

# NEEA Method for Measuring TV Screen-Average Dynamic Luminance with a Camera Photometer

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## Revision Control

V15 – Gregg Hardy, 11/2	Updated camera distance range to 1.53-1.55. Added Appendix E: Justification of camera distance.
V16 – Gregg Hardy, 11/16	Updated camera distance to $1.77x \pm 0.5''$ the screen width and updated Appendix E for same reason.
v17 – Gregg Hardy, 11/19	Updated cam distance and lens model.

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## Introduction

This document is intended to provide an explanation of a camera-based method of measuring the luminance of a TV that is playing dynamic video, covering the technical capabilities of the hardware, the image processing techniques employed, and the calibration procedures used.

Camera photometers have advantages over the spot photometers used to measure TV luminance today. Cameras are capable of viewing and measuring light output across the entirety of the screen, measuring light output during dynamic video play, and recording the TV image during the test.

Our goal is for the sum of all possible sources of error in our camera photometer approach to reach +/- <5% expected accuracy to the real luminance value as measured by a hypothetical 'perfect camera



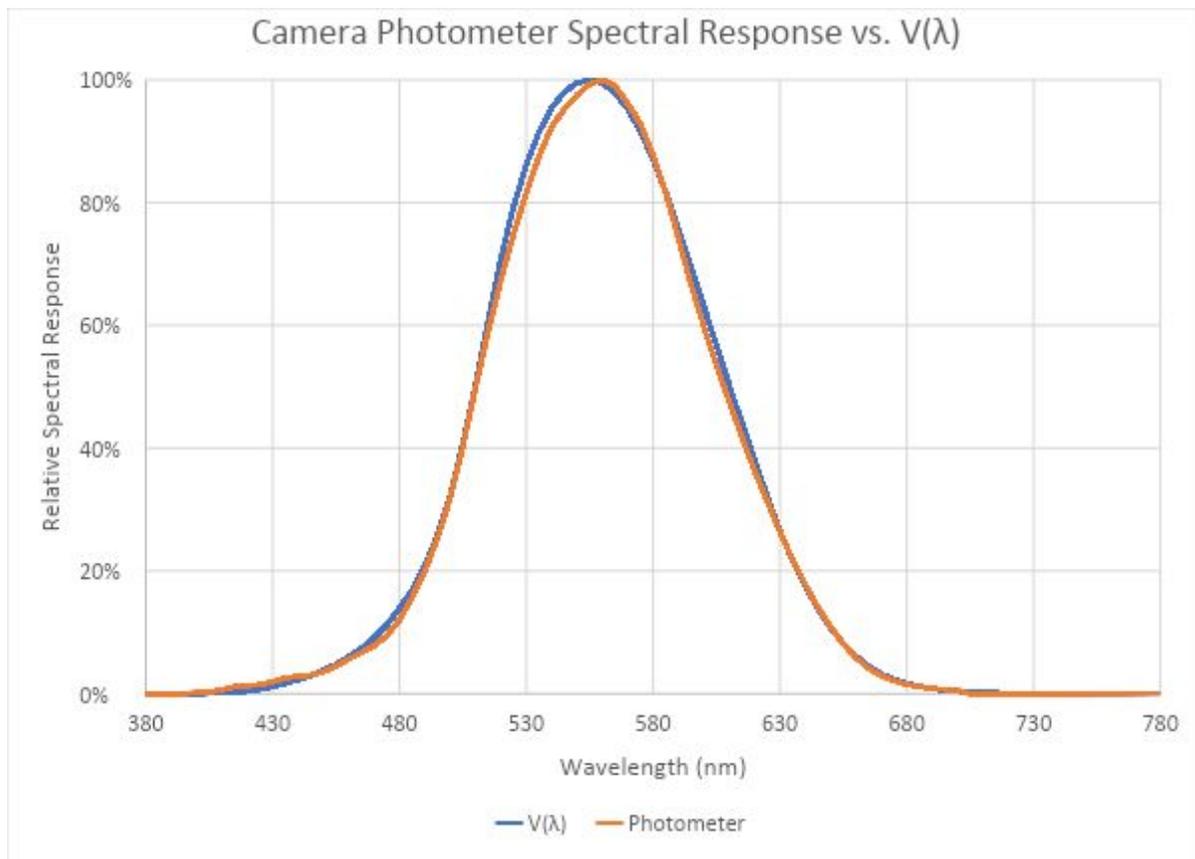
photometer'. We have met our goal, and we believe this accuracy estimate to be significantly more accurate than current measurement methods; this is explained in more detail in [Error Analysis](#).

## Background

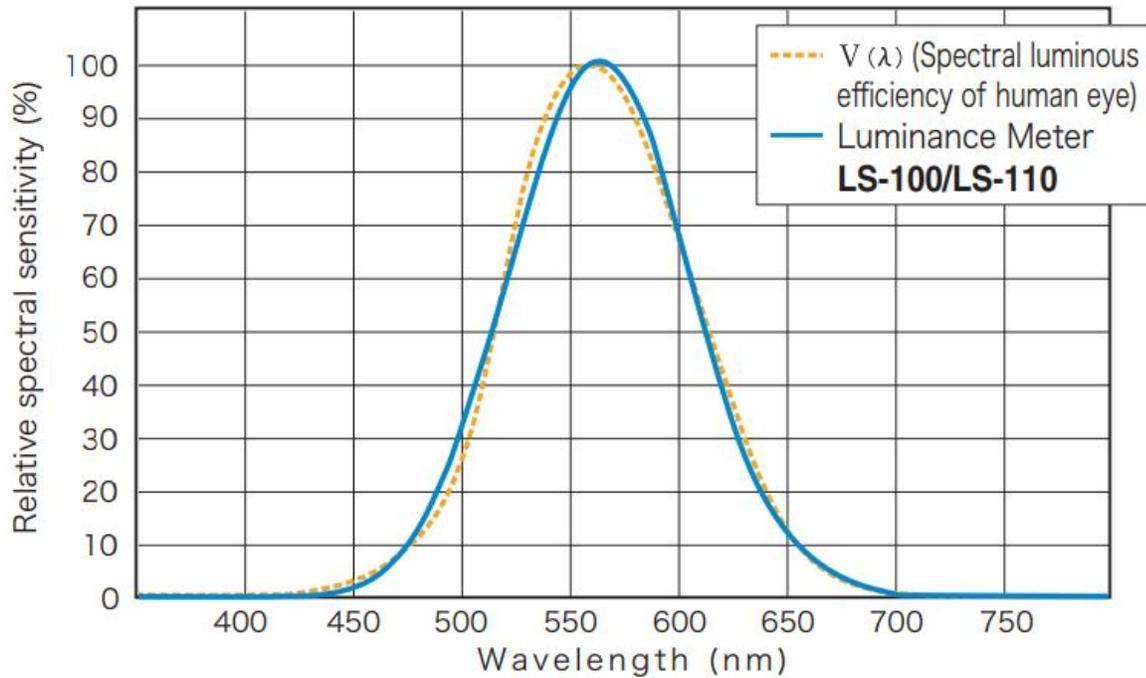
### CIE 1931 luminosity function

A camera photometer is intended to accurately measure luminance of a light source as observed by a human. To accurately measure the luminance observed by a human, the camera photometer system needs to have a response equivalent to the CIE 1931 luminosity function  $V(\lambda)$ . A more recent but less used alternative is CIE 1964 Standard Observer. We use CIE 1931 as do Konica-Minolta and other major photometer manufacturers.

We calculate the expected spectral response of our camera system from the spectral response of the sensor in the camera, and the transmissivity of the lens, photopic and neutral density filters.



Our filter match appears visually similar to that of an LS100/LS-110:<sup>1</sup>



$f'_1$  against Illuminant A

A metric for a system's fit to the CIE 1931 curve is defined in CIE 19476, 3.2.2, as an index "describing the deviation of the relative spectral responsivity of the photometer from the  $V(\lambda)$  function". Specifications for most luminance meters include the spectral mismatch against standard illuminant A. Although this does not quite fit our use case of measuring LED lights, it helps characterize the quality of our camera photometer against other systems. We characterize our theoretical accuracy for TV LED, QLED, and OLED light sources more specifically later. In absence of an LED standard illuminant, we similarly calculate our expected spectral mismatch index  $f'_1$  for our camera response  $s_{rel}(\lambda)$  against the photopic curve  $V(\lambda)$  for standard illuminant A  $S_A(\lambda)$  as<sup>2</sup>:

$$s_{rel}^*(\lambda) = s_{rel}(\lambda) * \frac{\int_{380nm}^{780nm} S_A(\lambda) * V(\lambda) d\lambda}{\int_{380nm}^{780nm} S_A(\lambda) * s_{rel}(\lambda) d\lambda}$$

$$f'_1 = \frac{\int_{380nm}^{780nm} |s_{rel}^*(\lambda) - V(\lambda)| d\lambda}{\int_{380nm}^{780nm} V(\lambda) d\lambda}$$

<sup>1</sup>[https://sensing.konicaminolta.us/wp-content/uploads/ls-150\\_160\\_catalog-8z1qyj292u.pdf](https://sensing.konicaminolta.us/wp-content/uploads/ls-150_160_catalog-8z1qyj292u.pdf)

<sup>2</sup> Equations lifted directly from ISO/CIE 19476: "Characterization of the performance of illuminance meters and luminance meters"

With spectral response estimates for our camera at 5nm<sup>3</sup>, we estimate our spectral mismatch index to be <3% to illuminant A, mostly driven by the filter match of the photopic filter we chose. This value is useful as a general comparison to the quality of the filter match of other photometers, like the LS150, but is not specific to our measurement case: TV LED, QLED, and OLED luminance.

### Spectral mismatch against TV light

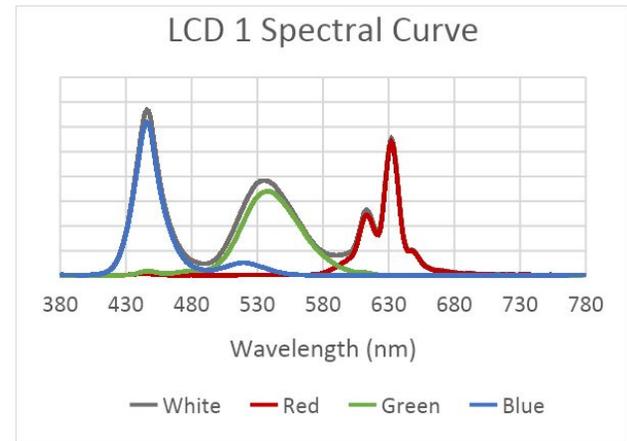
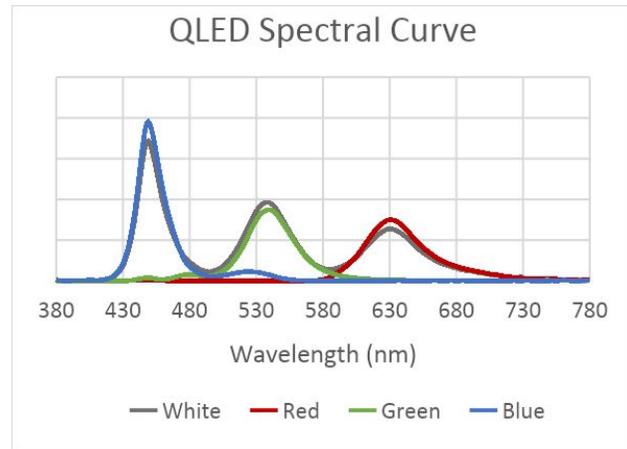
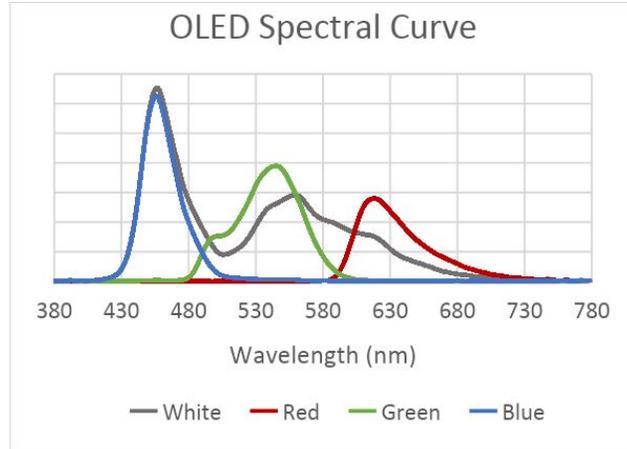
Looking visually at the spectral response of our photometer, we can tell that our system is likely to under-report luminance in the 580-640nm range, which is where the red channel of most TV displays is going to peak; in other words, our camera system is likely to be under-sensitive to reds. We observe the same difference at lower wavelengths, in blues; however, since blues tend to peak around 440-450 Hz and have overall less relative luminance than red, they are likely to contribute to error less significantly.

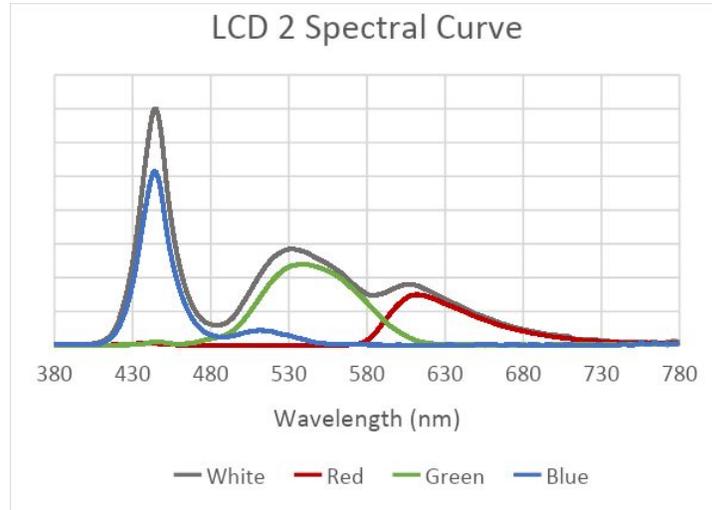
There are differences in spectral profiles between different TV technology types, so we cannot simply use a single color correction calibration for the camera system; given different peaks of reds, greens, and blues, and different overall curves, the differences between the spectral profile of the light of each TV is something our camera is sensitive to. We measured spectral profiles for the TVs in our lab with a SpectraScan PR650 spectroradiometer to confirm this, noting the difference in spectral profiles between OLEDs, QLEDs, and LCDs.

