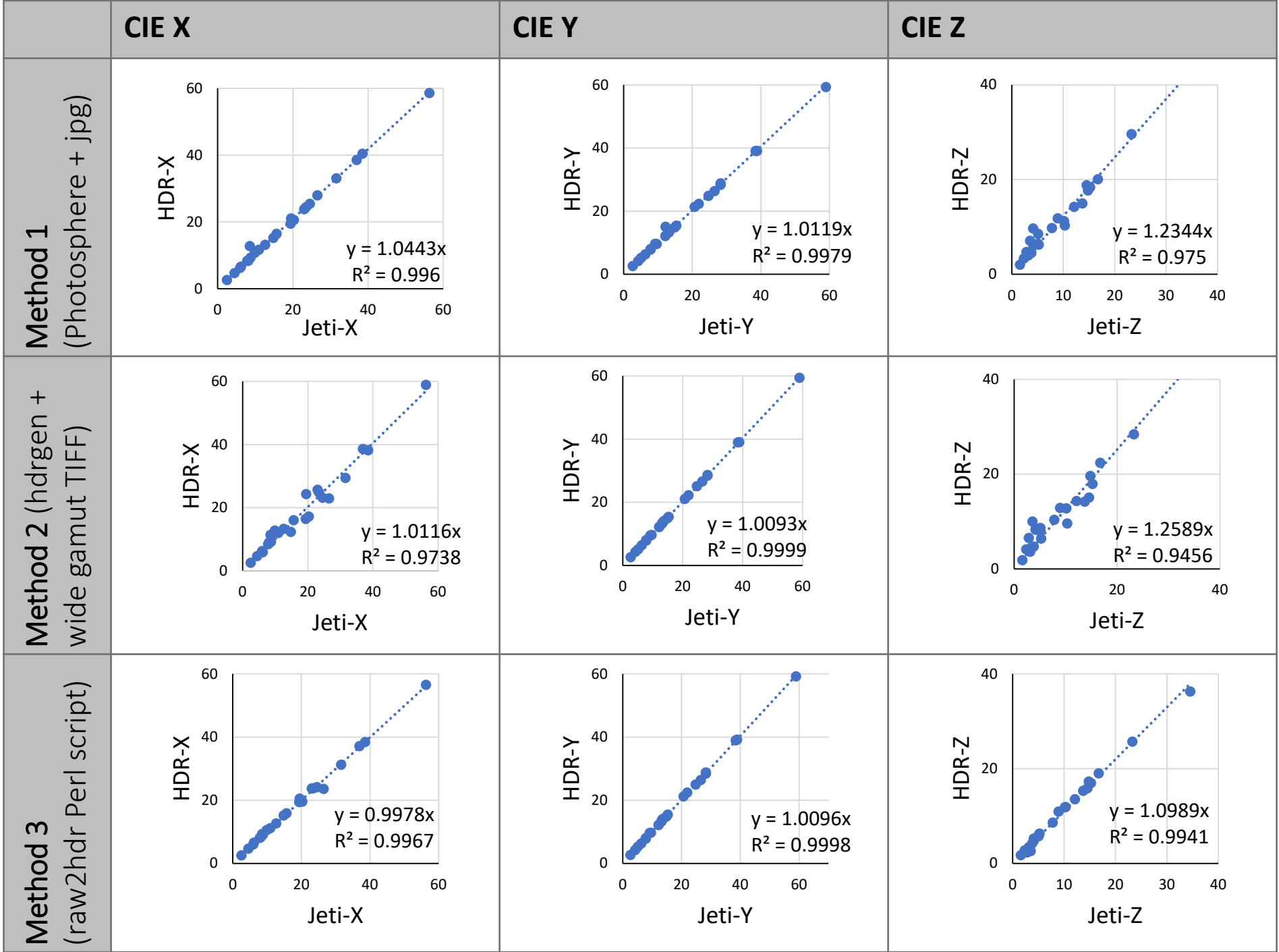


Chromaticity Diagram



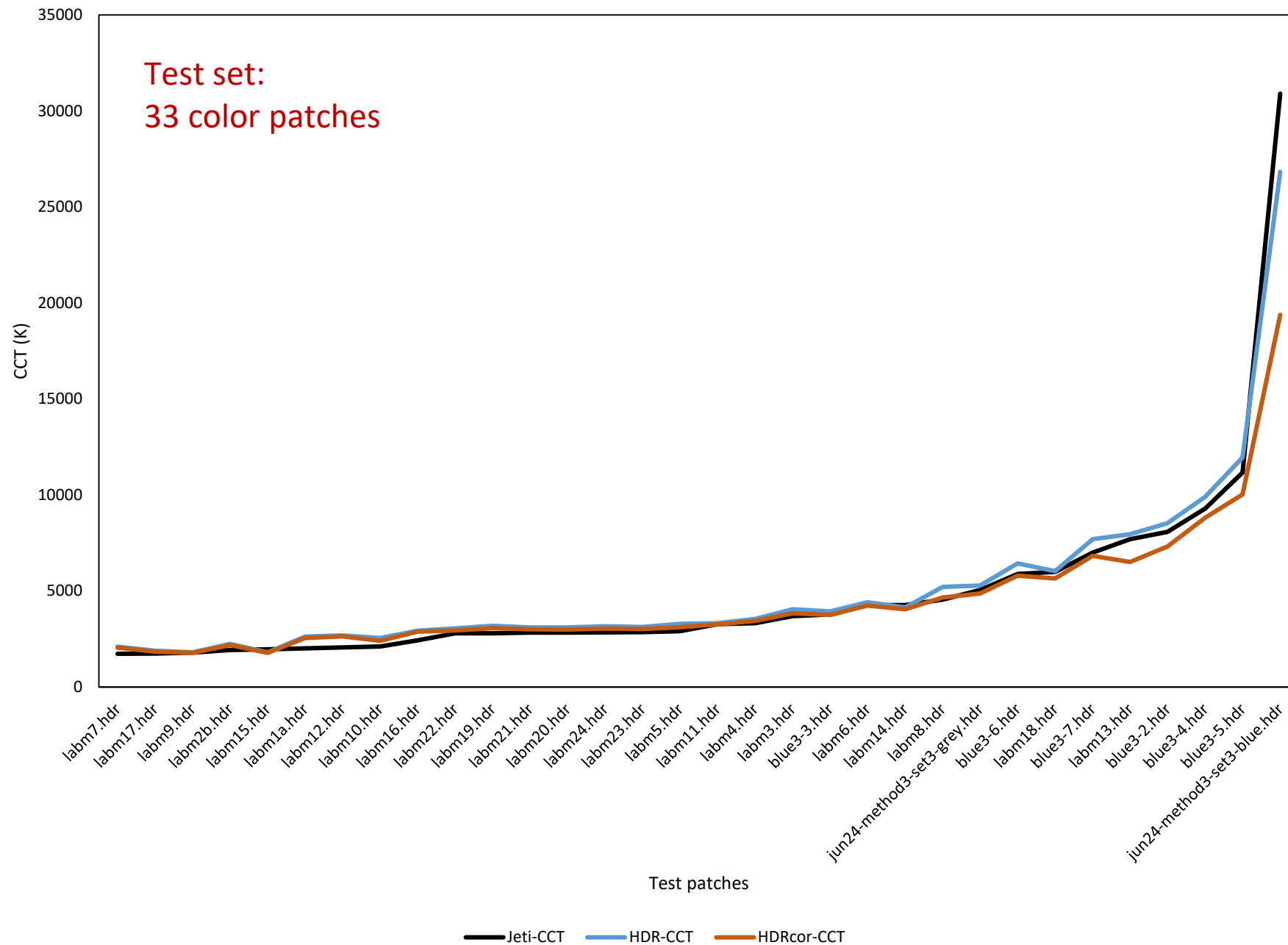
Process for color extraction

- HDR – in XYZE format
- Calibrate patch with luminance measurement
- Average XYZ in the area that corresponds to the spectrophotometer focus (2°) 
- Convert to CIE x,y
- Calculate CCT with McCamy method
- Compare with Spectrophotometer CCT

