Improving Color Reproduction Accuracy on Cameras (Supplemental Material)

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Overview

Here we provide supplemental details and results to accompany the main paper. The supplemental material is organized as follows. Section 1 provides details to the algorithm used to estimate the correlated color temperature (CCT) of an observed neutral object in the camera's RGB color space. This corresponds to Section 3.2 of the main paper. Section 2 shows the corresponding 2D plots of the chromaticity values of the color rendition color chart patches from multiple cameras. This corresponds to the experiments in Section 5.2 (multi-camera consistency) of the main paper. Section 3 provides additional results in terms of color reproduction angular error. This corresponds to the experiments in Section 5.2 (individual camera accuracy).

Method 2 (extension): Full color balance with interpolation While the full color balance allows the computation of a fixed CST that should be applicable to all illuminations, from Eq. (9), it is clear the errors for the estimated CST mapping will be minimized for a particular illumination when only a single i is used as described above. As a result, we can use the same interpolation strategy as described in Section 3.2 that used WB corrected images, but instead use full color balance and CST estimated using Eq. (9). Results for this extension approach are not included in the main paper, but can be found in this supplemental material. We present results of this extension (CB + 2 CSTs) incorporated to the tables in the main paper.

Method	Apple iPhone 7		Google Pixel		LG-G4		Canon1D		NikonD40		Sony α57		Olympus E-PL6	
	CC	I	CC	I	CC	I	CC	I	CC	I	CC	I	CC	I
CB + Fixed CST (all)	**0.80**	**0.91**	**0.88**	1.05	**0.81**	**0.86**	**0.84**	**0.63**	**0.93**	0.77	1.00	0.77	0.85	0.69
CB + Fixed CST (single)	0.95	1.04	1.41	1.45	1.17	1.17	0.95	0.76	0.98	0.80	0.99	0.76	0.82	0.67
CB + 2 CSTs	0.83	0.95	1.16	1.21	0.88	0.91	0.91	0.66	0.93	0.72	**0.93**	**0.73**	**0.82**	0.65
WB + 3 CSTs	1.36	1.08	1.27	**1.04**	1.55	1.24	1.04	0.70	1.07	**0.65**	1.04	0.74	0.86	**0.61**
WB + 2 CSTs (re-calibrated)	1.76	1.42	1.92	1.46	1.98	1.54	1.16	0.82	1.33	0.82	1.13	0.81	1.05	0.71
WB + 2 CSTs (factory)	3.07	2.46	2.28	1.75	2.74	2.04	1.58	1.18	2.02	1.26	1.14	0.79	1.12	0.75

Table 1. The table shows the comparisons of error between full color balance with fixed CST, diagonal matrix correction with using 3 CST, native cameras (re-calibrated for the datasets we use), and native cameras (factory calibration). Errors are computed on color chart colors only (denoted as CC), and on full images (denoted as I). The top performance is indicated in bold and green. The second best method is in blue.

Method	Mobile Phones 2900°K	Mobile Phones 4500°K	Mobile Phones 5500°K	Mobile Phones 6000°K	DSLRs 3000°K	DSLRs 3500°K	DSLRs 4300°K	DSLRs 5200°K
CB + Fixed CST (all)	**4.6**	**2.1**	**1.1**	**1.0**	**1.6**	**1.8**	**1.2**	**1.1**
CB + Fixed CST (single)	10.0	7.1	4.9	6.2	2.7	2.9	2.1	1.7
CB + 2 CSTs	7.3	4.7	3.5	4.8	2.2	3.4	1.9	1.7
WB + 3 CSTs	37.9	6.9	6.6	8.1	4.4	2.8	2.3	2.1
WB + 2 CSTs (re-calibrated)	44.9	11.3	9.5	16.7	6.7	3.2	3.4	5.9
WB + 2 CSTs (factory)	34.2	38.2	32.6	36.2	13.3	7.1	7.1	7.7

Table 2. This table reproduces the mean variance for color reproduction (in ProPhoto RGB chromaticity space) for mobile phone cameras and DSLR cameras of the 24 color patches on a color rendition chart. Results are shown for different scenes captured under different color temperatures. A lower variance means the color reproduction is more consistent among the cameras. (Variances values are $\times$1.0E-3). The top performance is indicated in bold and green. The second best method is in blue.

1. Estimating the illumination's CCT

The methods used to compute the color space transform (CST) based on interpolation in the main paper rely on the ability to estimate the correlated color temperature (CCT) of the scene's illumination. The algorithm for determining the CCT is presented here. More specifically, we describe the algorithm to map the estimated illumination of the scene (i.e. the camera's observation of an achromatic or neutral object) to its CIE xy chromaticity coordinates. From the CIE xy chromaticity coordinates, the correlated color temperature can be determined by projecting the CIE xy coordinates to its location on the Planckian locus in the CIE xy chromaticity space that is the basis for the correlated color temperature. The details of this CCT projection are outside the scope of this work and readers are referred to Wyszecki and Stiles [3] for more details.

Instead, we focus here on estimating the CIE xy coordinates. We feel this algorithm is worth noting, because as stated in the main paper, the goal of the combined white-balance correction and CST is to establish a mapping from the camera's color space to the CIE XYZ perceptual color space. However, the interpolation of the CST itself relies on mapping the neutral color to CIE XYZ, before the CST is established. The algorithm described here provides this mapping of the scene's illumination in the sensor's color space to CIE XYZ.

The algorithm presented is based on the algorithm used in Adobe's DNG [1]. The algorithm uses the two pre-calibrated CSTs and their corresponding CCTs. For the camera native method, as well as our proposed interpolation-based method described in Section 2 of the main paper, we use the pre-calibrated CSTs, $T_{\mathbf{l_1}}$ and $T_{\mathbf{l_2}}$ for CCTs values: 2500°K and 6500°K respectively.

The algorithm works by initially assuming that the CCT of the input is 5000K. It then estimates a new CST, $T_{\mathbf{l}}$ based on this CCT using the equations (7) and (8) in the main paper. The new CST is then used to map the camera's neutral point to a new CIE xy value (and a new CCT). This process is repeated until the neutral color's mapping to CIE xy converges to a specific CIE xy value. The final CCT of the scene's illumination is computed using this converged CIE xy value. The algorithm is presented in Algorithm 1.

Algorithm 1 Mapping the estimated illumination to its CIE xy value and CCT

Input: 1. Observed neutral object in the camera's RGB: *neutral*
2. Pre-calibrated CSTs: $T_{\mathbf{l_1}}$ and $T_{\mathbf{l_2}}$ and their corresponding CCT values 2500K and 6500K
3. Lookup function CCT(x, y)that returns the CCT of an CIE x, y chromaticity.

last.x $\leftarrow 0.34$ // Starting values correspond to CCT 5000K
last.y $\leftarrow 0.35$ // in CIE xy
maxNumberOfPasses $\leftarrow 30$
for *pass* $\in \{0, \ldots, maxNumberOfPasses - 1\}$ **do**
  $\mathrm{CCT}_{\mathrm{last}} \leftarrow \mathrm{CCT}(last.x,\ last.y)$
  $g = \mathrm{CCT}_{\mathrm{last}}^{-1} - \mathrm{CCT}_{\mathbf{6500}}^{-1} / \mathrm{CCT}_{\mathbf{2500}}^{-1} - \mathrm{CCT}_{\mathbf{6500}}^{-1}$
  $T_{\mathbf{l}} = g\, T_{\mathbf{l_1}} + (1 - g)\, T_{\mathbf{l_2}}$
  Apply $T_{\mathbf{l}}$ to *neutral* to map it to the updated CIE XYZ
  next $\leftarrow$ the updated CIE xy
  if $|next.x - last.x| + |next.y - last.y| < 0.0000001$ **then**
    last $\leftarrow$ *next*
    BREAK;
  end if
  last $\leftarrow$ *next*
end for
if $pass = maxNumberOfPasses - 1$ **then**
  last.x $\leftarrow (last.x + next.x) * 0.5$
  last.y $\leftarrow (last.y + next.y) * 0.5$
end if
last $\leftarrow$ *next*

Output: CCT(*last.x, last.y*).

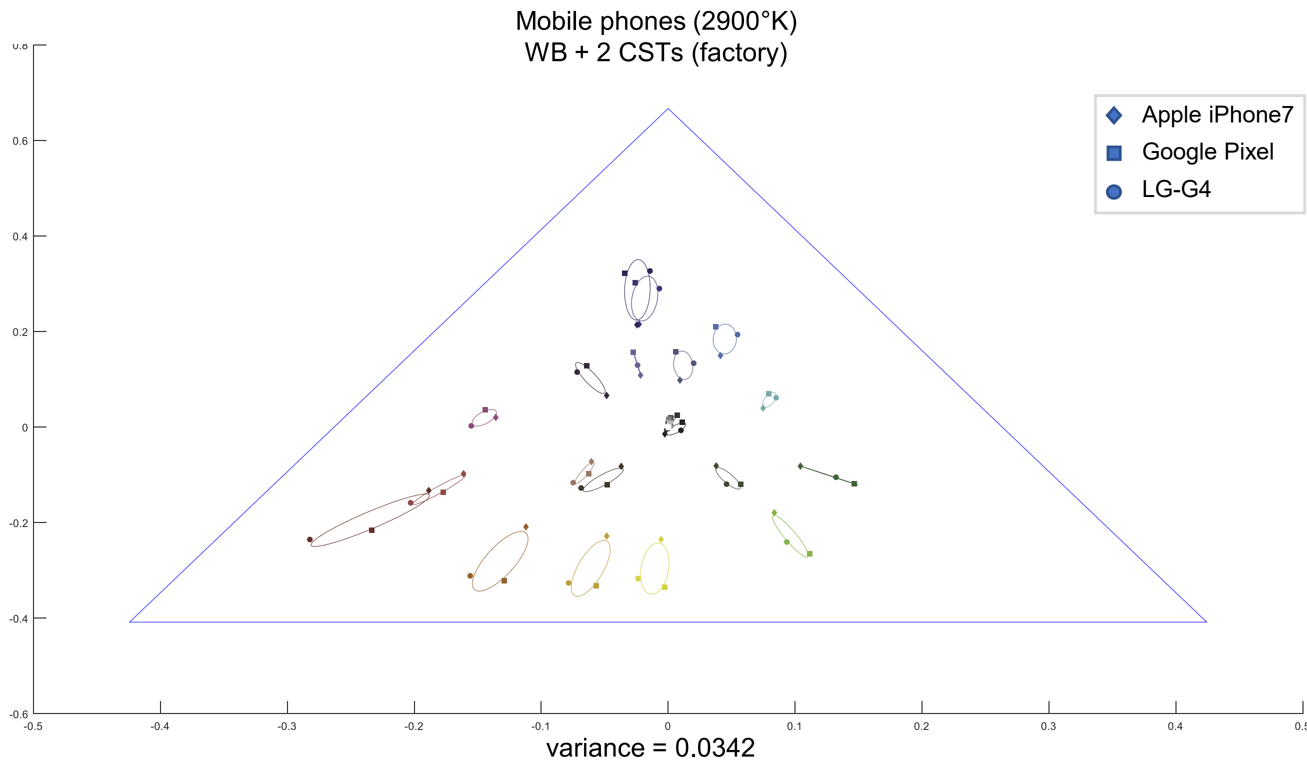

Figure 1. WB + CSTs (factory) consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

2. Plots of multi-camera variance

In this section, we present the chromaticity plots from the multi-camera consistency experiments described in Section 5.2 of the main paper. Recall that our multi-camera consistency experiments are performed per camera type (DSLR or Mobile Phone Camera) and for three different illuminations.