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<sup>3</sup> further precision in this estimation could be achieved by measuring the camera's response directly with an integrating sphere, rather than assuming the data from the sensor and lens datasheets are perfectly accurate.







Spectral profiles can vary across different TV types significantly, and even from one LCD panel to the next, with different peaks and shapes since our camera system is more or less sensitive to different areas of the visible spectrum, we risk TV-to-TV inconsistency. For example, we multiply our camera sensitivity by the spectral curves for the two LCD TVs, to get an idea of what the relative perceived luminance of each color is for the camera, vs. that of the human eye.

Observing the differences on the red and blue component curves for various TV profiles, it becomes apparent that the amount of error contributed by the filter match can depend on the spectral profile of the TV, particularly the peak wavelengths of the red and blue channels, and how heavily those colors which contribute the most contribute to the overall light of the clip.

Using a similar calculation of spectral mismatch as for illuminant A, replacing  $S_A(\lambda)$  with  $S_{TV}(\lambda)$ , we can calculate a general spectral mismatch index for the camera photometer, for saturated red, green, and blue screens, as well as white screens, on a few of the TVs we have in the test lab. Note that general spectral mismatch index is not an 'absolute' error calculation, but a weighted average of how far in general the curve deviates from the target curve, weighted by the profile of the light being measured. Absolute expected error is calculated in [Appendix A: Specific mismatch to TV LEDs](#).

#### Calculated general mismatch index against light sources for various TV types:

	Pure Red	Pure Green	Pure Blue	Pure White
LCD LED#1	2.9%	2.7%	2.7%	<b>2.7%</b>
LCD LED#2	2.8%	2.7%	2.7%	<b>2.7%</b>
QLED	2.8%	2.7%	3.0%	<b>2.8%</b>
OLED	3.0%	2.7%	4.6%	<b>2.7%</b>

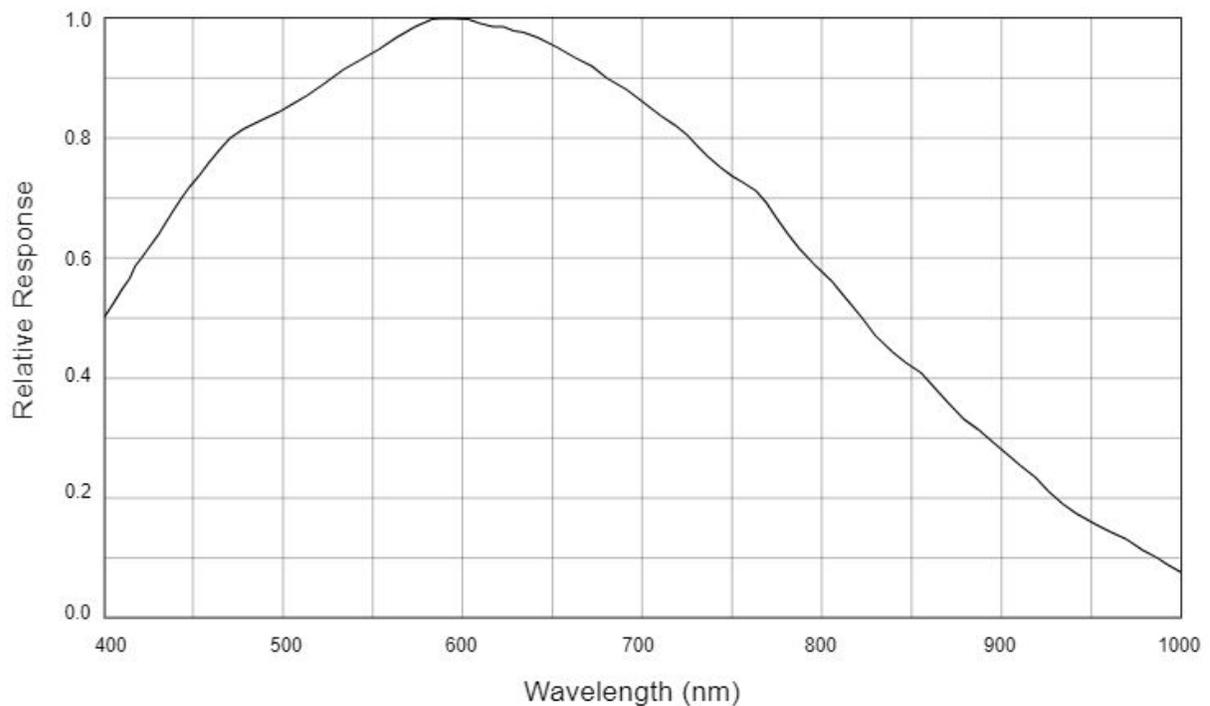
## Camera System

### Camera and Lens

We chose our camera and lens based on the geometry of our test set-up and the need to achieve continuous luminance measurement at approximately 6 frames per second with a data stream that can be processed real time by a conventional laptop. Other measurement devices designed to have a close match to the luminosity function exist, but have limitations making them prohibitive for this application. Spot photometers are incapable of measuring the full screen during dynamic video play, and other camera photometers that exist on the market today are not capable of taking multiple frames a second with continuous exposure. Our camera system solves both of those problems.

### Basler acA720-290gm Camera

The spectral response of our the camera (without lens), which is largely dictated by the micro-lenses on the Sony [IMX287LLR-C](#) CMOS sensors pixels, is<sup>4</sup>:



### Basler C23-0816-2M F1.6 f8.6mm Lens

The camera is placed a distance of 1.76-1.78 times the screen width of the TV screen per the rationale in Appendix E: Justification for Camera Placement Distance from TV. We chose this distance to facilitate portable-dark-room testing in retail environments with narrow aisles. Early feedback suggests that we might end up doubling this distance to be more representative of real-world viewing conditions, which would require switching to another lens with a narrower field of view.

<sup>4</sup> <https://www.baslerweb.com/en/products/cameras/area-scan-cameras/ace/aca720-290gm/>

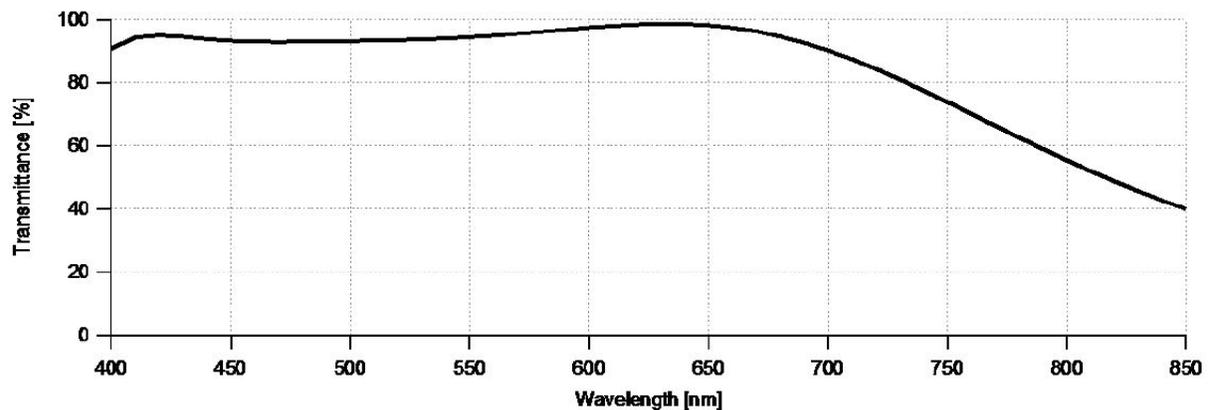


The camera line of sight is positioned normal to the plane of the TV screen and aimed at the center of the TV screen. This positioning simulates the perceived amount of light that a normal human viewer would observe when watching TV.

We selected the Basler C23-0816-2M F1.6 f8.6mm lens. An 8mm lens paired with the Basler camera allows for the full width of the TV to be in the image field of view when the camera is placed at a specified distance from the screen. The minimum working distance of the lens is 100 mm, less than 4 inches, well below the minimum TV screen width size.

For an observer centered in front of the TV, pixels at the edges of the TV screen will generally appear dimmer than pixels in the center of the image due to the beam angle of the pixels. The test software does not compensate for this viewing angle effect for the camera because the effect is also observed by a human viewer, and the test is intended to emulate the perceived intensity of a viewer.

Basler C125-0618-5M F1.8 f6mm lens transmittance (without filters) is<sup>5</sup>:



### Using Cameras to Measure Luminance

According to a paper by Hiscocks, 2014, the luminance of the light hitting the camera sensor pixel is directly proportional to the sensor reading value of that pixel in the image.

<sup>5</sup> <https://www.baslerweb.com/en/sales-support/downloads/document-downloads/basler-ace-gige-users-manual/>

$$N_d = K_c \left( \frac{t S}{f_s^2} \right) L_s$$

where the quantities are

$N_d$	Digital number (value) of the pixel in the image
$K_c$	Calibration constant for the camera
$t$	Exposure time, seconds
$f_s$	Aperture number (f-stop)
$S$	ISO Sensitivity of the film
$L_s$	Luminance of the scene, candela/meter <sup>2</sup>

In this system, the exposure time, aperture, and ISO of the camera are set at constant values. A calibration (described later in this document) is conducted to determine the calibration coefficient to convert pixel brightness to luminance. Our goal is to measure a TV's screen-average luminance during dynamic video play as perceived by the human eye from the near end of typical viewing distance range.

### Camera Exposure Settings

The frame rate of the camera is set as the reciprocal of the exposure time: for example, if the exposure time is 100 milliseconds, the frame rate is set as 10 fps.



Image acquisition is overlapping, such that during sensor readout, the next frame exposure begins. There is no delay between one frame ending and the next frame beginning: all light hitting the camera lens is recorded in an image. See [Basler documentation](#) for additional information.

The camera is set at a constant exposure time, aperture, and ISO for all tests with all TVs. We set the camera aperture so that signal level is approximately equal to twice the luminance level (cd/m<sup>2</sup>) at 6 frames per second. That enables our 12-bit camera to read a maximum of 2048 cd/m<sup>2</sup> (2008 after master black level adjustment discussed later). We chose 6 fps because it limited the image data rate to a level that an affordable laptop could process real-time.

Note: The Basler cameras run over a long period of time get fairly hot, and this can cause the screw used to fix the aperture to loosen; we recommend securing the screw with a viscous, fast-hardening paint like whiteout to prevent it from loosening over time and releasing the aperture; if the paint seal is broken, the tester knows the screw has loosened and can re-calibrate accordingly once they have secured the aperture again.

## Camera Filters

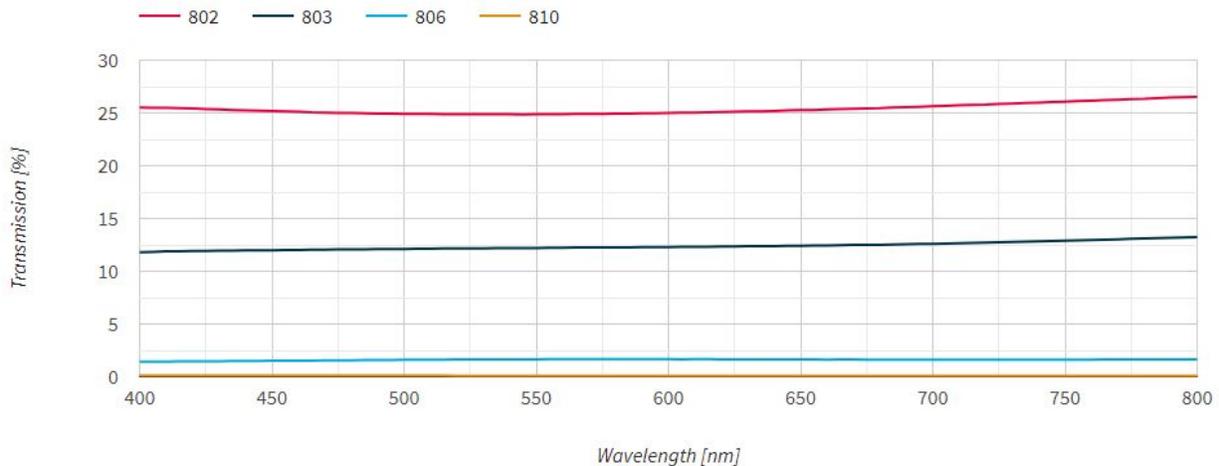
### B+W 43/47mm XS-Pro MRC-Nano 806 ND 1.8 Filter (6-Stop)

The addition of a neutral density filter allows us to measure brighter objects without over-exposing the pixels; reducing the incoming light by a factor of 64 with a 6-stop neutral density filter allows us to measure up to 2,048 cd/m<sup>2</sup>, as discussed above, with the aperture set approximately to the middle of its range.

The B+W neutral density filter was chosen for the following reasons:

1. It has a flat spectral response curve. See the following figure; the blue line (806) gives the transmission of this filter line across the spectrum.
2. It has a relatively uniform effect over the surface of the filter.

Any aberrations that do exist across the surface of the filter will be corrected for in the vignette calibration described in a later section.