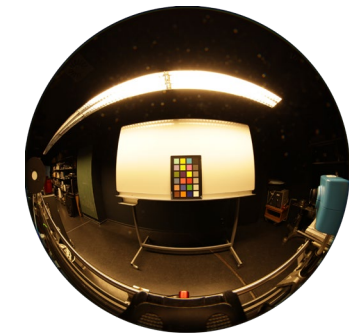


Calibration set:
24 Macbeth patches

Results – Method3



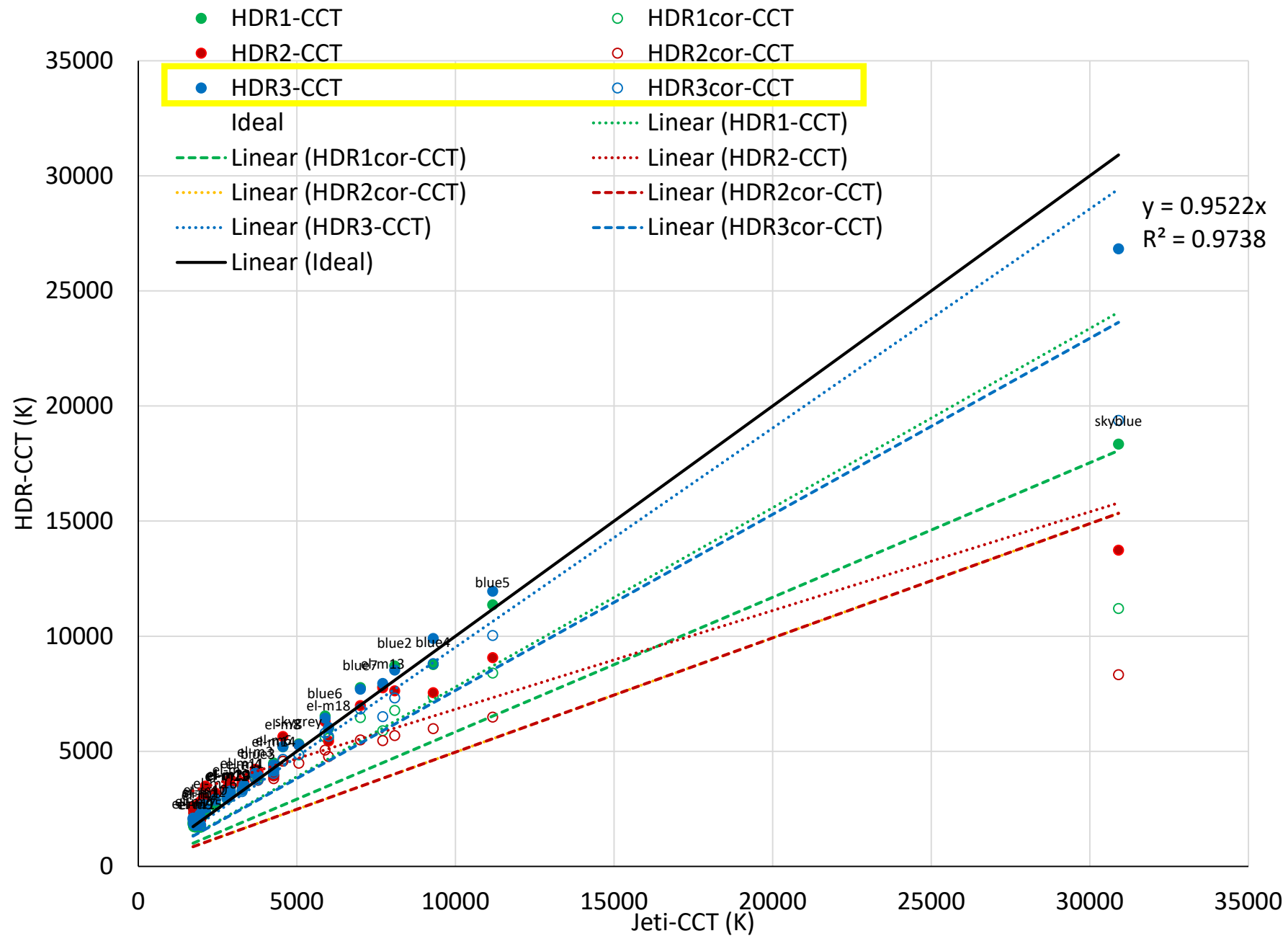