The following plots correspond to each result reported in Table 2 of the main paper. The plots show the mapping of a color rendition chart color patches projected into ProPhoto RGB chromaticity space. This experiment is performed to reveal which color rendition method results in the least amount of variance in the overall color values among multiple cameras.

Figures 1,2,3,4,5, and 6 show the variance for the mobile phone cameras under illumination 2900°K.

Figures 7,8,9,10,11, and 12 show the variance for the mobile phone cameras under illumination 4500°K.

Figures 13,14,15,16,17, and 18 show the variance for the mobile phone cameras under illumination 5500°K.

Figures 19,20,21,22,23, and 24 show the variance for the mobile phone cameras under illumination 6000°K.

Figures 25,26,27,28,29, and 30 show the variance for the DSLR cameras under illumination 3000°K.

Figures 31,32,33,34,35, and 36 show the variance for the DSLR cameras under illumination 3500°K.

Figures 37,38,39,40,41, and 42 show the variance for the DSLR cameras under illumination 4300°K.

Figures 43,44,45,46,47, and 48 show the variance for the DSLR cameras under illumination 5200°K.

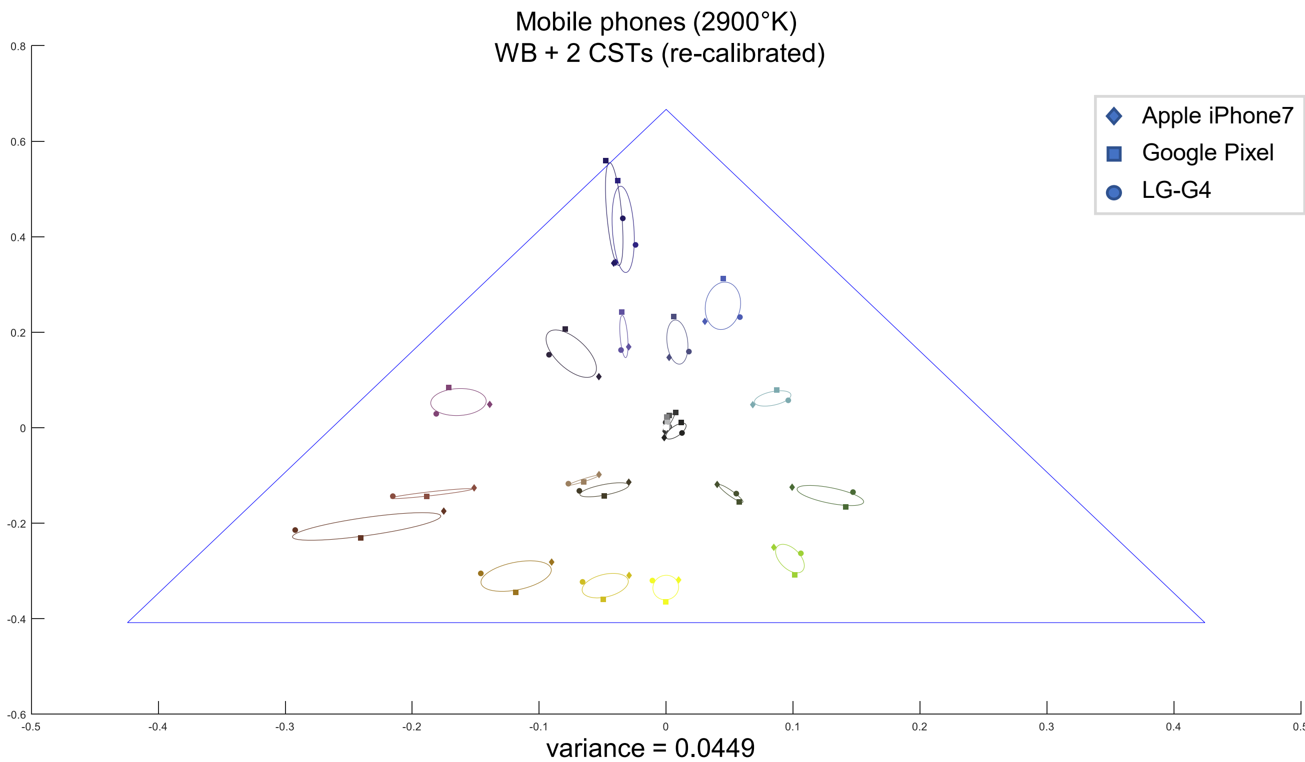

Figure 2. WB + CSTs (re-calibrated) consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