6

### Omega 558BP100 38mm photopic filter

To strengthen our camera system's fit to  $V(\lambda)$ , we choose an off-the-shelf photopic filter with a spectral mismatch index  $f_1'$  of <3%. We aim to achieve a close fit to luminosity function with the integrated camera system, the sum of the response and transmittance curves for camera, lens and filters. The final filter match of the camera photometer, with the photopic filter, the neutral density filter, the camera

<sup>6</sup> <https://schneiderkreuznach.com/en/photo-optics/b-w-filters/filtertypes/uv-clear/nd-800-series>

sensor response, and lens transmittance. We find that the combined response curve of all these components is a closer fit to  $V(\lambda)$  than the photopic filter curve by itself, primarily because the camera response mismatch offsets some of the photopic filter mismatch.

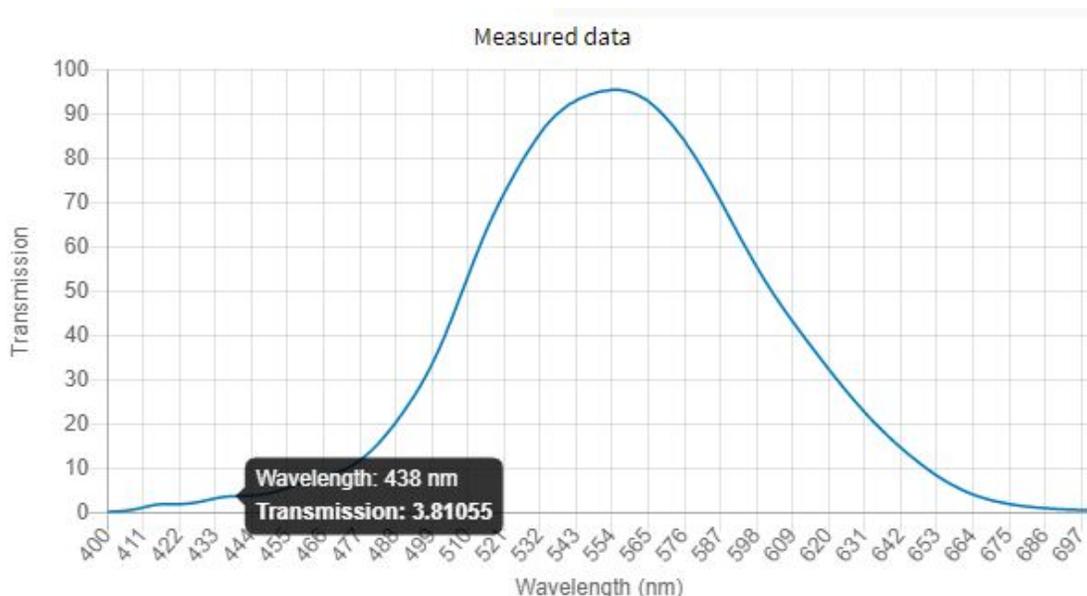


Figure 1: Relative transmission for the chosen photopic filter, Omega 55BP100

## Camera Calibration

Our camera photometer requires several calibration, configuration, and image processing steps to achieve accurate, repeatable measurements. We perform initial calibrations, to be updated periodically (e.g. annually), in our lab. Other steps must be performed for each TV tested.

### Initial/Annual Calibration

#### Aperture Setting

As mentioned above, we set the lens aperture so that we achieve an approximately 2:1 ratio between Basler signal level and  $\text{cd}/\text{m}^2$  as measured by our PR650. We then fix the lens in place by tightening a small thumb screw in the lens and by applying white-out to help fix the position and to make it obvious if the aperture setting has shifted. It is impossible to set the aperture to achieve exactly a 2:1 ratio; for example, if you achieved a 2:1 ratio setting the aperture using one TV, you might end up with a 1.94:1 ratio for a TV with a significantly different spectral power distribution. This step is intended to set the approximate ratio between signal level and  $\text{cd}/\text{m}^2$ . As discussed below, we perform a more precise TV light level calibration for each TV to achieve the needed accuracy level.

Setting the aperture this way still avoids pixel saturation for even today's brightest TVs—the brightest TV in our last round of testing, a TV rated for and co in our last round of testing, playing the dynamic clip



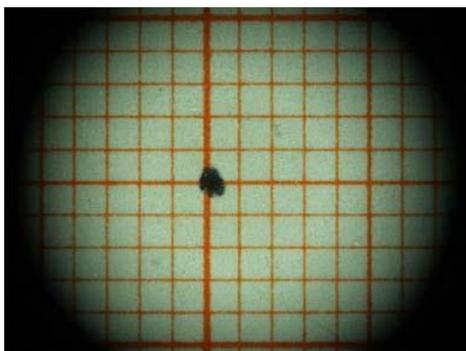
during the brightest picture setting, had a maximum pixel brightness reading of 1760 nits. Additionally, it is unlikely that clipping at around 2000 nits will present significant statistical error, as we expect only a negligible proportion of content to reach that level of brightness (a single area of the screen flashing bright for a fraction of a second during HDR content)

Though we previously chose a 1:1 signal to luminance ratio, we found that since the actual signal values in the 12-bit system are discrete, the achieved accuracy at low levels was too low with that level of granularity—a given pixel could only read 1, 2, 3, 4... nits. At that level of light, the percentage difference represented by this granularity was too large. Since some TVs can read in the single digit range during the dynamic test clip in dim light or dim picture settings, it made sense to increase the accuracy of the camera system at that range by doubling the granularity of the measurements.

### Vignette Effect Correction (Flat Field Correction)

The purpose of the calibration is to correct for the decreasing brightness of pixels farther away from the center of the image due to mechanical and optical effects of the lens and camera. This calibration is conducted once per camera per calibration period, at each distance the camera will be used for measurement. The vignette effect is separate from the “viewing angle” effect described in a previous section. This system does not compensate for the “viewing angle effect” for the camera because the effect is also observed by a human viewer. The vignette effect is corrected because it is unique to the camera optics.

An example of the vignette effect is shown here:



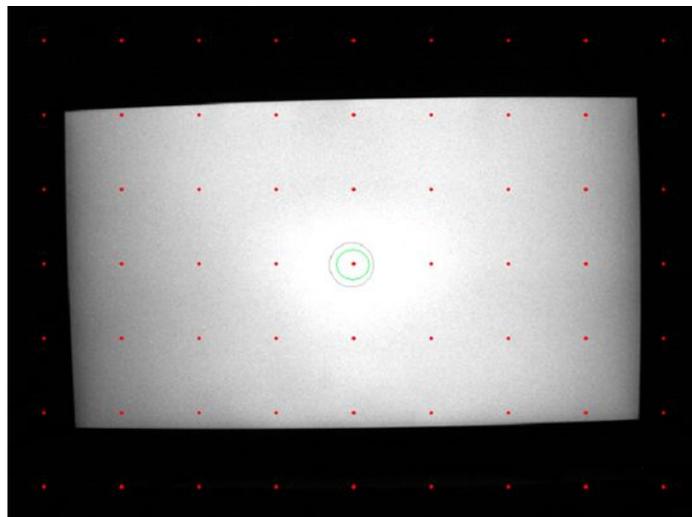
The calibration procedure is as follows:

1. Set the camera to the exposure time and aperture settings we are using for our tests. Attach the chosen neutral density filter.
2. Display the vignette calibration image on the TV (a uniform white image with a gray circular outline in the center)<sup>7</sup>

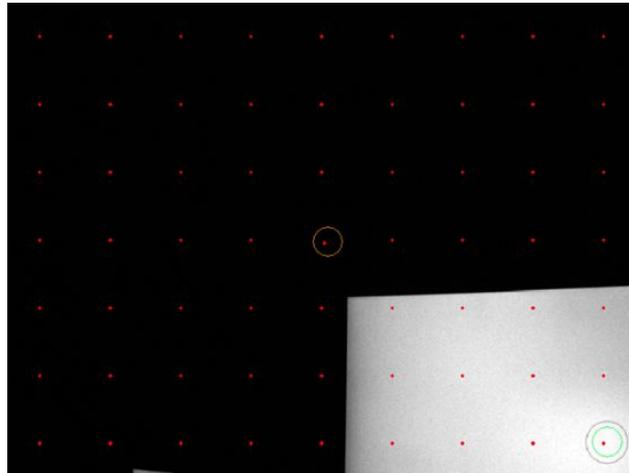
<sup>7</sup> We later moved to a black background outside the grey circle to reduce the risk that glare affects our calibration.



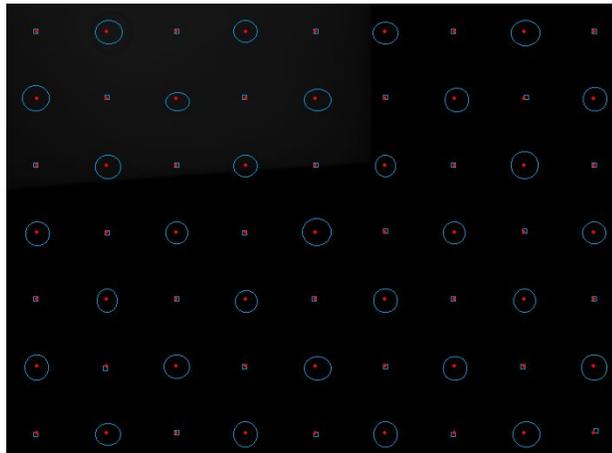
3. Take a brightness measurement of the marked circular area, with the circle lined up in approximately the center of the image. The image below reflects the view of the TV from the calibration tool.



4. Rotate the camera about its center of focus so that the red circle is located in a different part of the image.



5. Take another brightness measurement
6. Repeat Steps 4-5 until measurements across the entire image area are taken. A grid of small dots in the calibration software shows the intended array of measurements to take. The resulting set of data points will look something like this:



The calibration software will interpolate between all the measurements and create a vignette correction image that is applied to images during the test. It makes a 3-dimensional quartic fit using the least-squares method, with the x and y coordinates of the measurement as the independent variables, and the measured brightness as the dependent variable. A flat field image is created with this quartic regression.



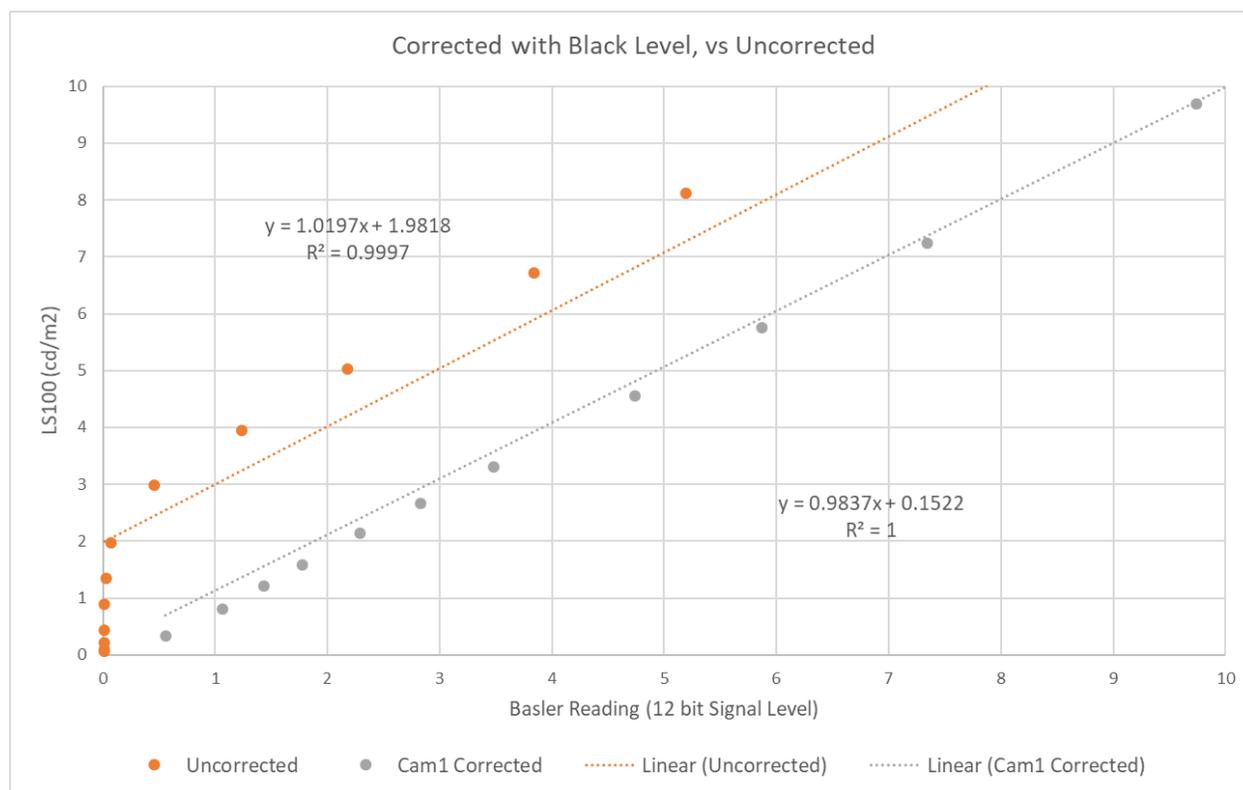
The test system uses this image to correct for the vignette effect by applying the following equation to the pixel values of acquired images:

$$\text{Corrected Image} = \text{Original Image} \times \frac{\text{Maximum Value of Calibration Image}}{\text{Calibration Image}}$$

#### Black Level and Dark Field Correction

At the low end of the camera dynamic range (pixel brightness values below 5), there is a nonlinearity observed for the relationship between the camera signal level and the actual measured luminance from the reference light meter. This is due to “black crush” (the camera compresses brightness values at the low end of the range). To compensate for this, the camera’s black level setting (which is 0 by default), is set to a positive number. The camera sensor increases the signal of all pixels by the black level setting. This results in more headroom on the low end of brightness, which mitigates the “black crush” effect and increases linearity of image brightness and luminance.





Dark field calibration is used to correct for image noise (dark current and fixed-pattern noise). The dark field image is obtained by taking a picture with the camera lens completely obscured. The camera is set to the same settings that are used for testing, including the black level. The brightness level of the dark field image is offset by the black level setting the same amount that every image that is acquired during a test is.