Labeled as blue3(2-6).hdr



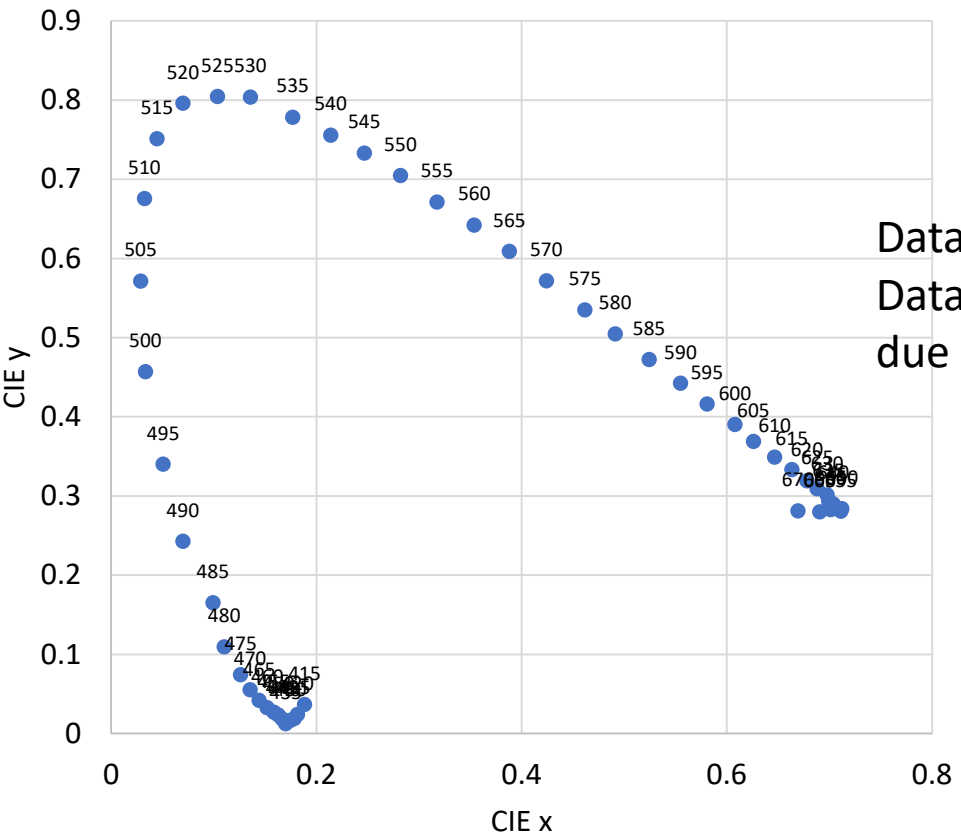
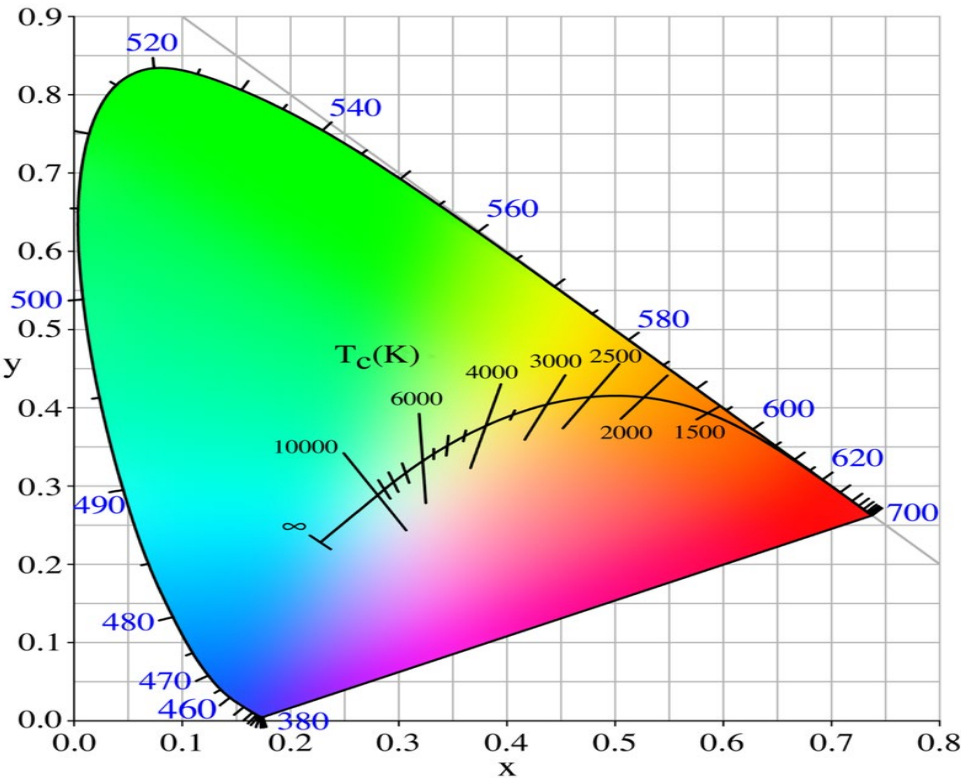
Labeled as labm(1-24).hdr