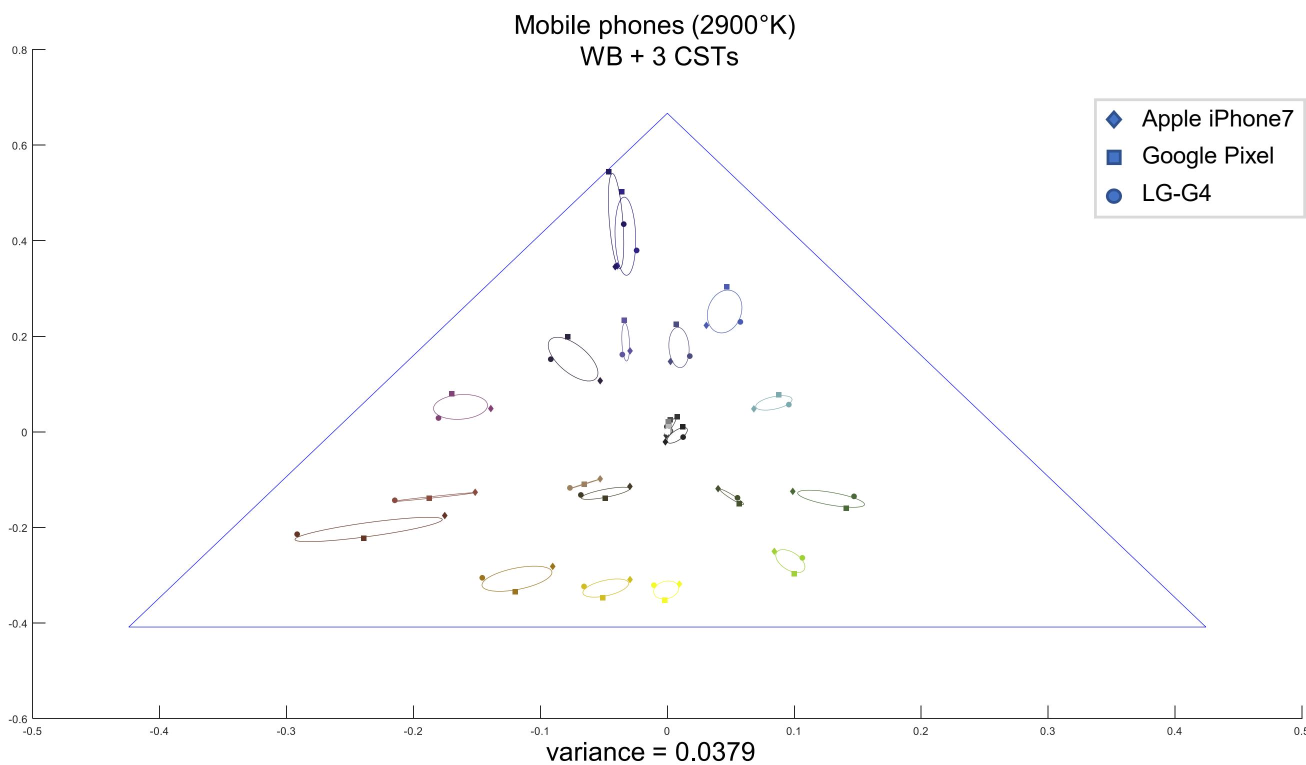

Figure 3. WB + 3 CSTs consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

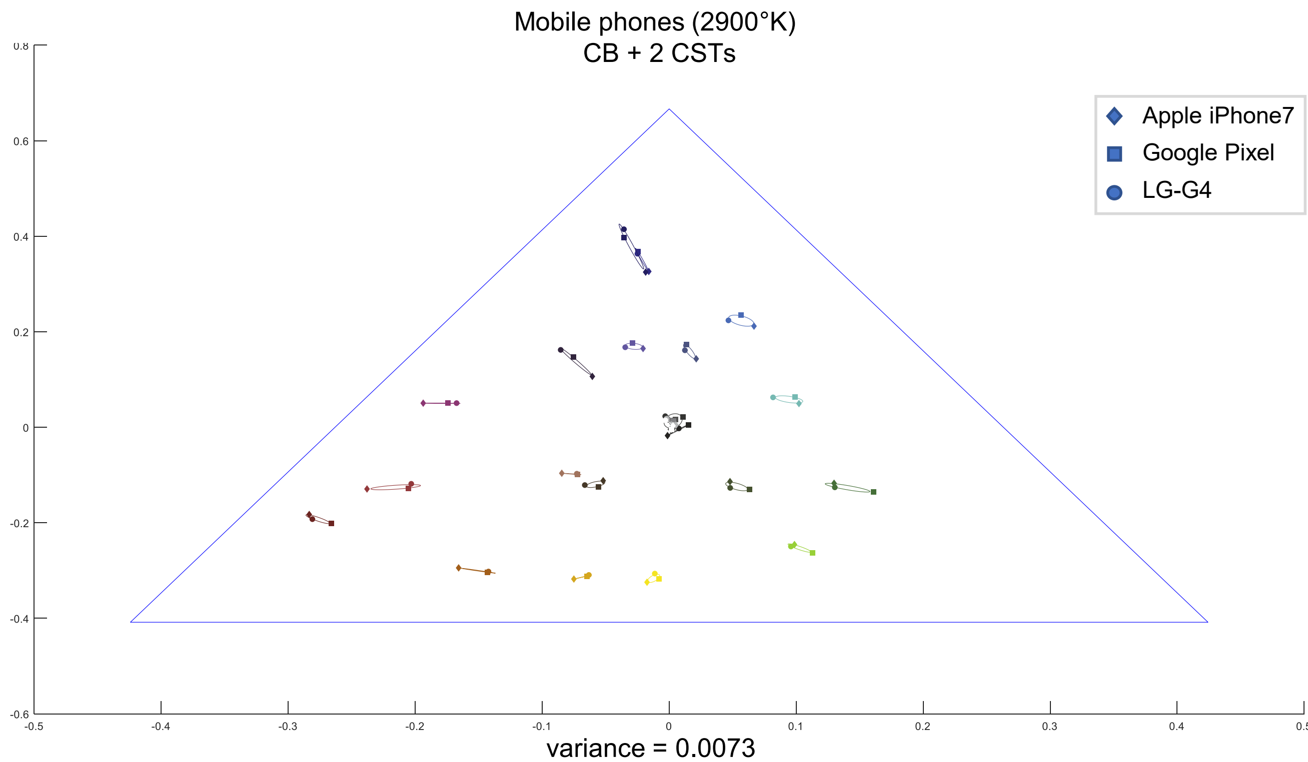

Figure 4. CB + 2 CSTs consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

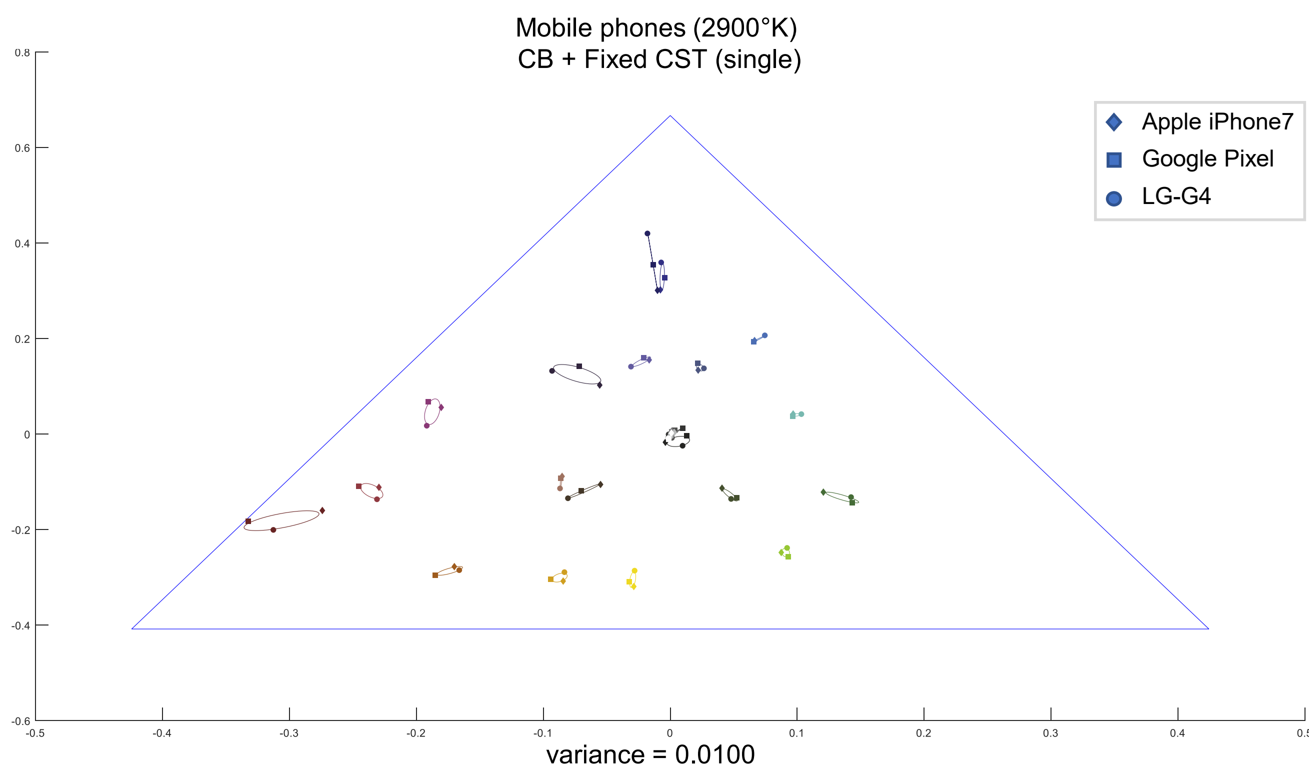

Figure 5. CB + Fixed CST (single) consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

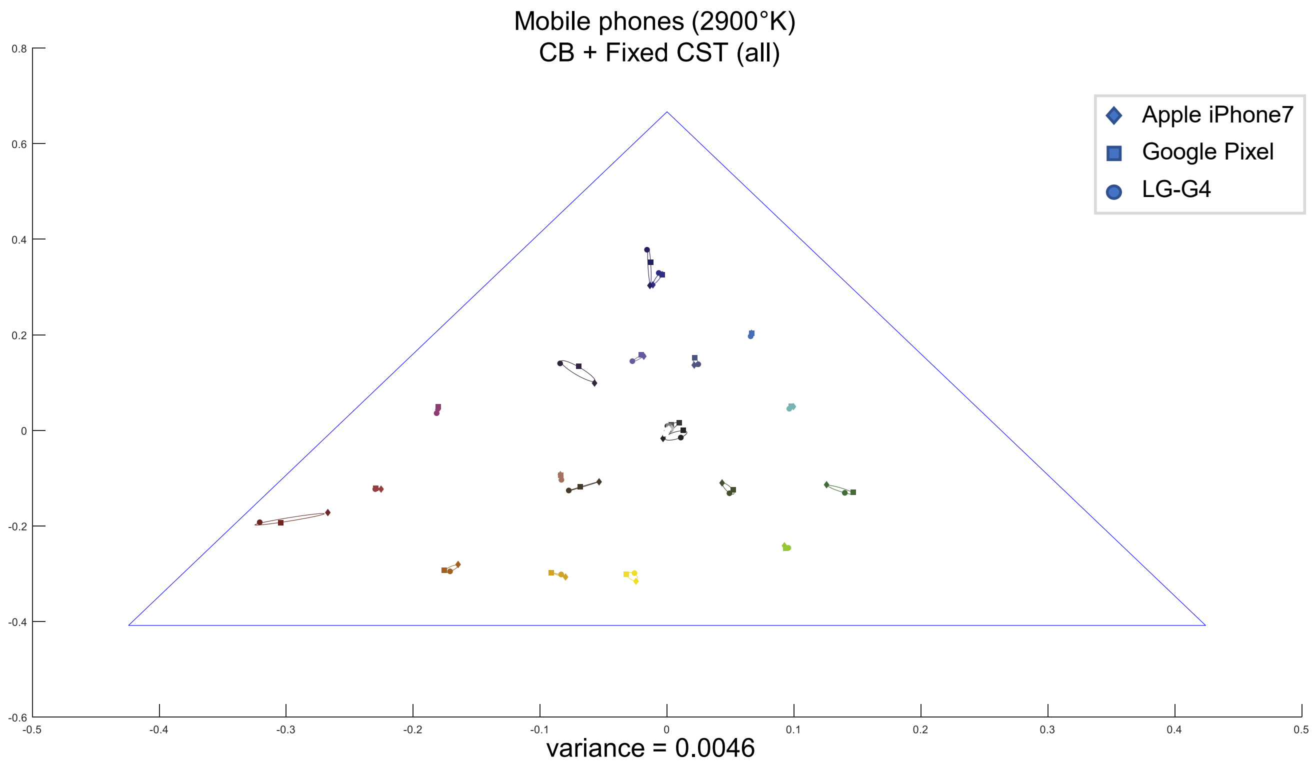

Figure 6. CB + Fixed CST (all) consistency among mobile phone cameras capturing the same scene under illumination 2900°K.

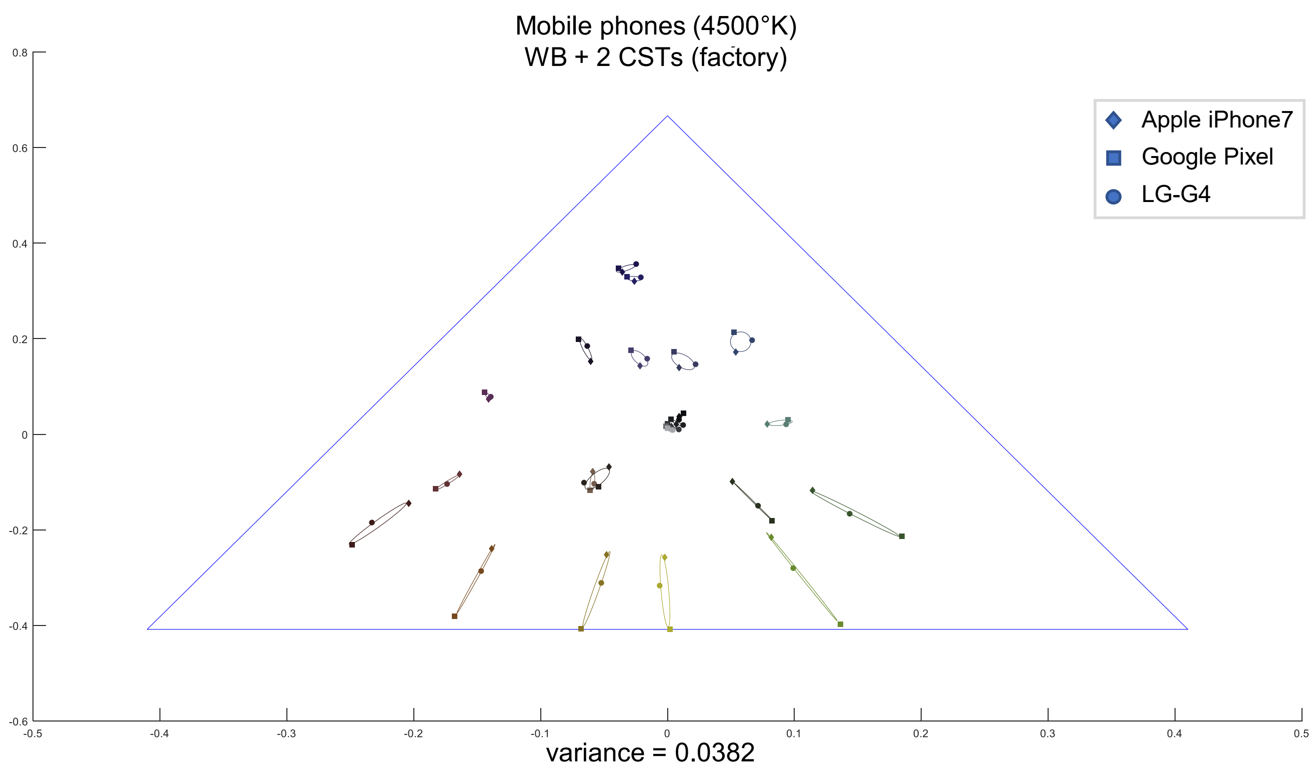

Figure 7. WB + CSTs (factory) consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