To apply the correction, this dark field image is subtracted from every acquired image from the camera. The brightness offset from the black level setting is compensated for as well with this correction.

$$\text{Corrected Image} = \text{Acquired Image} - \text{Dark Field Image}$$

Upon request, we can provide detailed pixel level maps that show what each of the corrections discussed above accomplishes.

For a pixel close to saturation, for example, the master black level of 80 brings the maximum signal down from 4096 to 4016; with the aperture set to read a 2:1 signal to luminance ratio, this translates to an expected cap of 2008 nits.

### Per-TV Image Processing and Correction Factors

The steps below are performed as an integral part of each TV unit test.



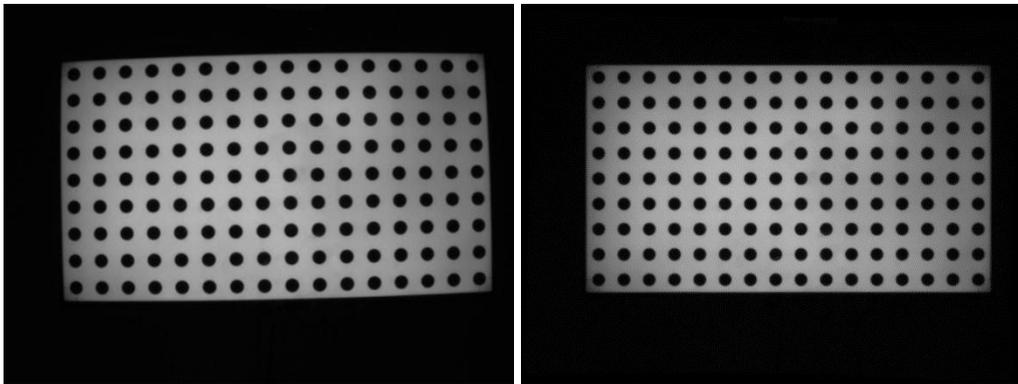
### Screen Detection

At the beginning of a TV test, immediately following the distortion and perspective correction, the test software detects the border of the TV screen by using a particle detection algorithm that detects the bright image against the dark surrounding environment. The pixels on the edge of this border sometimes overlap both the TV image and the dark environment. The edge pixels could have a small effect on the readings, so the rectangle region of the screen is reduced by one pixel in each direction. The luminance readings that are calculated for the rest of the test will now only use the portion of the camera image that is within the screen border.

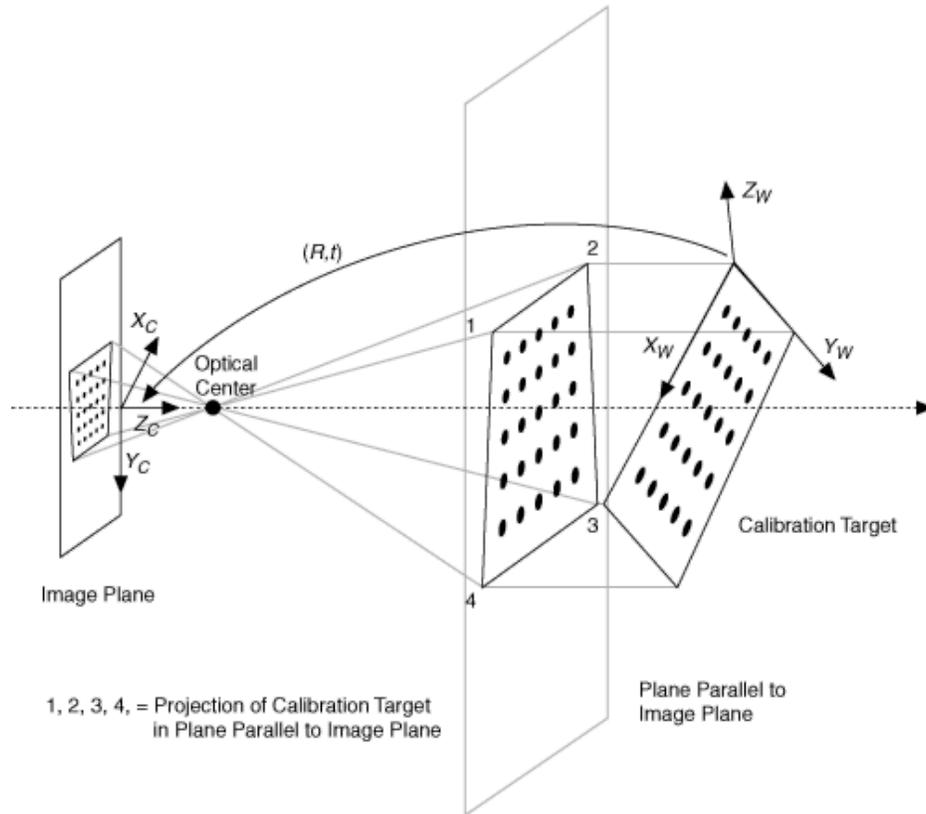
### Distortion and Perspective Calibration

The purpose of this calibration is to correct for spatial distortion of the wide-angle lens. This calibration is conducted once per test, at the beginning of the test.

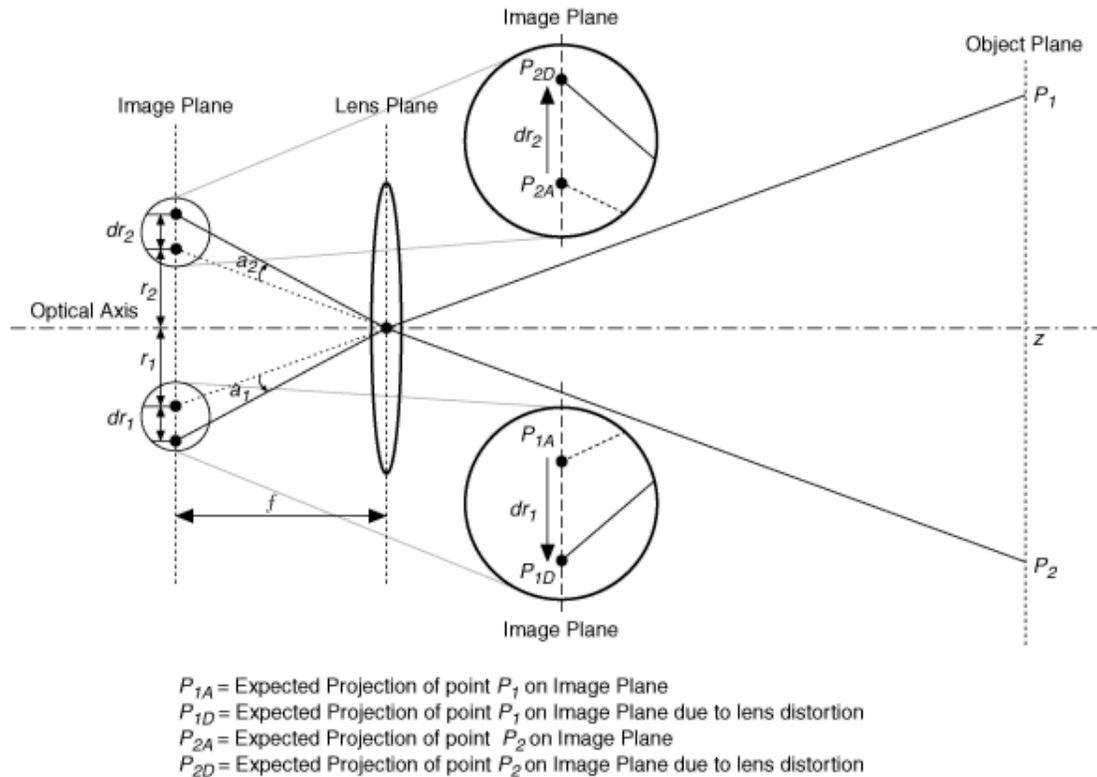
An example of the before-and-after for distortion and perspective correction:



At the beginning of the test, a rectangular grid of dots is displayed. The test system software identifies the position of the dots on the screen and develops a distortion model based on the positions. To correct for perspective, a transformation matrix is created that projects the tilted plane of the original image to a plan parallel to the image sensor.



To correct for lens and camera distortion, the software estimates a distortion model based on the following geometry:



The model equation is:  $x_{corrected} = \frac{2x}{1 + \sqrt{1 - 4K(x^2 + y^2)}}$

The coefficient  $K$  is estimated based on the position of the dots. The inverse equation is used with the estimated  $K$  to correct subsequent images. A correction based on these models is applied to images from the rest of the test. Further information about the vision software package used can be found on the [National Instruments website](#).

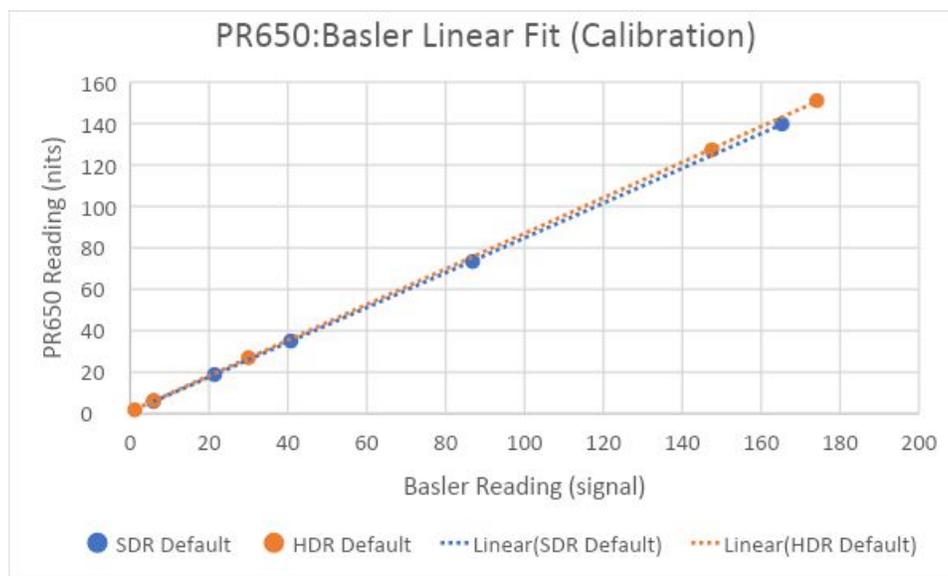
#### Luminance Calibration:

Rather than calibrate our cameras against a standard illuminant (e.g. Illuminant A), we calibrate the luminance of our cameras for each TV, a practice that ensures accurate results across the range spectral power distributions seen in today's LED and OLED TVs.

#### Color Correction Factors (CCF)

We calibrate the camera photometer against an individual TV's spectral power distribution by taking a range of greyscale values with the camera photometer and the reference luminance device (in our case, a PR650), and performing a linear fit minimizing relative difference error (Mean Square Percentage Error) between the two. For SDR, we use signal levels of 20%, 30%, 40%, 60%, and 90%. For HDR we use signal levels of 20%, 30%, 40%, 60%, and 75%. We play five frames continuously, for 35 seconds each with a 5 second black frame in between, taking a measurement at 15s, after which we expect TVs to be stable based on our research.

This enables us to make the relevant comparison between Basler and PR650 measurements. The additional 20s of buffer time is to allow for the long exposure time on the PR650, which uses adaptive exposure time, for low-light measurements. This final calibration adjustment *per TV* ensures that the adjusted Basler measurement reads very close to the reference luminance device.<sup>8</sup> The following figure shows the linearity of one calculated adjustment; high linearity here suggests that the timing on our calibration process ensures that the PR650 and Basler are measuring the same light output during the calibration clips.<sup>9</sup>



### Simultaneous Measurements

During the course of refining the camera photometer system and test process, we found that it is not accurate enough to take the readings with the camera photometer and the reference luminance device asynchronously. Repeatability testing across several TVs revealed variance of up to 10%, run-to-run, independent of the measuring device (see [Appendix B: Characterizing TV Instability](#)). Intuitively, if there is a difference in actual light output between two runs, the possible calibrations can vary by as much as the variance of the TV, leading to lower accuracy in the system. As an example to explain this, data from several runs on a particular TV is compiled in [Appendix C: Effect of TV Instability on Calibration](#). The expected accuracy in the calibration at a given luminance level would be proportional to the error displayed “run-to-run” during the calibration process.

Unfortunately, the reference luminance device cannot sit directly behind the camera photometer and take measurements of the exact same light simultaneously—the field of view of the reference device is obstructed by the camera photometer. Instead, we perform the following process:

<sup>8</sup> This type of light-source-specific calibration is often called a color correction factor (CCF). For more background on color correction factors, see this presentation:

<https://www.slideshare.net/theilp/pls-2014-is-measuring-led-illumination-with-a-lux-meter-accurate>

<sup>9</sup> Note that we made these measurements before opening the aperture to achieve a 2:1 signal to cd/m<sup>2</sup> ratio per the section on Aperture Setting above.

1. Set the reference device directly behind the camera photometer, with its measurement area centered on the following video signal (the same signal that we use for vignette calibration):



2. Tilt the camera photometer out of the way, then take a reading with the reference luminance device at least 10 seconds after the clip starts.
3. Without changing the clip, and within one minute of the clip starting, adjust the position of the reference device to be as close to parallel with the camera photometer as possible, but at a slight angle to measure the same area of the screen. Note: both the head-on and off-angle measurements should be taken between 10 seconds and a minute after the clip starts, to avoid the effects of initial luminance spikes as discussed later in [TV Stability and Timing Accuracy](#), and to avoid any Automatic Brightness Limiting features present on OLEDs and other TVs sensitive to static pattern burn-in.
4. Take a second measurement.
5. Use the ratio between the two measurements as a correction for the angular attenuation of the light coming off the TV, then take measurements on the color correction factor clips simultaneously with the camera photometer and the reference device.