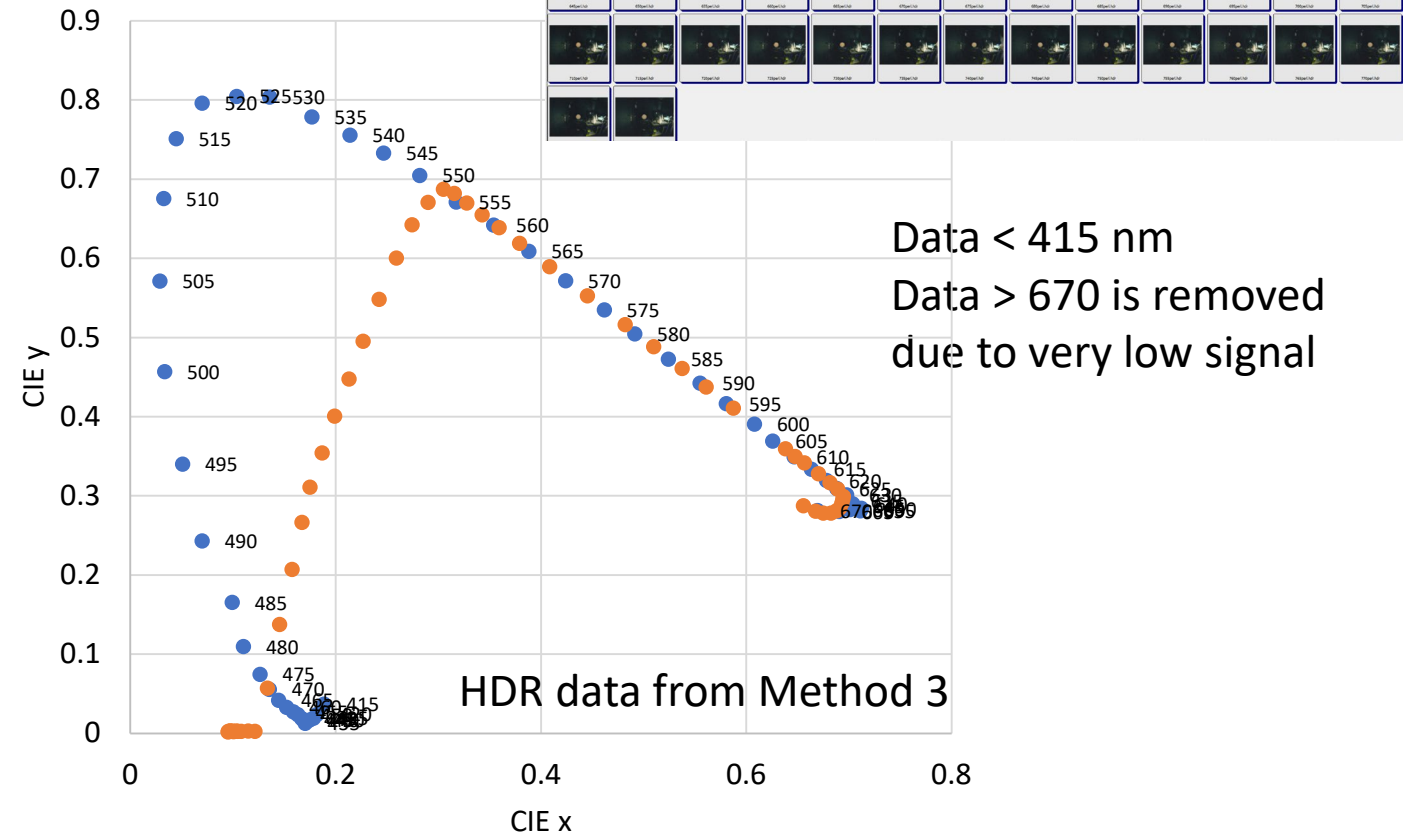
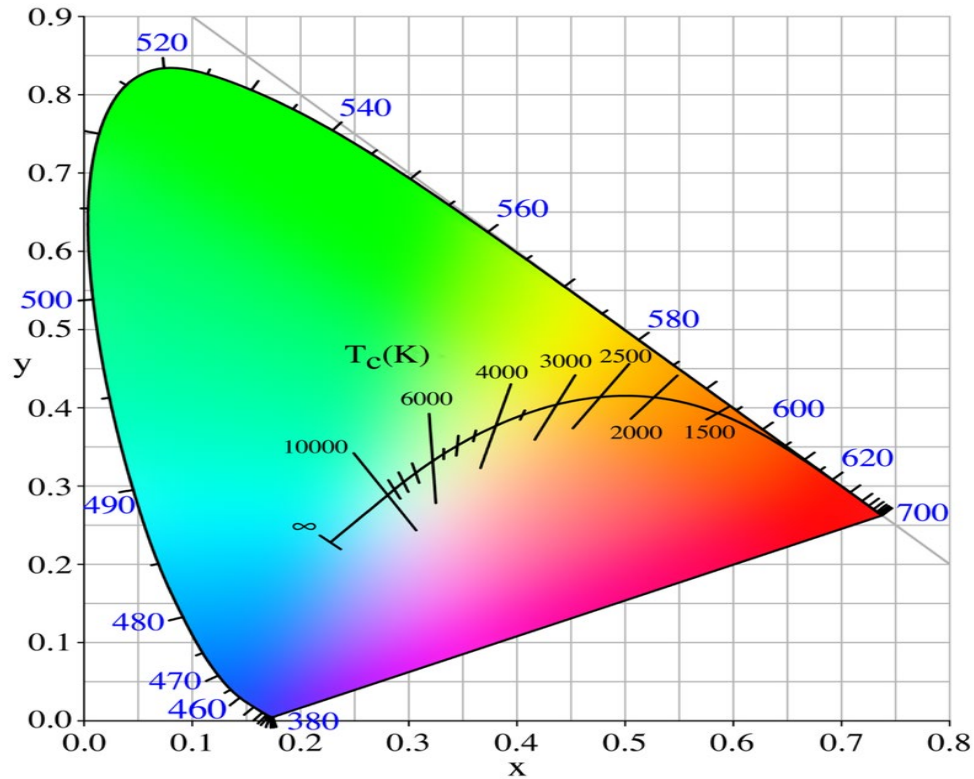
Labeled as
jun24-9-05-(blue-grey).hdr