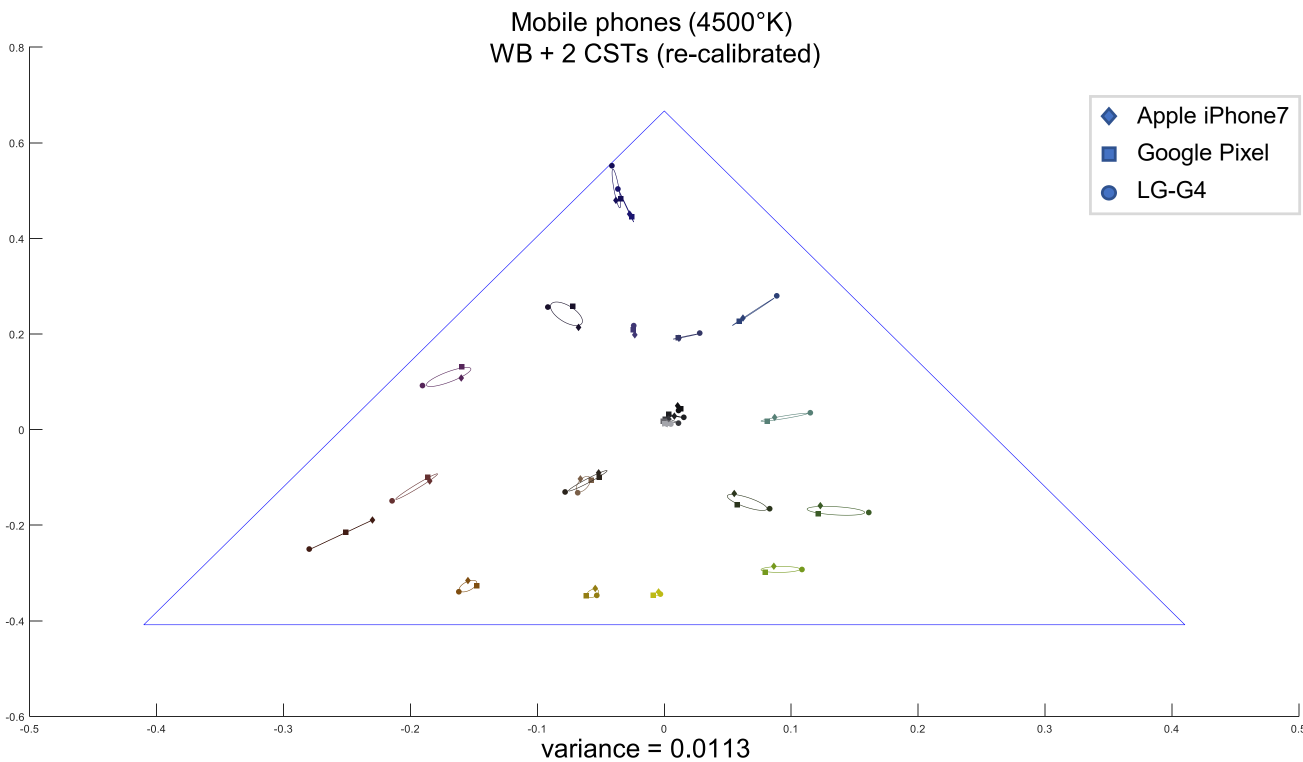

Figure 8. WB + CSTs (re-calibrated) consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

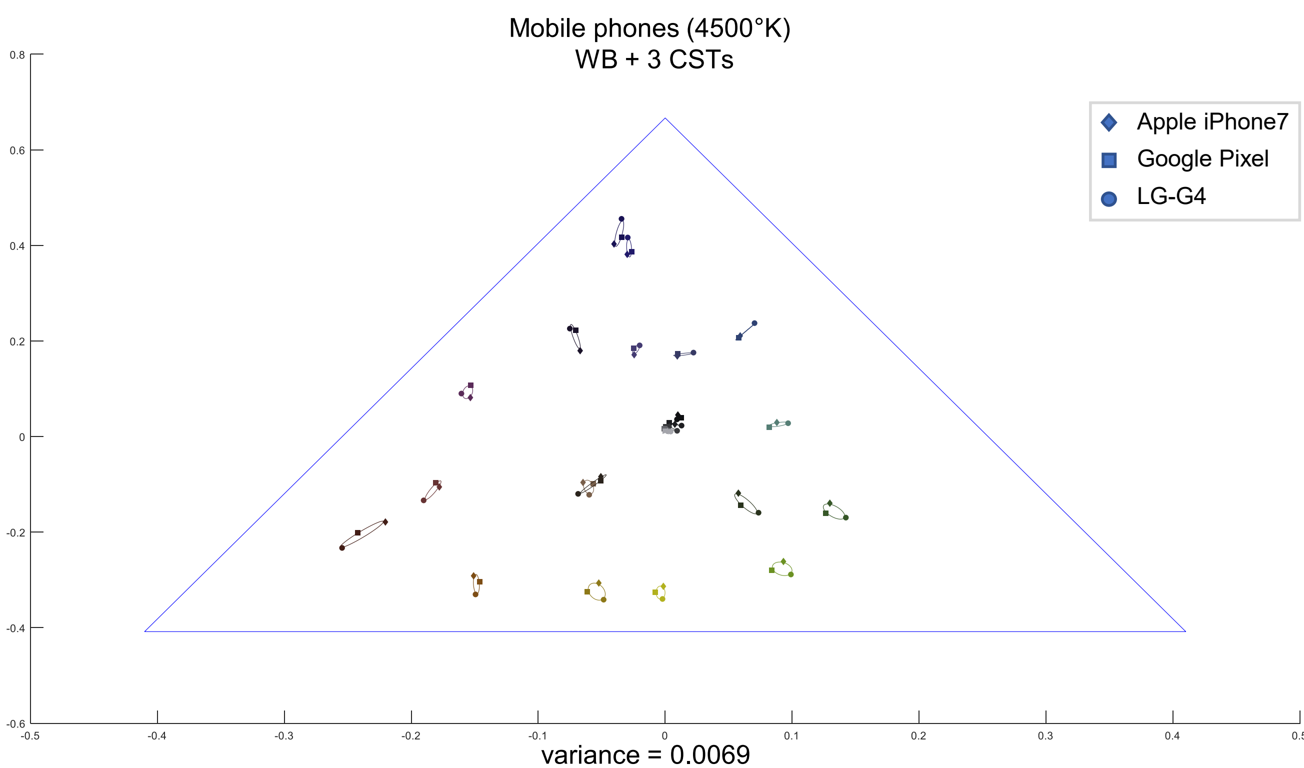

Figure 9. WB + 3 CSTs consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

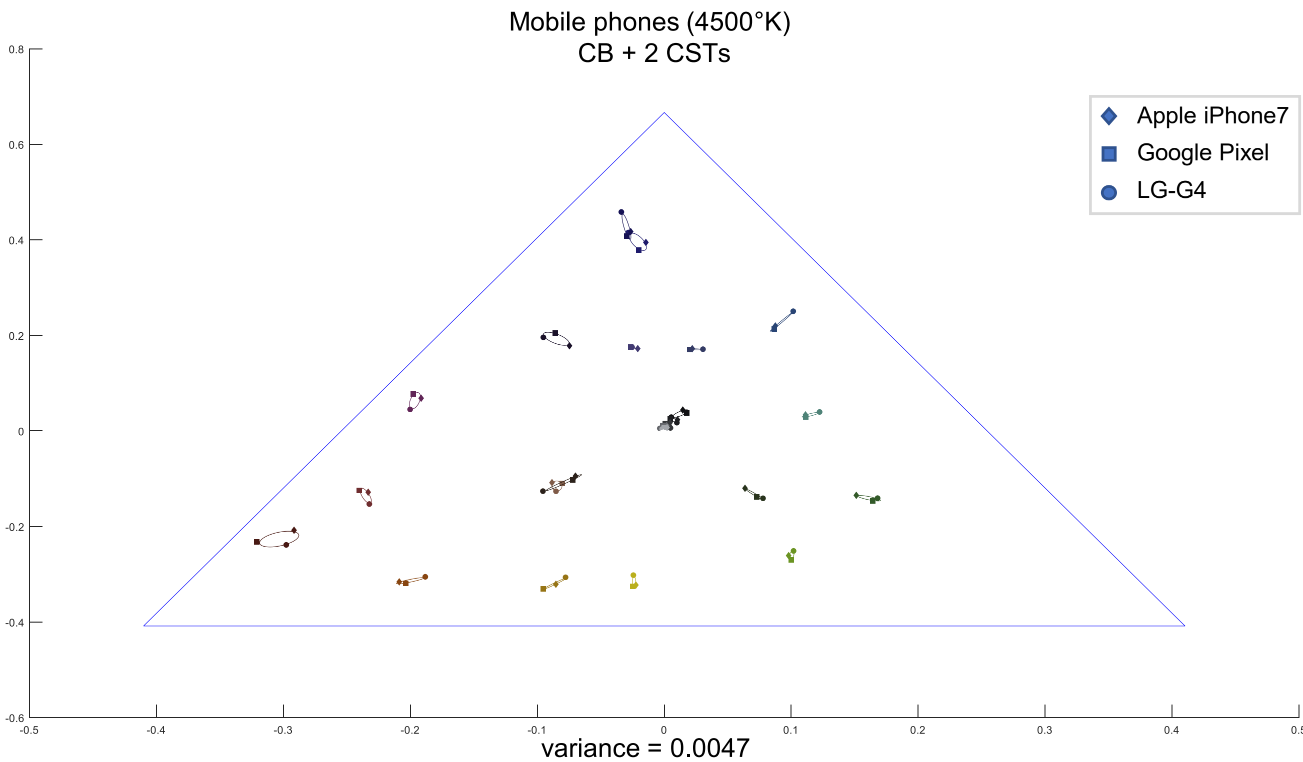

Figure 10. CB + 2 CSTs consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

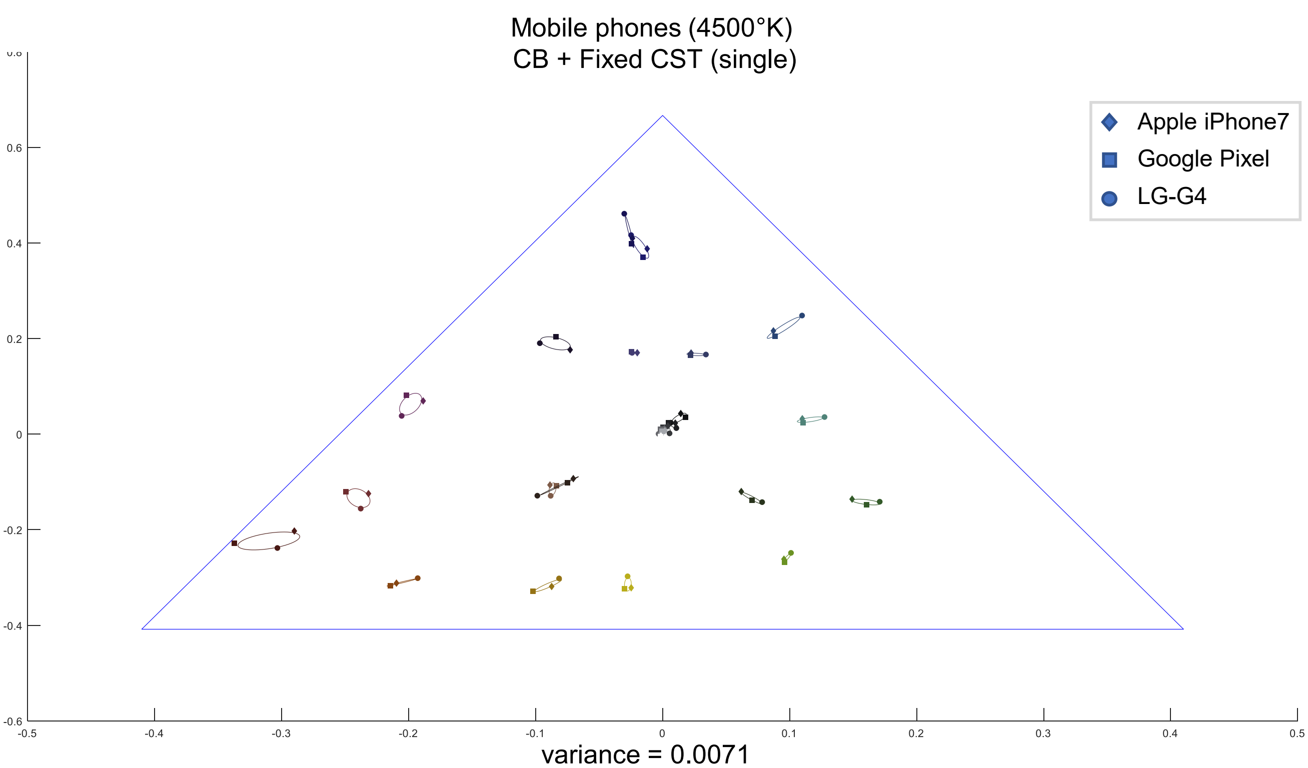

Figure 11. CB + Fixed CST (single) consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