#### *Using a Single Preset Picture Setting for Luminance Calibration*

We have observed for the small subset of TVs we have tested so far that the calibrations calculated for the camera do not vary significantly (slope typically varies <1%) across picture settings. This makes sense intuitively; unless the actual spectral light profile of the TV changes between picture settings or between SDR and HDR, the needed calibration should not change. Testing a larger set of TVs in November 2020 should give us the sample size we need to determine whether you can do a single calibration for a given TV, or indeed for a given technology type.

## Error Analysis

Below we first present a breakdown of the error of our camera system as used for TV testing. This error includes test process errors as well as camera specific errors as evident in the overview table below. We then compare the accuracy of our proposed approach (< +/-5.0%) to today's approach to measuring luminance.



## Error Breakdown (Camera Photometer)

The table below shows the error breakdown of our proposed camera photometer approach.

Error Source	Proposed Camera Photometer
Spot luminance device accuracy	+/-2% (Specified accuracy of a PR650, our reference spot photometer)
Spatial luminance measurement	+/-1% (Basler-based camera photometer method spatial accuracy relative to a Radiant Prometric Y29, our reference camera photometer)
Observed spot measurement accuracy (24 color pattern)	+/-2% (observed accuracy with method improvements: combination of filter match, TV stability, test timing)
Worst Case Total Accuracy	< +/-5.0%
Expected Repeatability: Observed device-to-device camera photometer variation for dynamic test clips on stable TVs (variations across lots of Basler camera sensors and lenses, filters)	+/- 1%

Below, we explain the method used to determine the accuracy figures shown in the above table:

- Assessing reference spot photometer accuracy.
- Determining spatial accuracy by comparing whole-sensor readings from our camera photometer against those of a Radiant ProMetric Y29 camera photometer using a white pattern.
- Determining experimental error due to TV stability, test timing, and filter match with a spot reading test, using static clips with colors representative of those found in the dynamic test clips.

### Spot Luminance Device

The PR650 gives a specified accuracy of 2%, calibrated against illuminant A. However, there is a key difference in how a spectroradiometer measures luminance to how a filter-based device like our camera or an LS150 measures luminance that leads us to believe that a calibrated spectroradiometer is highly accurate across light sources with different spectral power distributions. A spectroradiometer refracts incoming light across an array of sensors, giving granular data at small wavelength increments; luminance is then calculated directly from that data. Our research and the opinions of experts we have consulted leads us to believe this is more accurate than a filter-based approach.

### Spatial Error

For our camera photometer system, we measure the luminance of the entire screen and take the average luminance over all frames in a dynamic video. Clearly this accounts for spatial differences in the TV screen. We measured our spatial error by comparing our camera to a Radiant Y29, which has highly accurate vignette calibration and spatial corrections. We took Basler luminance profiles (recorded all Basler luminance values for pixels focused on the TV screen) and compared them to those taken by the Y29 on the same TV.



To simplify the calculation (the two devices take measurements at different resolutions), we down-sampled the luminance measurements to a 7x9 grid, the same resolution at which we perform our vignette calibration. This table represents the ratio of Basler:Y29 measured screen average for that region of the screen, normalized at the center, where we take spot measurements.

(X,Y)	-4	-3	-2	-1	0	1	2	3	4
-3	1.005	0.985	0.976	0.975	0.976	0.981	0.990	0.993	1.001
-2	1.009	1.002	0.994	0.995	0.991	0.995	0.995	1.002	1.001
-1	1.006	1.000	0.991	0.992	0.992	0.994	0.996	1.001	0.999
0	1.010	0.999	0.993	0.995	1.000	0.998	1.000	1.000	1.000
-1	1.006	0.996	0.987	0.990	0.997	0.996	0.998	1.000	0.998
-2	<b>1.011</b>	0.996	0.982	0.990	0.991	0.995	0.990	0.990	0.992
-3	<b>1.011</b>	0.988	0.967	<b>0.963</b>	<b>0.958</b>	0.964	0.967	0.972	0.989

The further the Basler measurement deviates from that of the Y29, the greater the potential spatial error. Though the relative magnitude of the difference is likely amplified due to small actual readings on the edges of the screen (where it reaches up to 5% difference), we'd still like to characterize exactly whether this contributes to error when measuring the dynamic test clip.

Fortunately, we are able to generate an overall color distribution for the test clip, to see whether, given our knowledge of the spectral response of our camera, spatial differences in color distribution of the clip would be enough to contribute significant error. We end up calculating that this could only account for <1% potential error in the measured screen average luminance, for the dynamic test clips; the overall distribution of the test clip color is relatively uniform, and spatial error, usually due to imprecise placement of the camera, is negligible. We still include it, however, for our worst-case calculations. For reference, this is the averaged picture of the IEC SDR clip; it is uniformly grey:

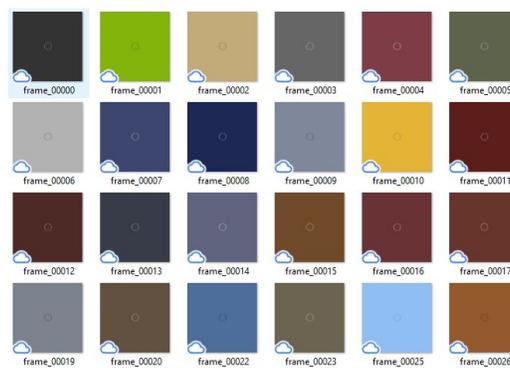




### Experimental Error

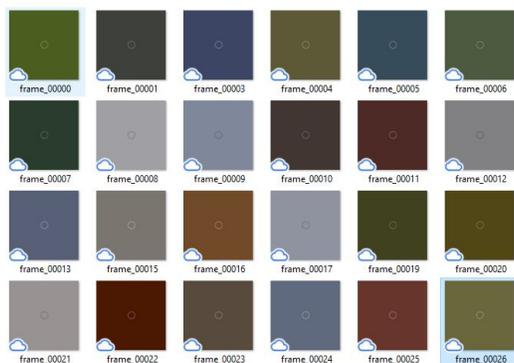
Ideally, we would measure the error of our camera photometer against a known-accurate reference camera. However, calibrated camera photometers available in the market today cannot measure luminance fast enough for use measuring dynamic video and we observed low filter match to the luminosity function. So, we experimentally verify the camera system luminance error (minus spatial error) by calibrating against static patterns. We selected 24 solid colors randomly from the SDR and HDR clips, to represent the range of hues, saturation levels, and brightness in the clips themselves.

SDR frame colors:



HDR frame colors:





We measure each frame with both the Basler and the PR650, inside the circle (the PR650 is only capable of measuring spot luminance). We take an average of all 24 readings to simulate averaging the readings across an entire test clip. In our final check, we reduced the cases to just the default SDR and HDR preset picture settings to save time; we didn't see a remarkable difference in error in the brightest mode versus the default mode in SDR initially. We ended up with the following adjusted measurements, representing an experimentally bound accuracy of  $\pm 2\%$  to the PR650. Since we know the PR650 has a near-perfect fit to the photopic curve, and claims 2% accuracy to luminance measurements, this gives us confidence that experimentally, we are at least 4% accurate in the *worst* case, and strong confidence in our method of calibrating the camera photometer to a white screen, per TV.

TV	Default SDR average luminance ( $\frac{cd}{m^2}$ )			Default HDR average luminance ( $\frac{cd}{m^2}$ )		
	PR650	Basler	Accuracy	PR650	Basler	Accuracy
LCD 1	73.86	73.19	-0.9%	70.08	70.03	-0.1%
LCD 2	58.55	58.54	0.0%	43.36	43.45	0.2%
LCD 3	83.77	83.53	-0.3%	75.20	75.39	0.3%
LCD 4	61.20	61.38	0.3%	55.53	55.62	0.2%
LCD 5	46.04	46.10	0.1%	28.56	28.73	0.6%
QLED 1	83.67	83.03	-0.8%	46.93	47.06	0.3%
OLED 1	51.01	51.95	1.8%	50.02	50.73	1.4%
OLED 2	33.84	33.65	-0.6%	28.24	28.15	-0.3%

Though most of the TVs in this set tested under 1.0% error when compared to the PR650, we did observe up to 1.8% on one of the OLED TVs. OLEDs have the most theoretical error from the filter match; when calibrating against white content on an OLED, we expect the calibration to potentially be off by up to 0.5%: see [Appendix A: Specific mismatch to TV LEDs](#). OLED TVs also have Automatic Brightness Limiting, and we have observed less predictable stability characteristics on OLED TVs, so it is unsurprising that one of our OLEDs shows the largest experimental error, 1.4-1.8%. We attribute most of this observed error to factors like TV stability and test timing.



### Process Improvements

Reducing the measured error to this level was non-trivial and required several considerations to be made in the test setup. These were:

- Observing TV stability across our test sample, we noticed that many TVs take up to 10s to plateau in luminance and power after a static pattern is displayed. To ensure that the measurements of the camera photometer and the reference LMD are taken under the same conditions, we added a timer to our color correction clip, and the exposure for the LMD begins at the same period of the clip that the Basler measures. Not following this procedure can lead to non-linearity in the relationship between the Basler readings and those of the LMD, which is attributed to TV stability, rather than to any characteristics (including filter match, black crush, etc.) of the two devices.
- We observed that the OLED screen burn prevention feature, Automatic Screen Brightness Limiting, kicked in when playing the first version of the 24-color test clip, as the ring around the measurement area was detected as a static pattern. To prevent this from affecting test results, we put a 5 second black frame between each color frame to refresh the internal timer of the TV.
- Camera photometer positioning errors relative to the TV can cause significant variation across test runs, particularly for TVs whose luminance varies more widely across angles. We ensured that our camera sensor and reference LMD sensors were positioned within 1cm tolerance of one another, and that that position was centered directly perpendicular to the center of the TV. Not following this procedure can lead to non-linearity in the relationship between the Basler readings and those of the LMD. We did this by
  - ensuring the TV was parallel to the back wall of the test lab within 1cm
  - measuring from the center of the TV to the side wall and floor and ensuring that the Basler camera was centered exactly.
- We ensured that temperature did not vary by more than 2 degrees Celsius from the start of a test to the end of the test, by controlling the A/C conditions in the room before and after the test, and performing all tests sequentially (i.e., not performing the first part of the test with the Basler one day, and the second part with the reference luminance meter the second day). We do not have data to characterize how important this is, but were careful about it nonetheless. Further research would be required to check whether the current acceptable temperature range would need to be modified.

### Error Breakdown (Current Test Method)

Above, we show that our proposed camera photometer approach can achieve error of  $< +/-5.0\%$ . Below, we put this value in context with the much larger error associated with today's luminance measurement approach.<sup>10</sup>

#### Worst Case Error

Error Source	Spot Photometer	Proposed Camera Photometer
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<sup>10</sup> See Appendix D: Policy Context on Current Luminance Measurement Approach for discussion of the error associated with today's spot luminance policy limits.



Spot luminance device accuracy	+/- 9% (observed with LS100 calibrated against Illuminant A)	+/-2% (PR650 calibrated against Illuminant A, but with better filter match) <sup>11</sup>
Spatial luminance measurement accuracy	+/- 100% (spot reading can misrepresent screen average luminance)	+/-1% (Basler-based camera photometer method spatial accuracy relative to a Radiant Prometric Y29, our reference camera photometer)
Observed spot measurement error	>+/- 100% (measurement within first 5s of bright screen can vary widely)	+/-2% (observed error with method improvements)
Worst Case Total Accuracy	>> +/- 100%	< +/-5.0%
Expected Accuracy	High error given temporal issues mentioned above	+/- 1.0%

We observed the spot reading error when measuring luminance of a grey screen with a KM LS-100 spot photometer compared to our PR 650 spectroradiometer. One would expect a similar error with the IEC 3-bar pattern. KM calibrates the spot photometer to standard illuminant A, and TV test labs commonly test TVs against this calibration. Because the LS100 has a poor fit to the CIE 1931 luminosity function (relative to the PR 650 or the newer KM LS-150), and LED and OLED TVs have SPDs that differ significantly from illuminant A, we see significant error in the readings, which could be reduced if the LS-100 were calibrated against a more accurate device (e.g. PR 650 or LS-150) for each TV. Rather than do that, we recommend that test labs perform spot measurements with a more accurate device, which would result in error values in the range of our camera photometer. We also observe that TV stability error (with U.S. federal test method) could be reduced by ensuring that the measurement is taken while the TV is stable (e.g. after initial ramp up if applicable and before automatic brightness limiting if applicable). We propose this method when determining color correction factors in the new approach; it could be applied to the 3-bar measurements in the current approach.

#### Error with Improvements to Spot Photometer Method

Error Source	Spot Photometer	Proposed Camera Photometer
Spot luminance device accuracy	+/- 2.5% (expected with LS100 calibrated against LED)	+/-2% (PR650 calibrated against Illuminant A, but with better filter match)
Spatial luminance measurement accuracy	+/- 100% (spot reading can misrepresent screen average luminance)	+/-1% (Basler-based camera photometer method spatial accuracy relative to a Radiant Prometric Y29, our reference camera photometer)

<sup>11</sup> It is possible that this error is greater for an LS-150 type device, as it's calibrated to standard illuminant A, and Konica Minolta recommends calibrating an LS-150 against the light source being measured using a gain factor as we do with our TV light calibration method. Until standard LED illuminants are developed, there is not currently a way to ensure high traceable accuracy for LED light measurement on an LS-150; we recommend the use of PR650/655 or similar device until traceable LED illuminants are developed for calibrating LS-150 type devices.

Observed spot measurement accuracy	>+/- 2% (expected error with method improvements)	+/-2% (observed error with method improvements)
Worst Case Total Accuracy	> +/- 100% for TVs with	< +/-5.0%

With the two improvements, the Federal method error is reduced significantly but can still be >100% in the worst case. In other words, two TVs with the same spot photometer luminance measurement can deliver amounts of light to a typical viewer that differ by 100%. When the spot photometer method was developed, TVs used CCFL backlights that were relatively constant compared to today's TVs with local dimming. And the spot measurements were used to ensure that the default preset picture setting was at least 65% as bright as the brightest setting to avoid gaming (i.e. a ratio, not an absolute reading).