Jeti Recordings in Setup 2 with Narrow Band Source

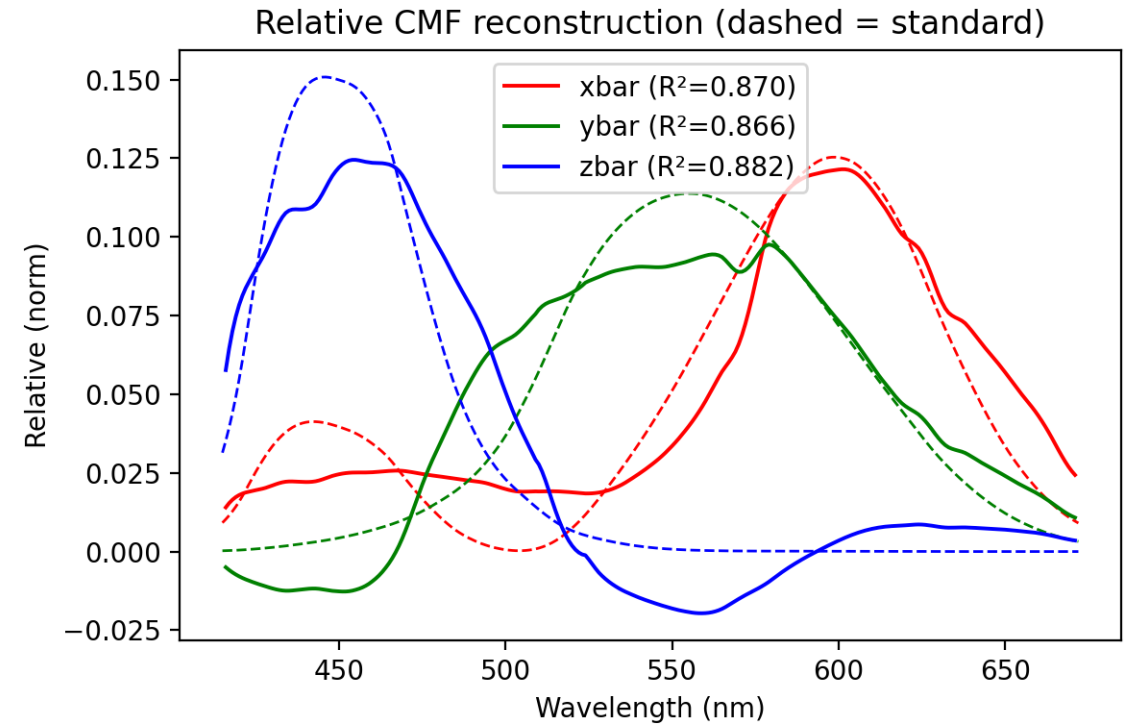
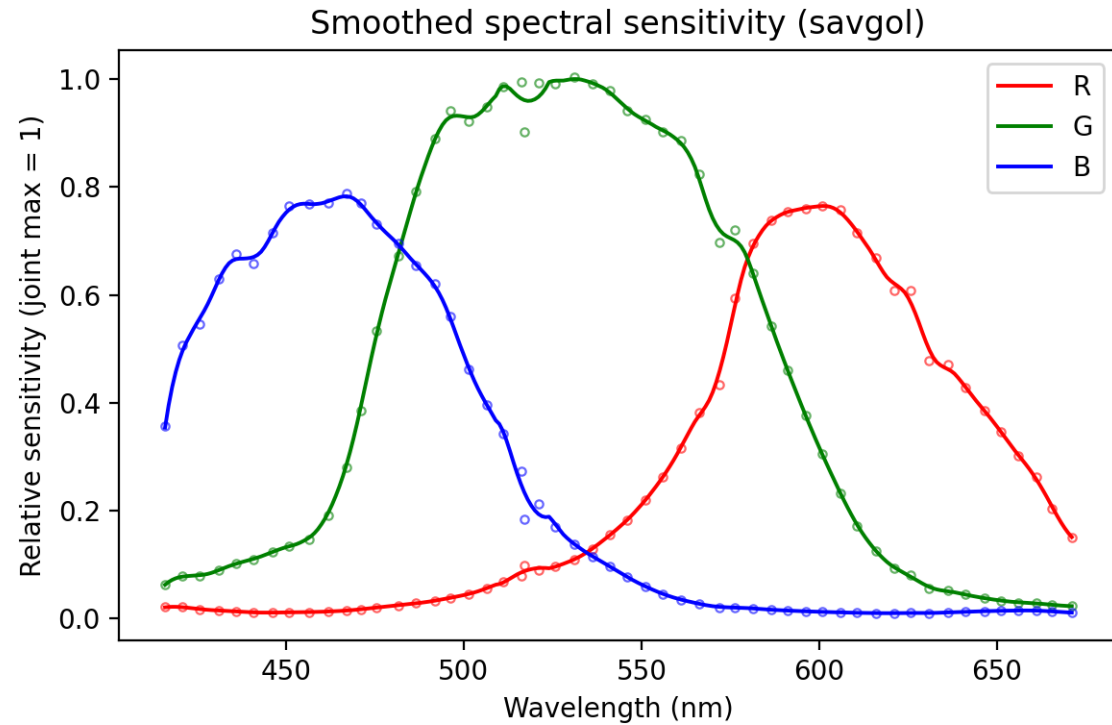