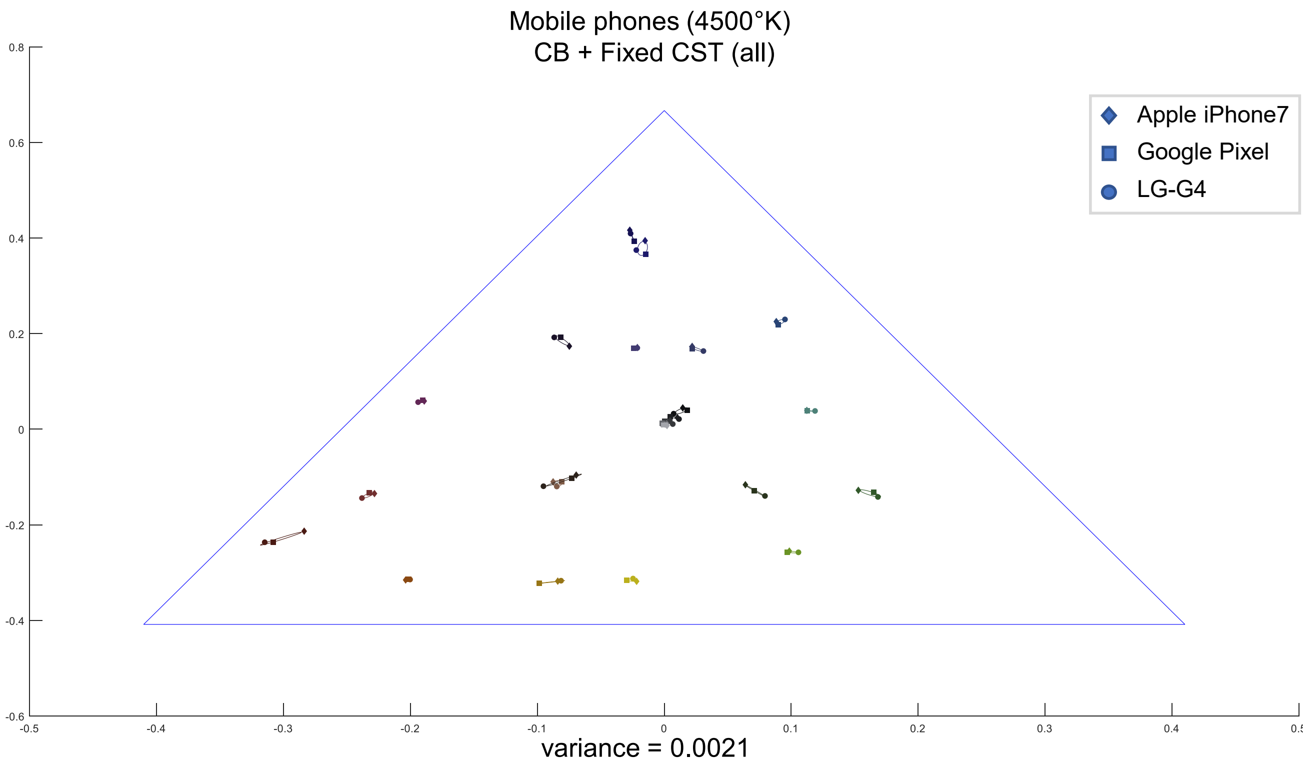

Figure 12. CB + Fixed CST (all) consistency among mobile phone cameras capturing the same scene under illumination 4500°K.

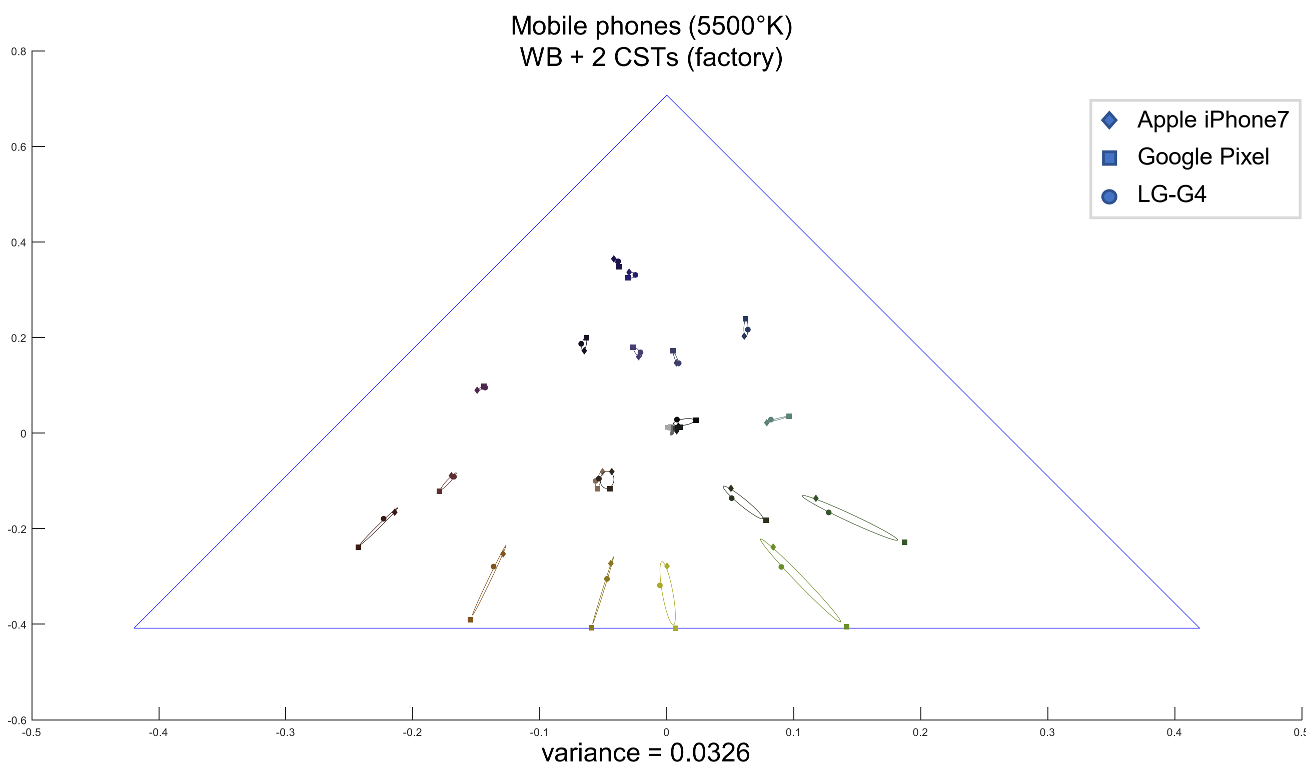

Figure 13. WB + CSTs (factory) consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

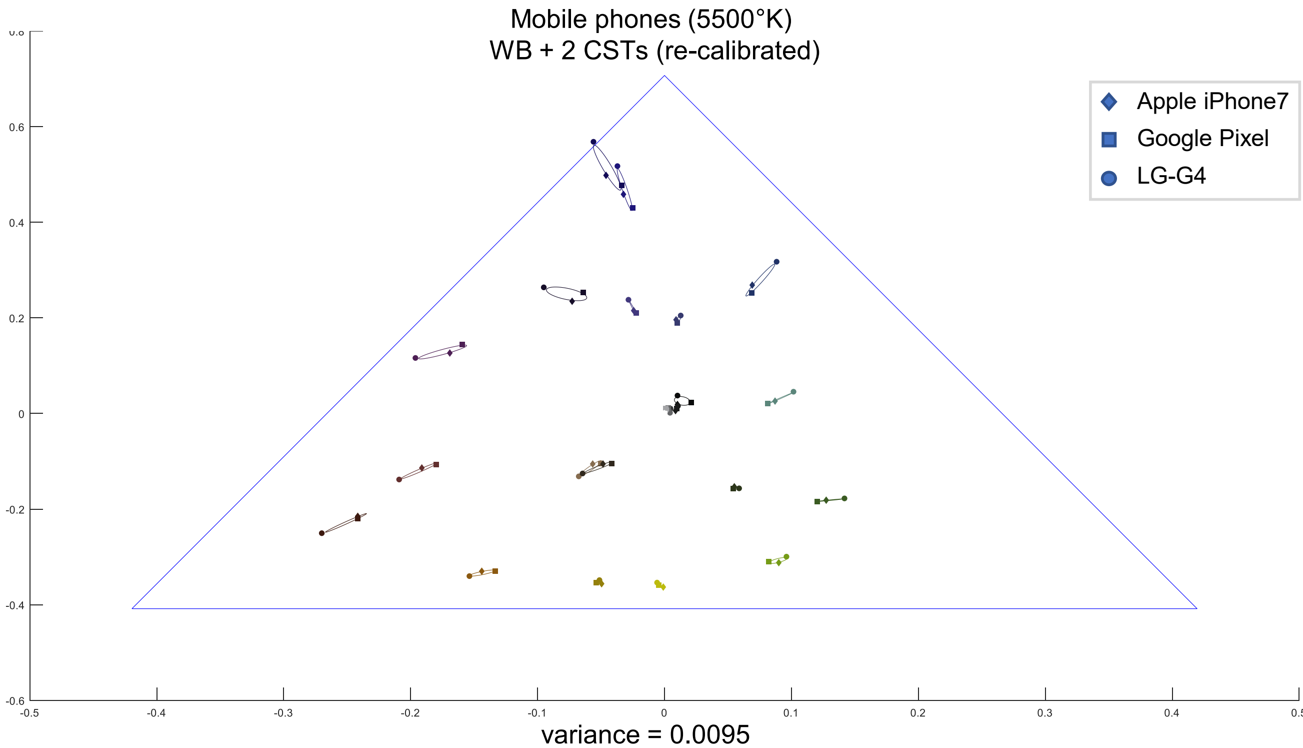

Figure 14. WB + CSTs (re-calibrated) consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