It is our belief that the spot measurement may have been more appropriate for that policy and technology scenario. However, local dimming involves dynamic backlight adjustment, and new policies (e.g. ENERGY STAR v8) set minimum brightness levels which effectively mean that TVs with high spot readings relative to screen-average luminance have an advantage since all certified TVs are required to achieve a minimum spot luminance level. So, we define light delivered to the viewer while playing dynamic video content as the desired metric and assess up to 100% error to the current static-pattern, spot-measurement method.

#### Luminance Measuring Device Spectral Accuracy

The current test method is non-specific about the source of the accuracy calibration for the luminance measuring device; DOE refers to IEC 62087-1 5.1.7, which states "The LMD shall have an accuracy of  $\pm 2\% \pm 2$  digits of the digitally displayed value or better." However, the method does not dictate to which standard illuminant that accuracy should be measured. All devices we checked that claim certain accuracy to the photopic curve measure to standard illuminant A, an incandescent, rather than to an LED. It goes without saying that standard illuminant A has a significantly different spectral profile than any of the TV light sources. If we expect that even the small differences between different TV sources require individual calibration, clearly calibrating against an incandescent is inappropriate.

We experimentally verified that certain calibrated instruments who state accuracy to standard illuminant A do not necessarily exhibit the same degree of accuracy against TV screens, even with just a white screen displayed on the TV. A recently calibrated LS100 and an LS150 we have in our lab, each read within 2% of the PR650 on an incandescent white light source with spectral power distribution close to illuminant A. Meanwhile, on a QLED displaying a white screen, the two instruments read 330 nits and 337 nits, while the PR650 read 361 nits. This amounts to a potential difference in measured luminance of 9% if the device is not calibrated against an LED. This is just a single data point; however, a TV with sharper peaks in its spectral power distribution could be worse.

With this in mind, we do not expect every device claiming 2% accuracy to illuminant A to achieve the same accuracy to TV screens. At the very least, we recommend requiring LED-specific calibration of any luminance measuring device, even those with a strong filter match using a similar process to the one described in [TV Light Calibration](#), possibly in addition to some requirement for general spectral mismatch index  $f_1'$ .

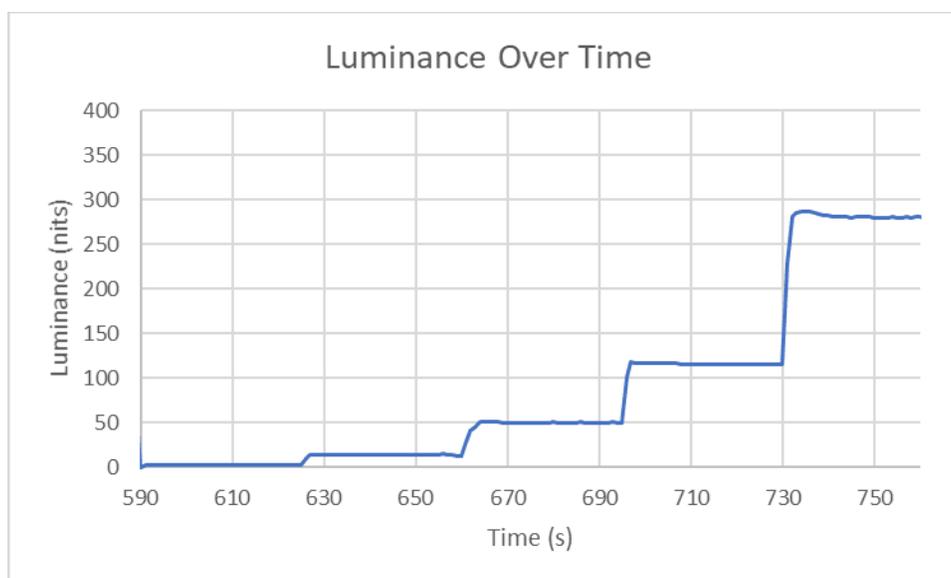


### Spatial Accuracy

The current test method only measures at the center of the screen, which does not account for spatial differences in light output of TVs; some TVs, due to the geometry of their backlight or other design reasons, end up with significantly less measured from the viewer's perspective at the edges or corners. Using a single measurement at the center of the screen to characterize average screen luminance necessarily means extrapolating that measurement to the edges of the screen. However, from our testing last fall, we observed that for some TVs, in the brightest picture settings, center screen brightness can be up to 2x (100% error) brighter than the average screen brightness perceived by the viewer. This rewards uneven lighting as perceived by the viewer in the current test method. We expect this error would be reduced if we backed the camera further away from the TV as is currently being discussed.

### TV Stability and Timing Accuracy

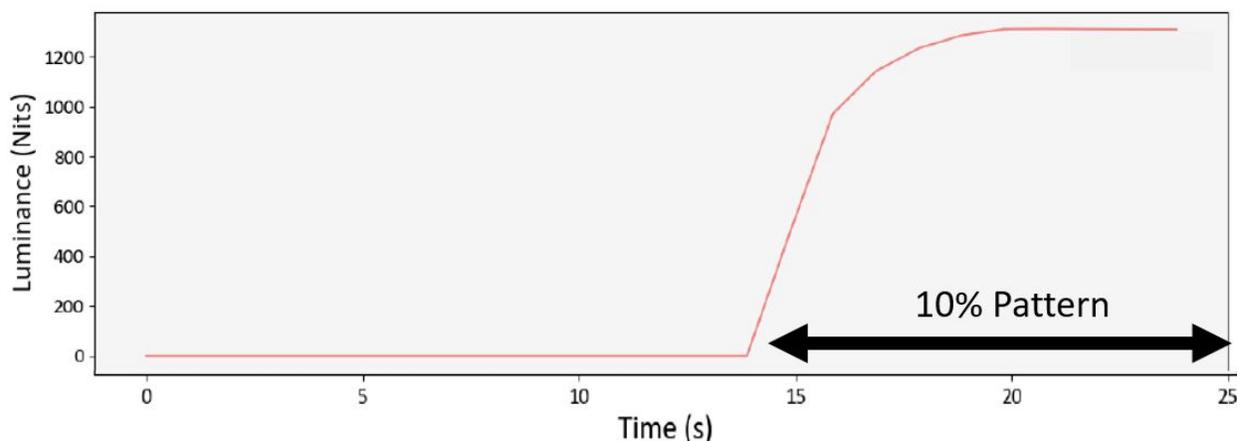
The current method requires the measurement of a single static pattern (the three-bar signal described in 62087-3) within 5 seconds of providing the signal to the TV. Merits of measuring luminance dynamically versus a single measurement notwithstanding, this method can produce highly variable results, depending on the TV. As part of our investigation into possible sources of error for our method, we observed that some TVs, particularly when the static pattern is bright, spike in brightness within the first 10 seconds of a static pattern appearing, before stabilizing at a normal level. The following figure highlights this behavior, sampled from our testing, representing (in the worst case) a drop from 287 to 280 nits, a difference of 2.5%:



In other cases, starting a bright static clip from dark (especially for bright TVs), the TV takes time to ramp up the backlight—for the following TV, a tester measuring even between seconds 1 and 5 of the clip



starting could read anywhere from 600 to 1200 nits; at the very least, a test method needs to account for these stability readings by delaying a static reading.



Stability notwithstanding, TVs will dim their backlight locally to save power when dynamic content is playing; this is not reflected by current luminance measurements, as a single static measurement does not reflect the overall brightness of content typically displayed by the TV.

### Camera-to-Camera consistency

To verify that the camera system is reliable, and the process is repeatable, we came up with a test to verify that multiple cameras delivered the same final luminance measurements. We chose three TVs—from three different manufacturers—that displayed low variation between runs in actual luminance output as measured by multiple luminance devices; see [Appendix B: Characterizing TV Instability](#). For each TV, we ran through the CCF calibration first in each picture setting, followed by the SDR dynamic test clip in the default picture setting and the brightest picture setting, and the HDR dynamic test clip in the default picture setting. All test clips were run with ABC off to ensure that any variability in light sensing or measurement was not a factor—attempting to isolate the potential error to the camera system.

We did this for four different cameras, and had a fifth ‘shadow’ camera set up at an angle (but not moving between tests) as a reference for determining whether relative luminance changes between runs was due to the camera system, or the unit under test. The results are summed up in the followed tables:

#### TV 1

	Luminance (nits) SDR Default	Luminance (nits) SDR Brightest	Luminance (nits) HDR Default
Camera 1	53.50	57.70	33.20
Camera 2	53.50	57.54	33.01
Camera 3	53.59	57.69	32.90
Camera 4	53.32	57.54	33.04
Average	53.48	57.62	33.04



Variation (%)	0.5%	0.3%	0.9%
Shadow (%)	0.1%	0.2%	0.4%

**TV 2**

	Luminance (nits) SDR Default	Luminance (nits) SDR Brightest	Luminance (nits) HDR Default
Camera 1	34.21	61.07	21.47
Camera 2	34.00	61.60	21.24
Camera 3	34.41	61.59	21.30
Camera 4	34.31	61.46	21.39
Average	34.23	61.43	21.35
Variation (%)	1.2%	0.9%	1.1%
Shadow (%)	1.9%	1.9%	0.9%

**TV 3**

	Luminance (nits) SDR Default	Luminance (nits) SDR Brightest	Luminance (nits) HDR Default
Camera 1	37.71	55.29	18.44
Camera 2	37.45	54.82	18.14
Camera 3	37.23	55.30	18.35
Camera 4	37.12	54.68	18.17
Average	37.38	55.02	18.27
Variation (%)	1.6%	1.1%	1.7%
Shadow (%)	1.6%	1.1%	0.6%

Variation observed between cameras across the runs was comparable to variation observed from the shadow camera, which did not move between runs. The shadow camera's readings varied by no more than 2% across each run for each picture setting; generally, this correlated to the variation observed with four different cameras. On the first TV, where the shadow camera's readings varied by no more than 0.4%, the adjusted readings from the four cameras varied by an additional 0.5%.

It is difficult to extract exact error bounds from this data since the largely negligible difference between two given runs could come from either the camera or the TV; however, we can comment on the high degree of repeatability during these tests: <2% across 4 cameras for each of three TVs, where the shadow camera also observed <2% variation. This suggests that any differences observed beyond that bound between the runs of two test labs should be independent of the camera photometer system—in other words, any given unit of our camera photometer system, with calibrations done correctly against a highly accurate reference device, can be expected to meet our stated accuracy levels.

## Further Improvements

Further improvements to the system's fit to the photopic curve  $V(\lambda)$  could be made through the order of a custom filter that takes into account the spectral response of the camera sensor and transmittance



of the lens when correcting for the filter match, improving our camera system's overall fit to the photopic curve. At this time, however, we do not recommend that approach for short-term testing, as there is long lead time on the filters, NRE of about \$20,000, and the increase in precision might be incidental. We would like to learn more about the statistical variation in camera/CMOS spectral response curves and to get feedback from TV manufacturers before investing in the development of a custom filter.

Theoretical error could be bound more confidently by running the cameras through an integrating sphere to characterize the spectral response of the camera photometer at higher granularity, as well as giving us an understanding of how widely the spectral response can vary between the individual parts that make up the system. To measure each camera's spectral response curve, we would need an integrating sphere fitted with a monochromator; these systems are in the \$80,000 range, which is expensive and not necessary. It may be useful to purchase a much less expensive integrating sphere fitted with an LED standard illuminant, in a year or so when they become available.



## Appendices

### Appendix A: Specific mismatch to TV backlights

With knowledge of the spectral response of our camera system, and the spectral power distribution of the TV units under test, we can come up with a theoretical spectral mismatch factor based on the equations in ISO/CIE 19476: “Characterization of the performance of illuminance meters and luminance meters”<sup>12</sup>. We can do this calculation for the test clip for a given TV, for the theoretical expected deviation in measured luminance during a dynamic test clip from calibrating against a white screen, if all other sources of error are eliminated (see [Experimental Error](#)).

$$s_{rel}(\lambda) = \text{spectral response of camera}$$

$$V(\lambda) = \text{photopic curve}$$

$$S_C(\lambda) = \text{spectral power distribution of calibration source}$$

$$S_M(\lambda) = \text{spectral power distribution of light being measured}$$

$$F^*(S_M(\lambda)) = \frac{S_C}{S_M} = \frac{\int_{380nm}^{780nm} S_C(\lambda) * s_{rel}(\lambda) d\lambda}{\int_{380nm}^{780nm} S_C(\lambda) * V(\lambda) d\lambda} = \frac{\int_{380nm}^{780nm} S_M(\lambda) * s_{rel}(\lambda) d\lambda}{\int_{380nm}^{780nm} S_M(\lambda) * V(\lambda) d\lambda}$$

#### Calculated Spectral Mismatch Correction Factor Against Pure White Calibration

	Pure Red	Pure Green	Pure Blue	Pure White	SDR Clip Average	HDR Clip Average
LCD LED#1	1.012	1.000	1.001	<b>1.0</b>	1.0026	1.0025
LCD LED#2	1.003	0.999	0.998	<b>1.0</b>	1.0000	1.0000
QLED	1.002	0.998	1.011	<b>1.0</b>	1.0002	1.0005
OLED	1.013	0.998	1.040	<b>1.0</b>	1.0042	1.0048

The sharper wavelengths of the QLED and OLED (see the spectral power distributions in [Spectral mismatch against TV light](#)) lead to greater expected error, but in general, when we calibrate to white screens, the amount of error theoretically attributed to the filter match is negligible (at most 0.5%) compared to that which can come from simple experimental sources like camera placement, TV stability, etc. We do not calibrate against a calculated ‘off-white screen’ representative of the clip average, as factors like TV stability, electro-optical transfer functions, and differences in TV technology make the actual average light output hard to predict; using a white screen simplifies the process.