Recordings in Setup 2 with Narrow Band Source



Real-world spectra is not narrow band!

Method4 - Reconstruction



After pairing camera RAW (CR3) images and JETI SPDs, the spectral responses of the R, G, and B channels are characterized. RGB signals are converted into a per-second value (DN/s) to eliminate the impact of exposure time, and then normalised by the measured radiance of the SPD.

For each wavelength, the median is calculated from all valid images. Images are rejected when overexposed (threshold $\geq 90\%$ of RAW white level of any channel) or underexposed (threshold $< 2\%$ of RAW white level of all three channels simultaneously).

The resulting spectral RGB sensitivities are then used to reconstruct $V(\lambda)$, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, and the melanopic action spectrum. Each reconstructed weighting function is represented by a set R, G, and weighting coefficients.

The script calculates these coefficients based on non-negative least squares (all ≥ 0), as well as unconstrained linear least squares, where negative coefficients are permitted. The latter can better match the weighting functions.

7. Conclusions

- **Recommendation:** Method 3: raw2hdr Perl script with dcraw and exiftool
- Use luminance calibration, if you are measuring both color and intensity (especially with Method 3)
- How close is good enough for CCT or CIE (x,y) values?
- Caution with saturated colors

Acknowledgments



University of Washington, College of Built Environments
Johnston-Hastings Research Travel Support Fund



TU Berlin Daylighting and Indoor Lighting Group

Spectral calibration of HDR Photography



Mehlika Inanici¹ and Martine Knoop²

¹University of Washington, Department of Architecture

²Technische Universität Berlin, Faculty of Electrical Engineering and Computer Science

¹inanici@uw.edu ²martine.knoop@tu-berlin.de