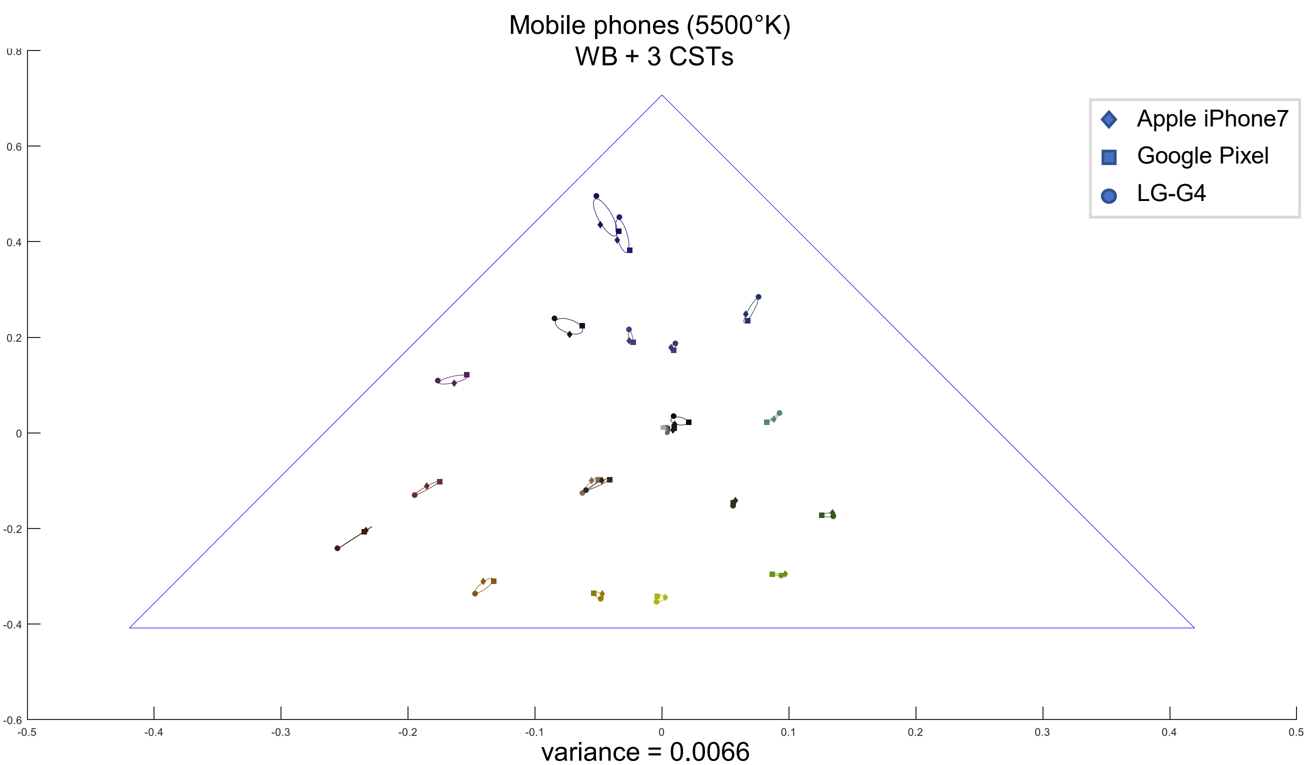

Figure 15. WB + 3 CSTs consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

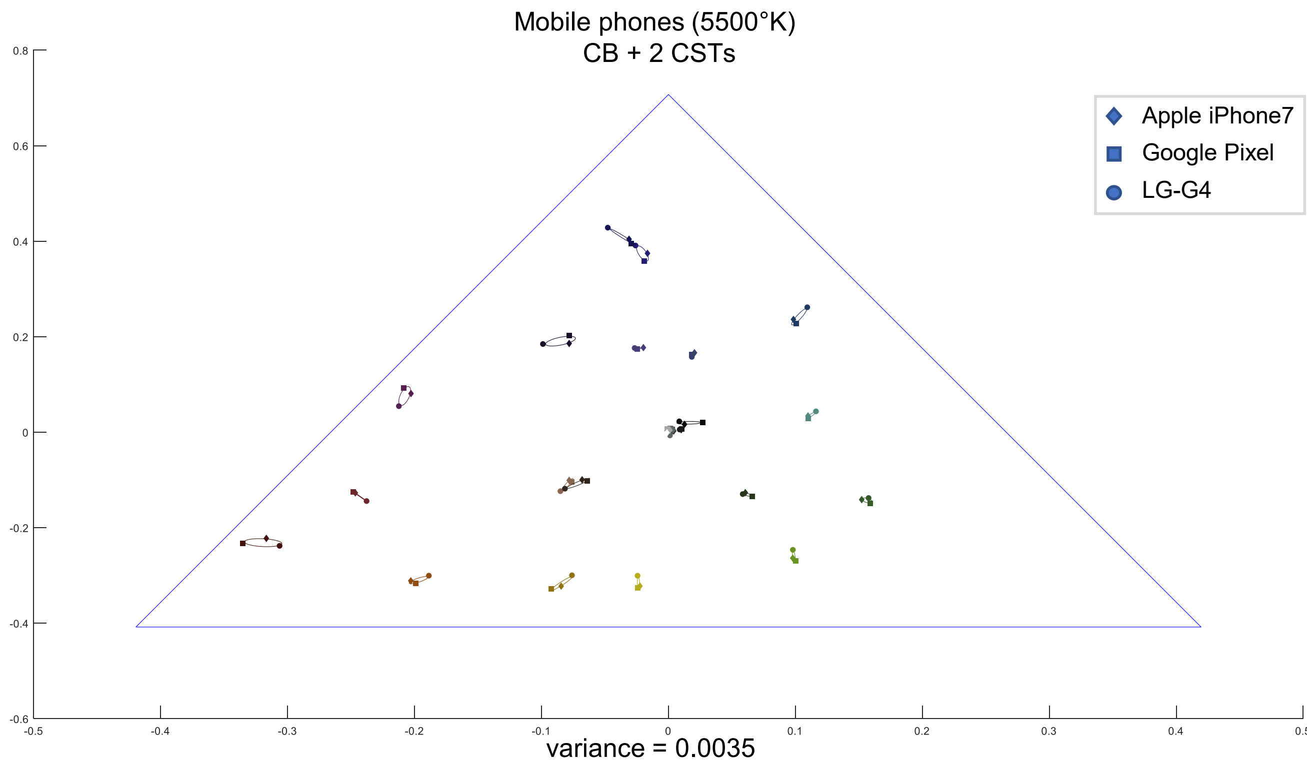

Figure 16. CB + 2 CSTs consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

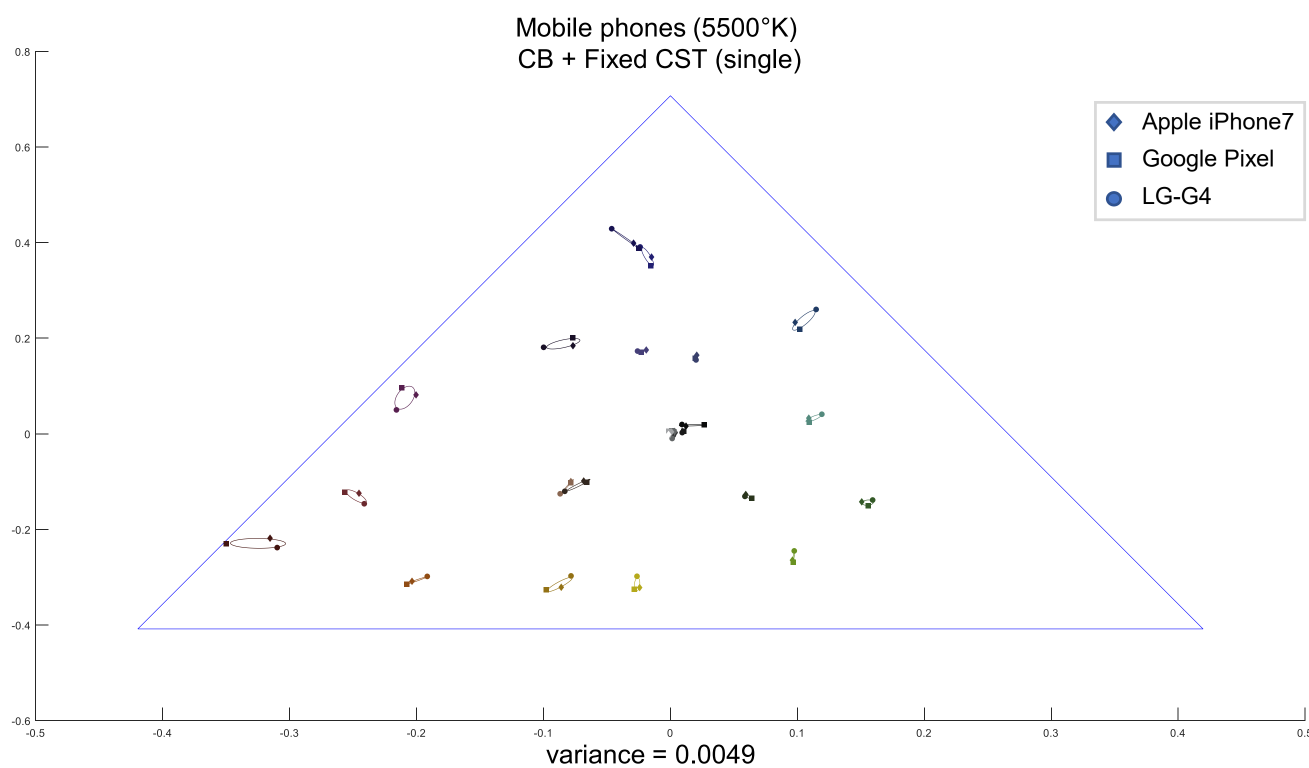

Figure 17. CB + Fixed CST (single) consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