<sup>12</sup> Equations modified from ISO/CIE 19476: “Characterization of the performance of illuminance meters and luminance meters” 5.2.4: “Relative Luminous Responsivity and Spectral Mismatch Correction Factor”



## Appendix B: Characterizing TV Stability

In order to isolate error from the camera system and test process, it is necessary to measure accuracy against a TV we consider to be a reliable source of light. Unfortunately, not all TVs on the market can be guaranteed to output the exact same amount of light, even if factors like temperature, humidity, and test timing are controlled. We set up our camera photometer and the PR-650 to take data on a TV. We tested doing a calibration followed by a test clip from one day to the next, keeping test timing identical. We did not move the devices between tests, so that no additional error would be introduced by measurement device placement. On several TVs in our small set of TVs, we observed a high degree of variability in observed luminance—to properly vet the cameras, it was necessary to identify several TVs with better consistency characteristics than these TVs.

We calculate variability across multiple test runs as  $\frac{\text{max}-\text{min}}{\text{average}}$ . Here are some example errors from day to day for a TV that we do not consider consistent enough to use as trustworthy reference luminance sources for vetting the cameras:

### TV variability across 4 days of testing for one of our OLED TVs

Picture Mode	Frame 1 (dimkest)	Frame 2	Frame 3	Frame 4	Frame 5 (dimkest)	Dynamic Test Clip
SDR Default	8.1%	5.8%	5.7%	5.6%	5.0%	3.8%
HDR Default	12.7%	9.7%	8.7%	7.2%	6.7%	3.3%
SDR Default (PR 650)	12.7%	9.7%	8.7%	7.2%	6.7%	N/A
HDR Default (PR 650)	48.3%	7.8%	5.4%	5.6%	4.7%	N/A

Before using a TV as a trusted luminance source for vetting the camera photometer approach, it is important to first characterize the level of variability observed for the TV as an error bound in which error variability between runs cannot be distinguished between the source and measurement device. For the camera-to-camera checkout step, we verified first that a given TV used in that step would vary by no more than 2% back-to-back on a test clip, and no more than 5% on a test clip day-to-day. In other words, none of the values in an equivalent table for a 'stable' TV would be greater than 5%; for a test done with back-to-back tests (without turning off the TV, on the same day), the equivalent table would be bound by 2%.



## Appendix C: Effect of TV Instability on Calibration

To demonstrate the potential effect of TV instability and inconsistency between even back-to-back runs on the potential calculation of signal to luminance calibration for a given TV, we compare the calibrations done synchronously do those done asynchronously for the same TV for the same camera. This data is lifted from the color calibration step of the four-camera test for one of the ‘stable’ TVs use to measure [Camera-to-Camera Consistency](#).

The following table contains the calculated calibrations for each picture setting using the original camera data for the first run as the x-value in the calibration fit. The y-value is the (synced) reference data for each run, the first being synced with the original run and the other three being from the other, asynchronous runs. Expected CCF error is calculated at a given luminance level

	SDR Default		SDR Brightest		HDR Default	
	Slope	Intercept	Slope	Intercept	Slope	Intercept
<b>Run 1 (synced)</b>	0.5144	0.7848	0.5139	0.7272	0.5122	0.7429
<b>Run 2</b>	0.5204	1.1307	0.5258	0.9313	0.5162	0.8439
<b>Run 3</b>	0.5239	0.5507	0.5268	0.475	0.5122	0.7429
<b>Run 4</b>	0.5155	0.8922	0.5123	0.6972	0.515	0.6906
<b>Expected CCF Accuracy at 10 nits</b>	4.5%		4.5%		1.6%	
<b>Expected CCF Accuracy at 50 nits</b>	1.8%		3.0%		1.0%	
<b>Expected CCF Accuracy at 100 nits</b>	1.6%		2.8%		0.9%	

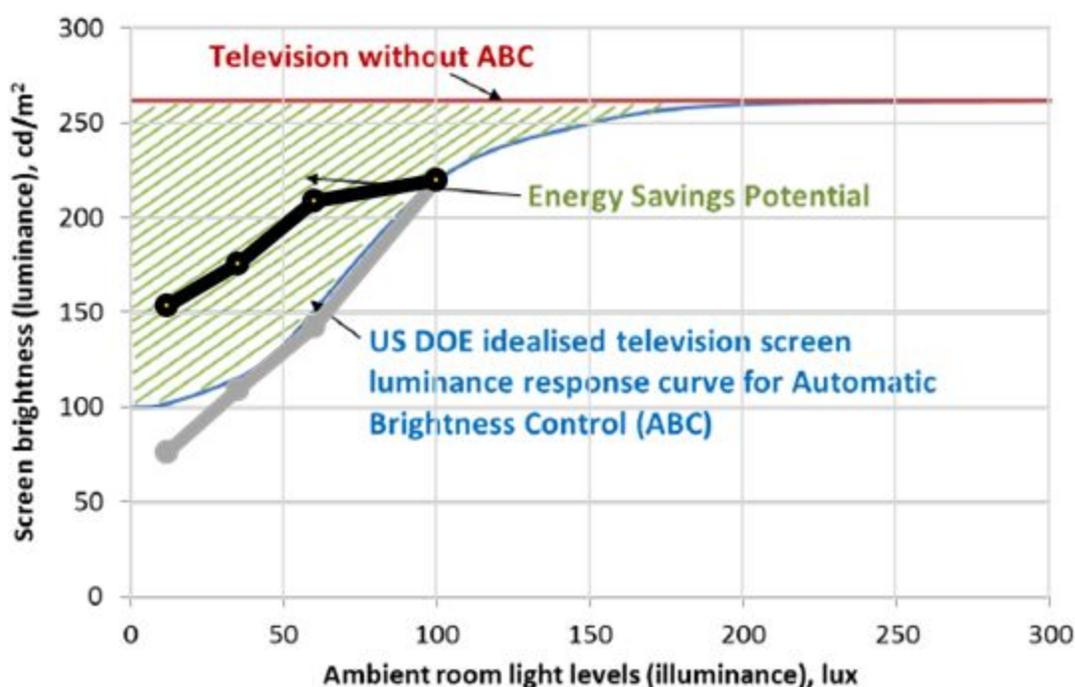
*Especially at low light levels, the calibration process is sensitive to differences between runs, and the error introduced will be proportional to the error observed between runs. Full 50 TV testing will give us a full picture of what the range of ‘stability’ errors can be; however, performing the CCF calibration synchronously prevents this factor from introducing additional error in the test process and camera system.*



## Appendix D: Policy Context on Current Luminance Measurement Approach

US and EU policy use minimum luminance requirements to discourage manufacturers from offering luminance levels in their default setting which are not fit for purpose to score better on the energy efficiency test. We have evaluated the basis for these limits below. We find that there are flaws and uncertainties associated with the basis for these levels. We present this data in support of the proposed camera photometer approach, which can be used to accurately measure how efficiently a TV generates light from the viewer's perspective. In the Error Analysis section of this document, we explain how inaccurate the current spot luminance approach can be; here, we show that the policy basis for spot luminance limits is error prone as well.

A 2012 DOE study<sup>13</sup> documents the rationale behind the idealized luminance curve that Europe used as the basis of the ABC qualification criteria (see Figure below).



*Illustration of ABC limits for Europe compared to overall savings potential*

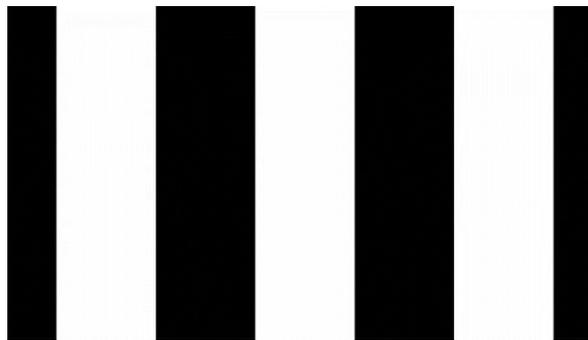
The DOE study references Matsumoto and others, who used a static pattern to measure centre-of-screen luminance with a photometer. As discussed in prior memos, centre-of-screen measurements are not an accurate representation of how bright a TV is from the viewer's perspective. Screen-average is a better metric that we have not had the tools in the past to measure. And Matsumoto's data is based on a 40% peak pattern similar to the 50% peak pattern shown below (In Matsumoto's case, 40% of the screen area was white).

<sup>13</sup> [https://www1.eere.energy.gov/buildings/appliance\\_standards/pdfs/tv\\_tpnopr\\_room\\_illuminance\\_abc\\_031912.pdf](https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/tv_tpnopr_room_illuminance_abc_031912.pdf)

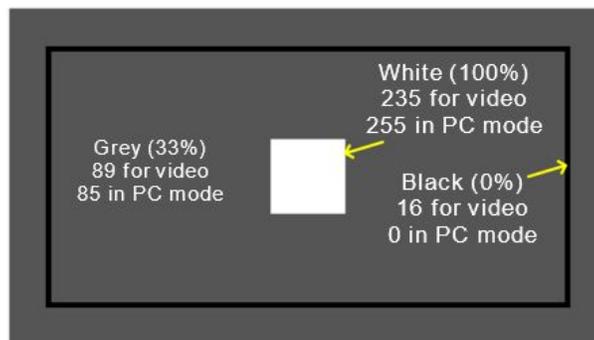


While Matsumoto used a 40% peak window, DOE and EU use the following patterns:

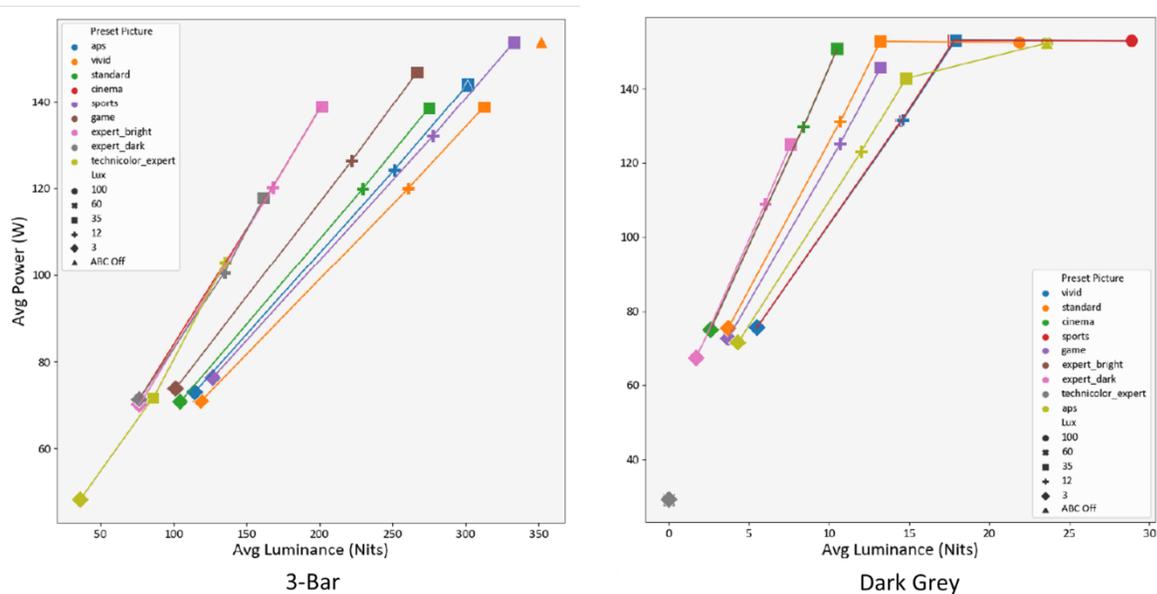
- DOE: three bar video signal (IEC 62087-2:2015, 4.2.2.1)



- EC: box and outline video signal (IEC 62087-2:2015, 4.2.2.2).



So, it is likely that the results are not comparable because TVs respond differently to the different patterns. For example, in 2019, NEEA demonstrated that a monochrome 33% grey pattern produced a non-linear relationship between power and luminance for some TVs; whereas the 3-bar pattern did not.



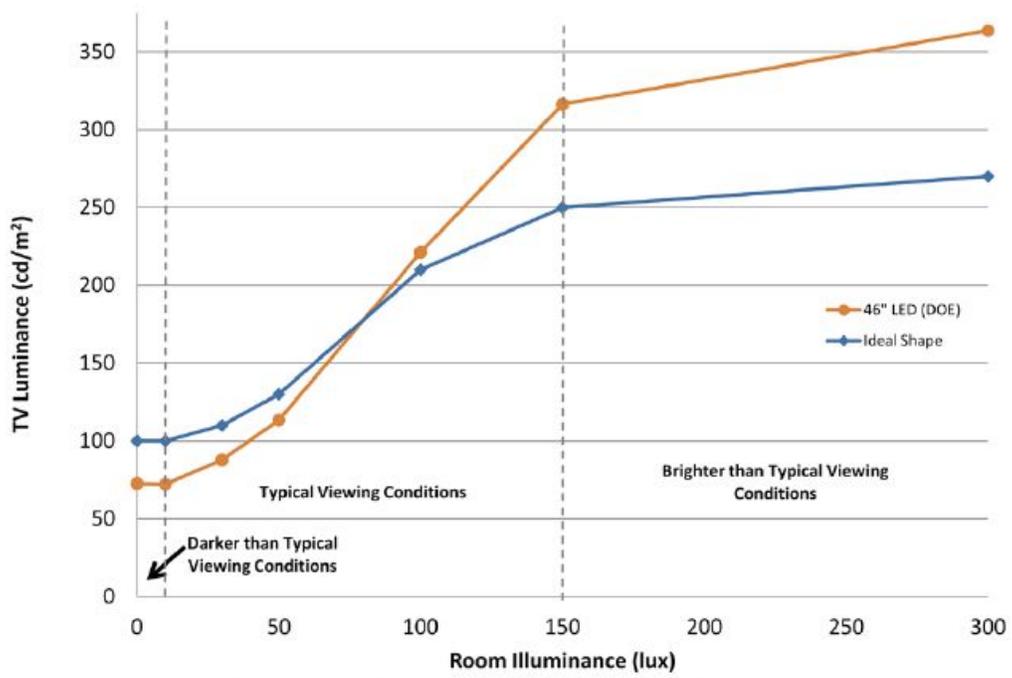
3-bar vs dark grey: LED TV

And yet, both ENERGY STAR v8 and EU luminance limits are based on the DOE ideal luminance curve<sup>14</sup>, which is based in part on Matsumoto. The 2012 DOE illuminance study states, “The ideal TV luminance levels for dark room conditions in Figure 1.3.1 are based on Imaging Science Foundation’s (ISF) recommended brightness level for TVs in a dark room setting, while the luminance levels for brighter conditions are based on a 2010 study on appropriate luminance levels, which found that at 100 lux, subjects preferred a TV brightness range from 160 to 248  $\text{cd}/\text{m}^2$ .” And this is based on undocumented video content with an Average Light Level (ALL), presumably the same thing as APL’, of 25% vs. 34% for the IEC dynamic test clip and based on an angular screen size of 20 degrees, which is a function of screen diagonal and viewing distance from the TV, which have changed since this data was collected. Also note that the ideal appears to be based on the average of the preferred luminance level for young (160  $\text{cd}/\text{m}^2$ ) and old (248  $\text{cd}/\text{m}^2$ ) people. Because the range between the two is so large, neither group is likely to be satisfied with a TV set to the “ideal” luminance value.

<sup>14</sup> Section 1.3.1 of

[https://www1.eere.energy.gov/buildings/appliance\\_standards/pdfs/tv\\_tpnopr\\_room\\_illuminance\\_abc\\_031912.pdf](https://www1.eere.energy.gov/buildings/appliance_standards/pdfs/tv_tpnopr_room_illuminance_abc_031912.pdf)



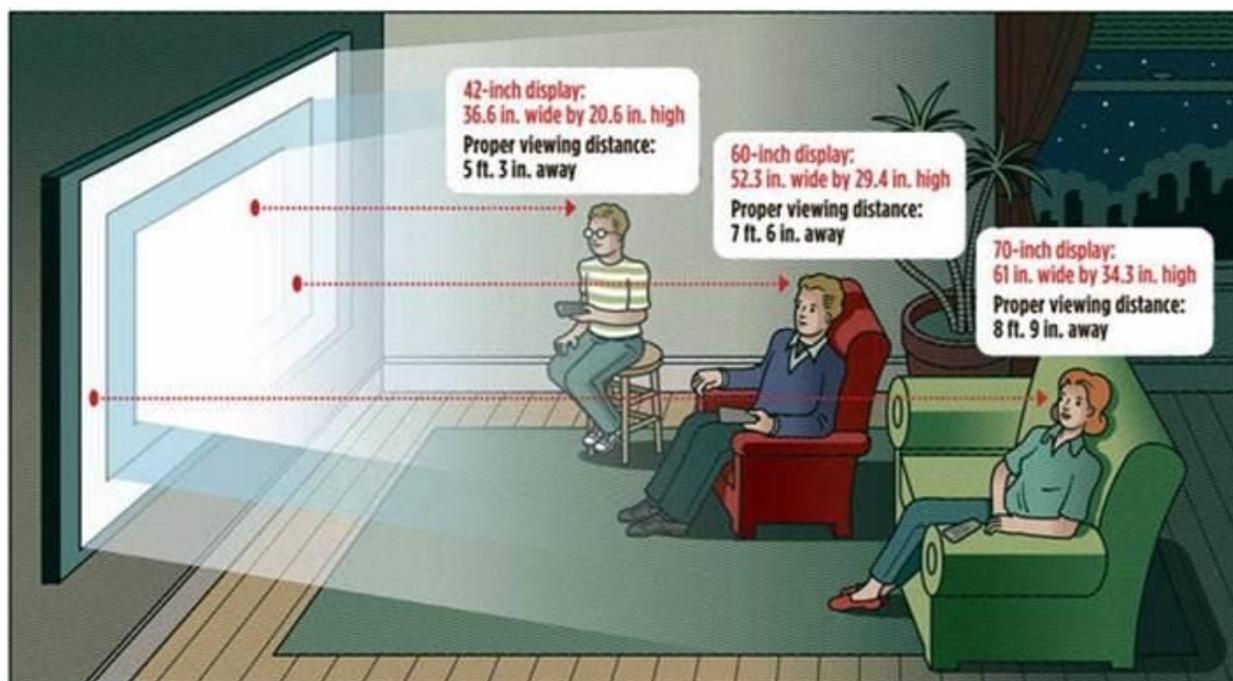


Ideal DOE ABC Luminance Curve



## Appendix E: Justification for Camera Placement Distance from TV

A TV stakeholder presented data that suggests a recommended viewing distance of 2H-2D. 2 x height is approximately 1 x diagonal for a 16x9 TV. This range can be expressed as approximately 1-2D with an average of 1.5D, which is what is shown in the figure below:

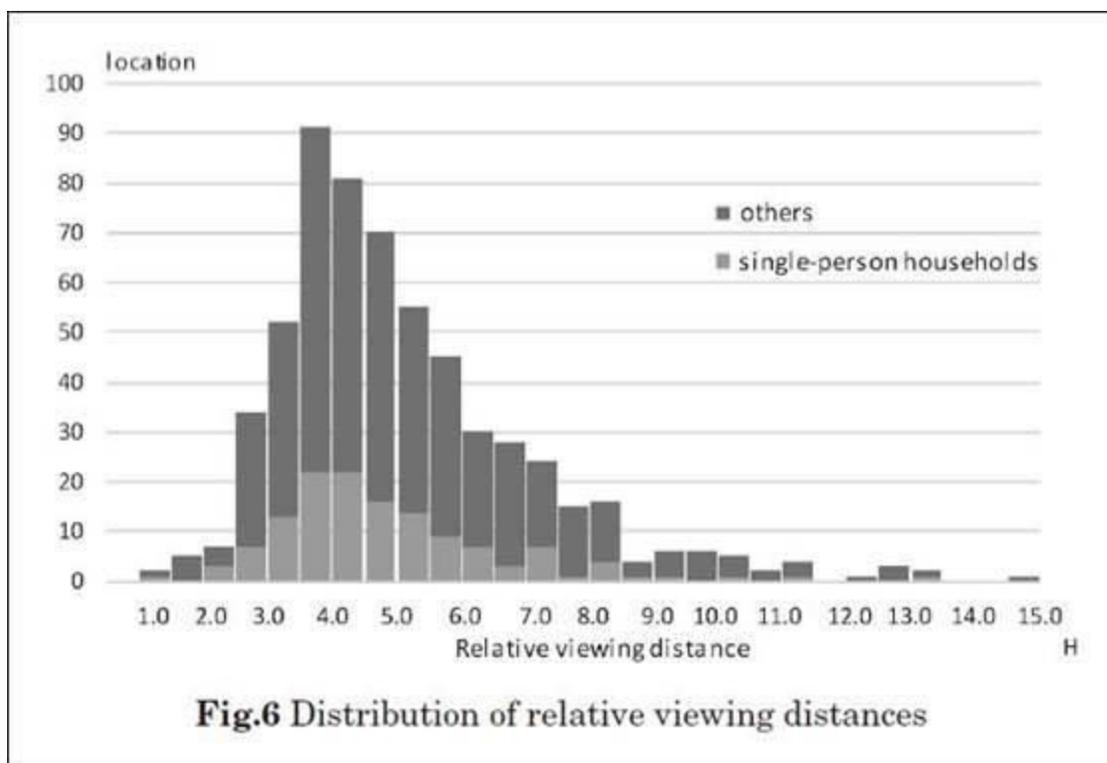


ITU-R Rec. BT.20221 specifies relative viewing distances of 3.2 H (H is the screen height) for 2K television system, 1.6 H for 4K, and 0.8 H for 8K. This translates approximately to the following for 16:9 TVs, the most common aspect ratio:

- HD: 1.5D
- 4K: 0.8D
- 8K: 0.4D

Yagi et. al.<sup>15</sup> show that the average installed TV in Japan in 2019 had a viewing distance of 5H (or ~2.5D for 16:9 TVs), but installed TVs skew towards smaller HD TVs. We are focused on new TVs sold, which are bigger and higher resolution. Yagi et. al. point out that size and resolution are driving the H to distance ratio down over time. And we're designing a test method for use going years into the future.

<sup>15</sup> A Survey of Television Viewing Conditions at Home in Japan, 2019



Basler lens options are shown below. The TV must fill the lens field of view, and there is no zoom capability. So each lens supports a specific distance where the TV width fills the FOV (for 16:9 TVs).

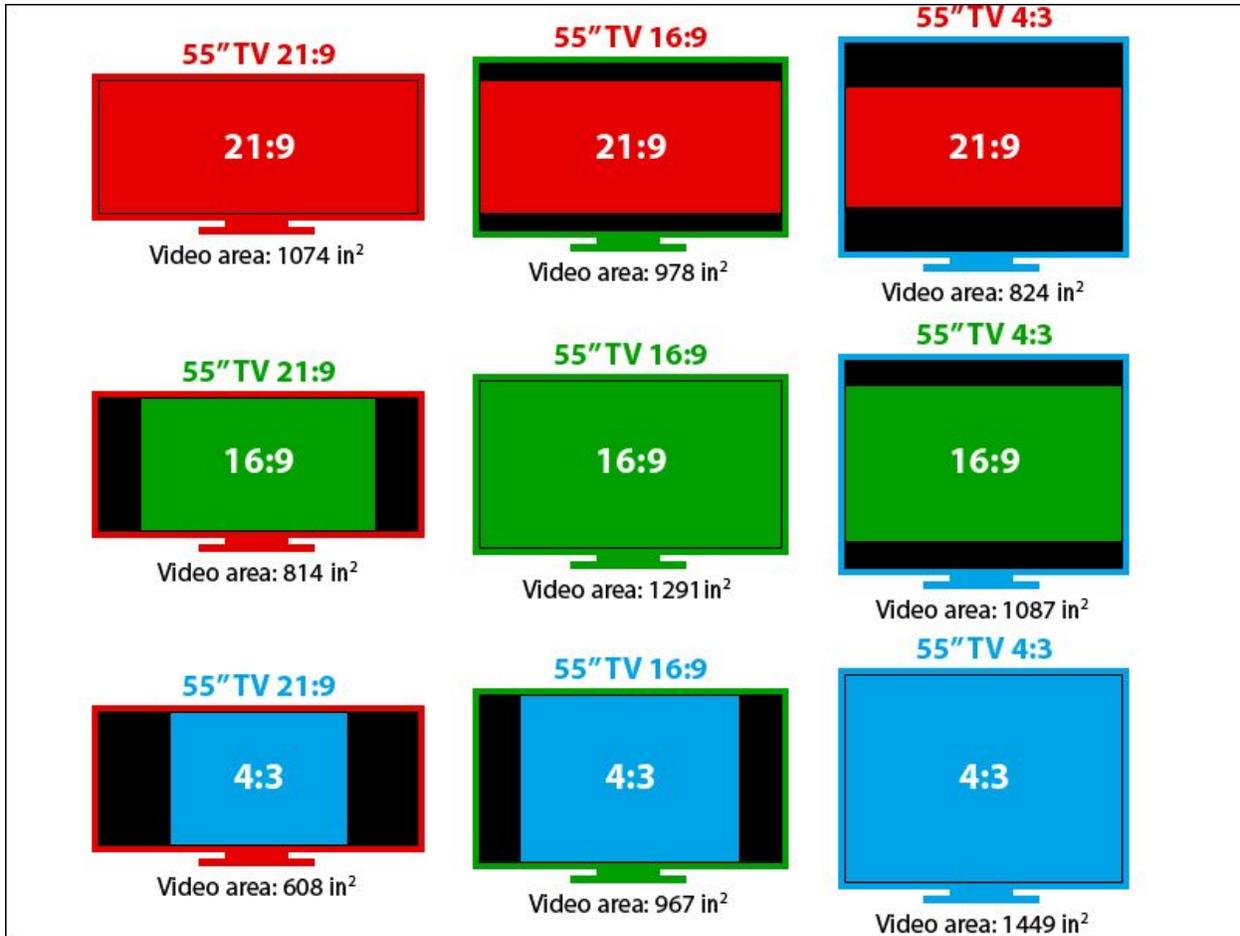
1. 1.06D
2. 1.53D
3. 2.12D

We believe that there may be a 4% difference in expected luminance readings between the first and second options and even 2% difference between the latter two based on the data in the “appendix” below.

So we recommend 1.53 x diagonal (1.53D) because we expect it to be representative of real world viewing distance over the timeframe in which this test method is in use, because it aligns with the above stakeholder data on viewing distance, and because it requires less lab space than 2D. Even if viewing distances do not continue to fall, measured screen-average luminance should not vary much between 1.53D and 2.12D per the data in the appendix below.

For TVs with an aspect ratio other than 16:9, we recommend placing the camera at a distance where the TV width fills the camera FOV as it does for the 16:9 case at 1.53D. In the case of a 21:9 TV, the distance from the camera to the TV would be > 1.53D since the screen diagonal is smaller than the diagonal for a 16x9 TV of the same width.





<https://www.rtings.com/tv/learn/what-is-the-aspect-ratio-4-3-16-9-21-9>

Glad to look at additional data if needed. Hope to get alignment around 1.53 x screen diagonal by EOW if possible when are 1.53D and 2.12D lenses arrive so that we can start calibrating cameras with the final lenses and return the others.

**Note:** We have kept the same camera distance, but we now represent it as a multiple of screen width (1.76-1.78 times the screen width). We do this because it simplifies the calculation for screen that have an aspect ratio other than 16x9.