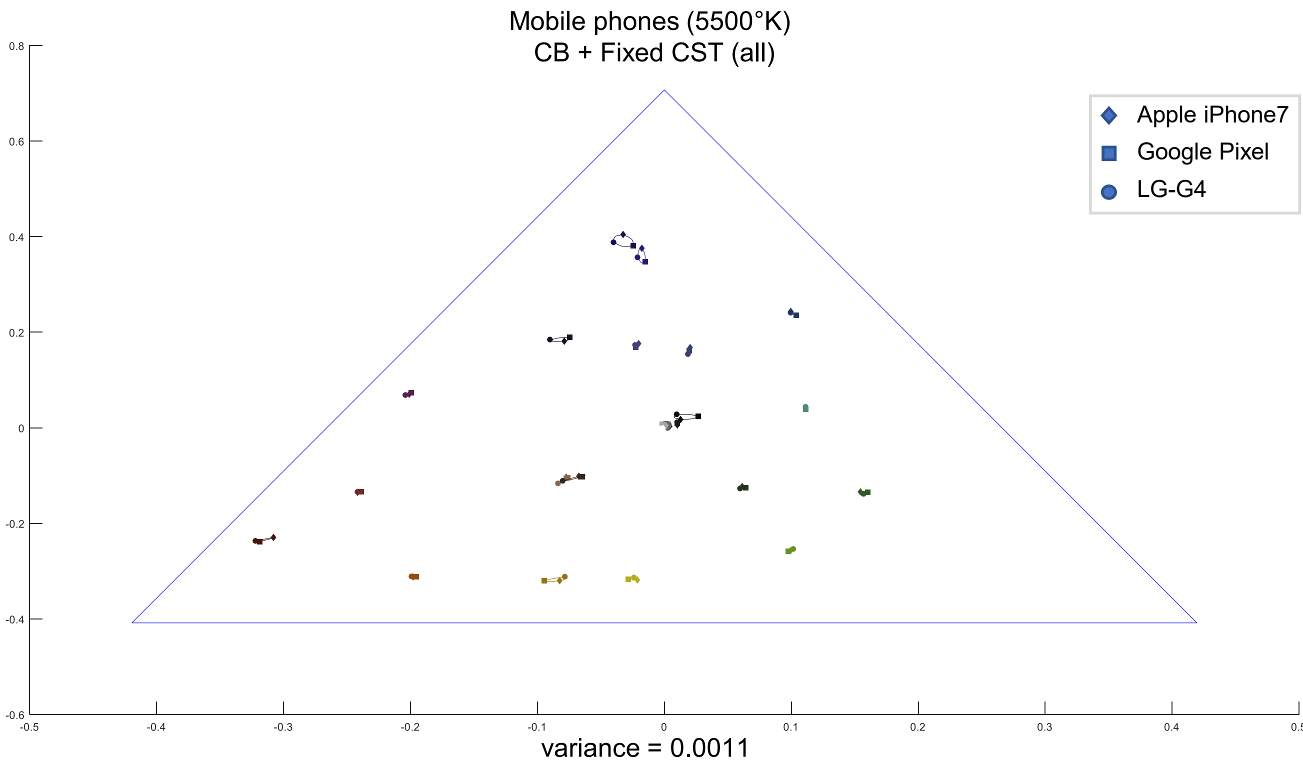

Figure 18. CB + Fixed CST (all) consistency among mobile phone cameras capturing the same scene under illumination 5500°K.

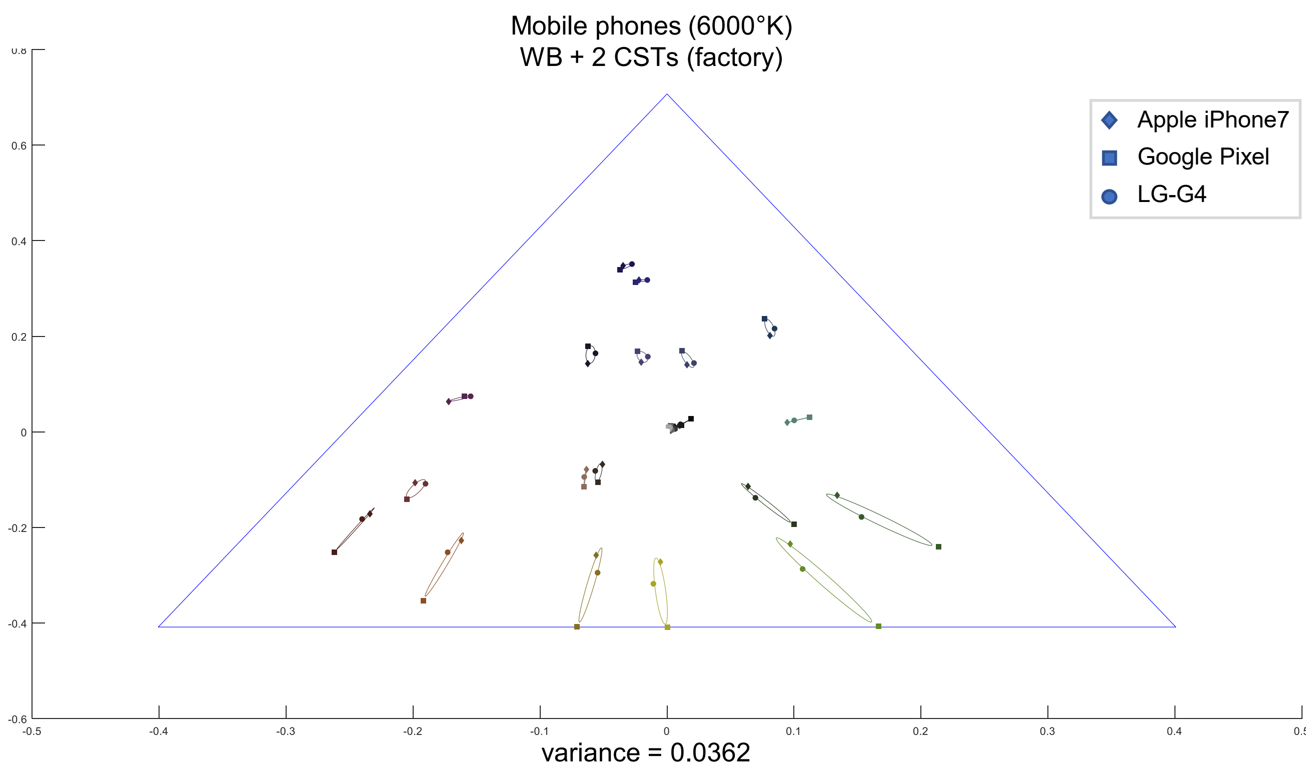

Figure 19. WB + CSTs (factory) consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

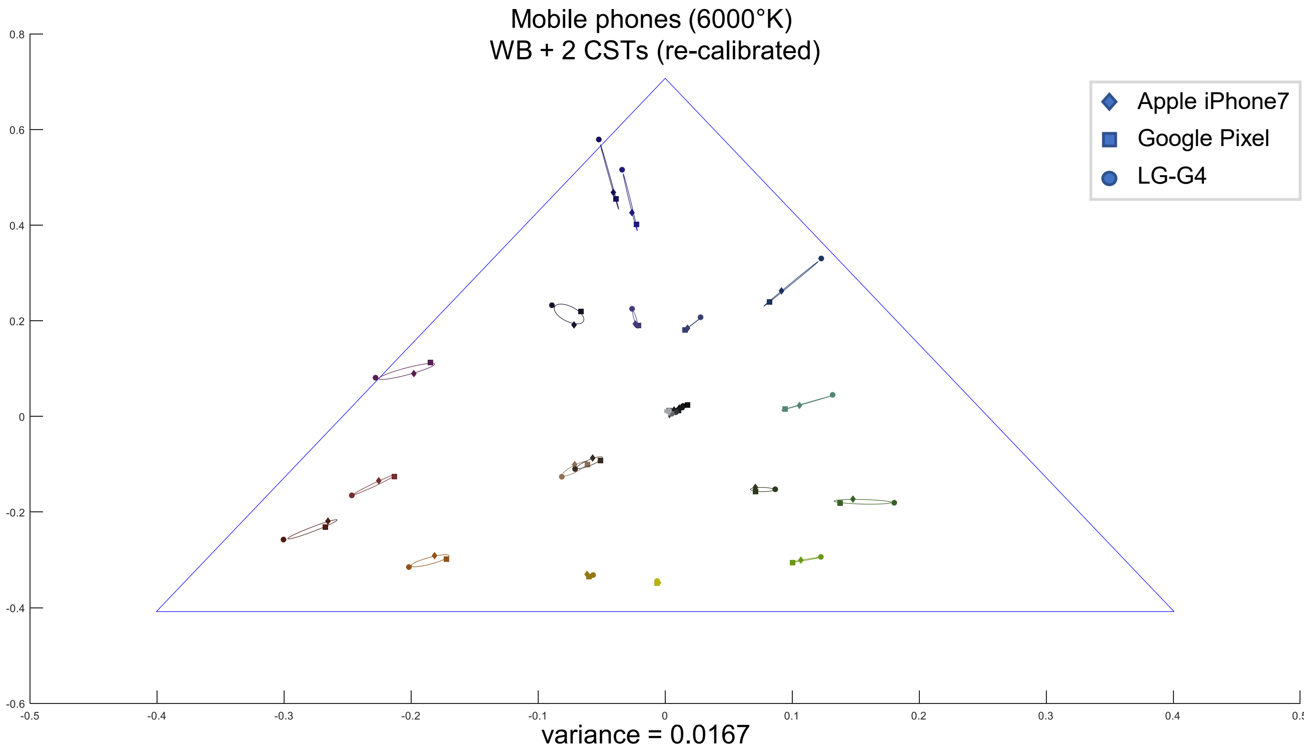

Figure 20. WB + CSTs (re-calibrated) consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

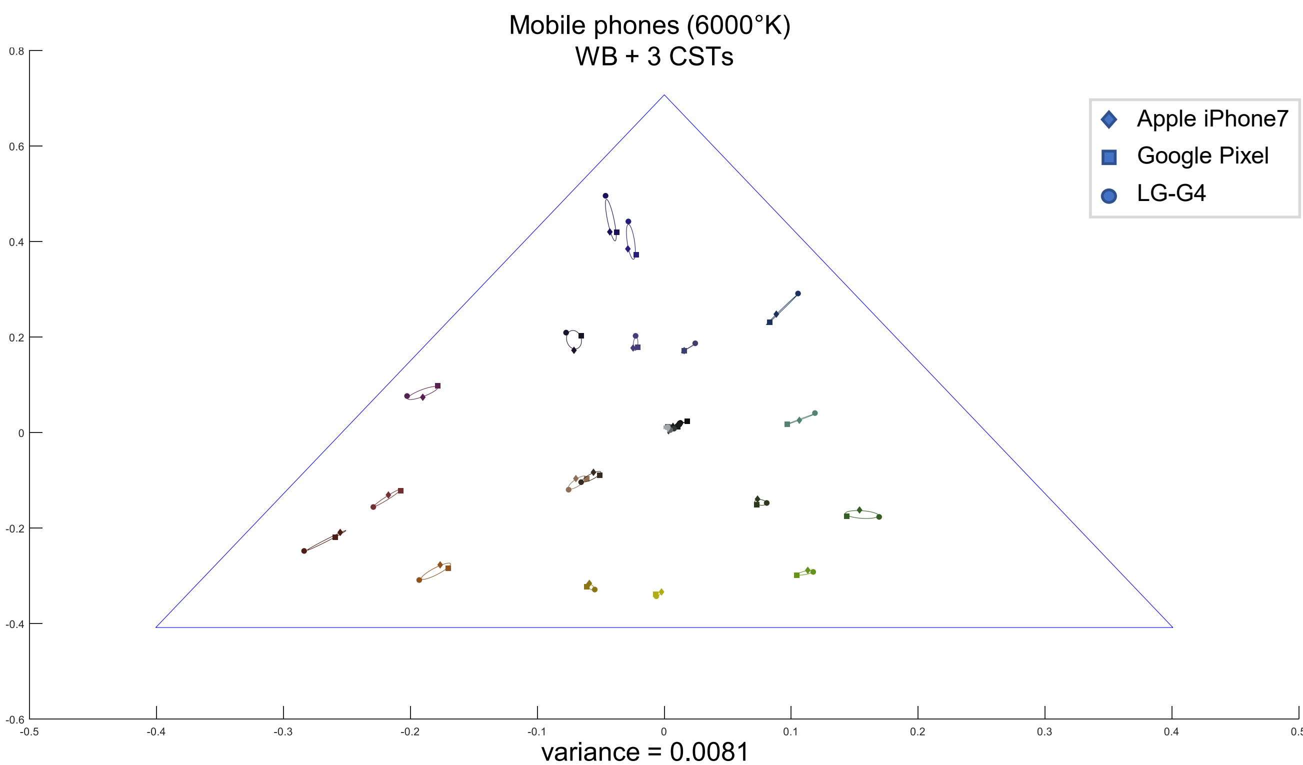

Figure 21. WB + 3 CSTs consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

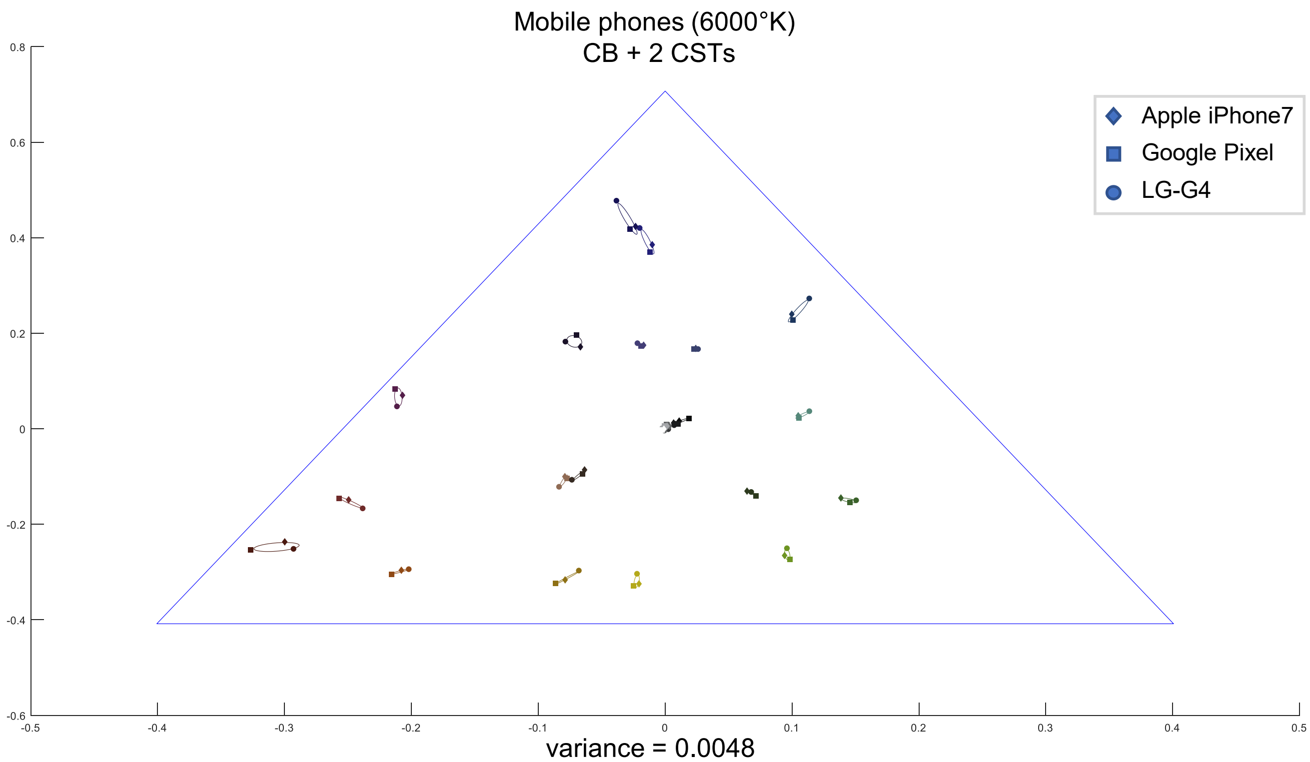

Figure 22. CB + 2 CSTs consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

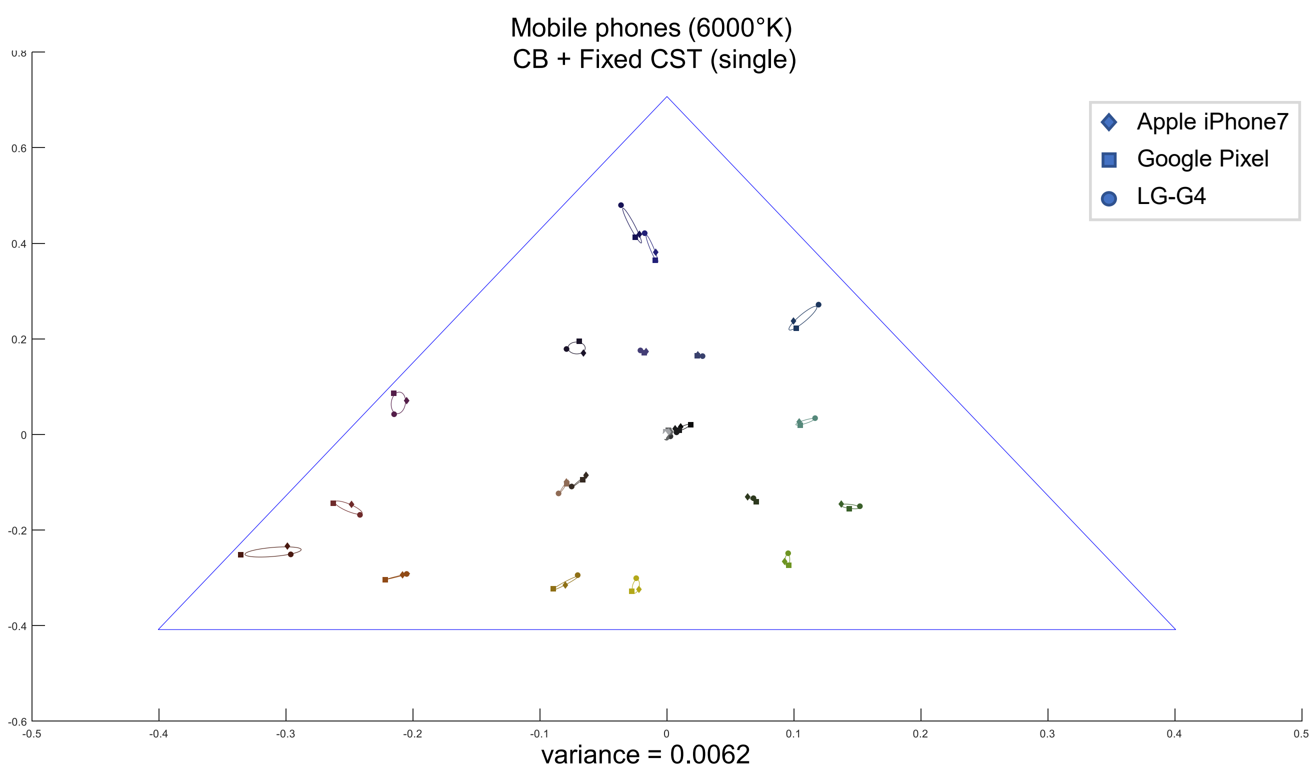

Figure 23. CB + Fixed CST (single)consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

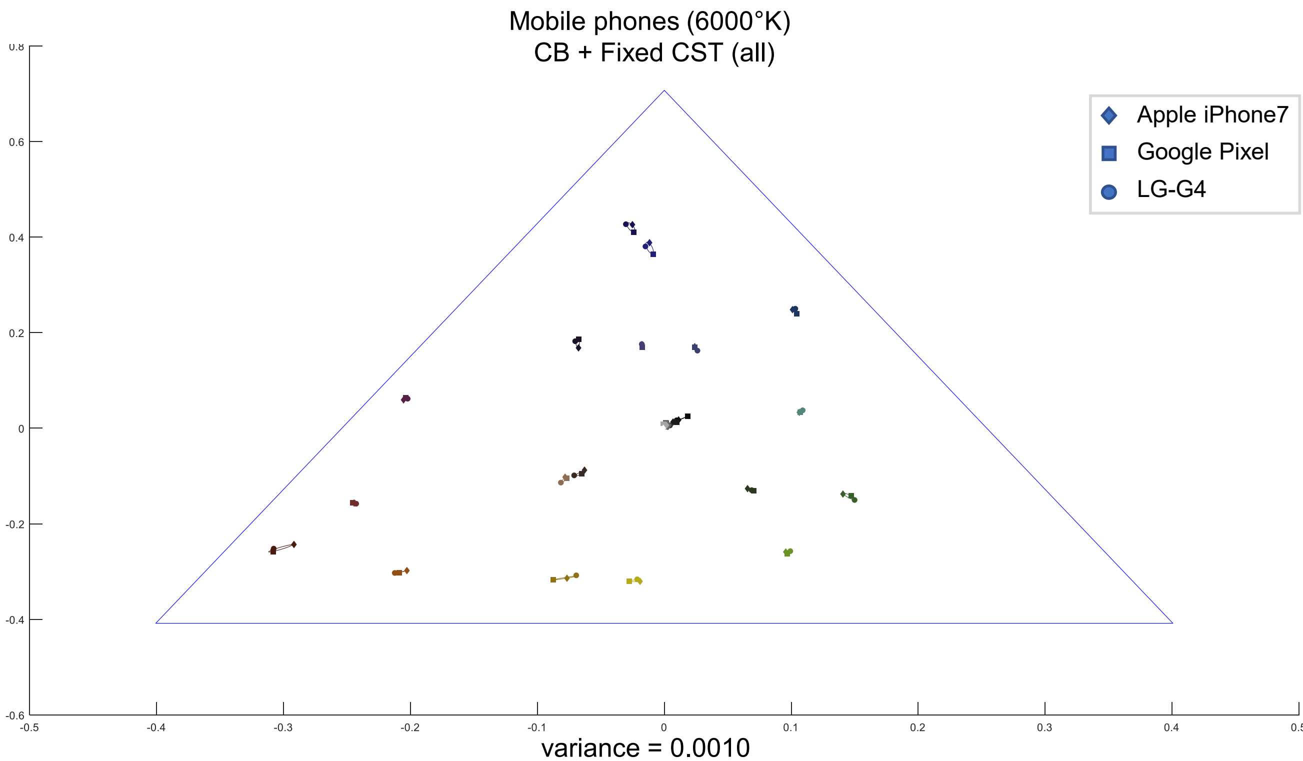

Figure 24. CB + Fixed CST (all) consistency among mobile phone cameras capturing the same scene under illumination 6000°K.

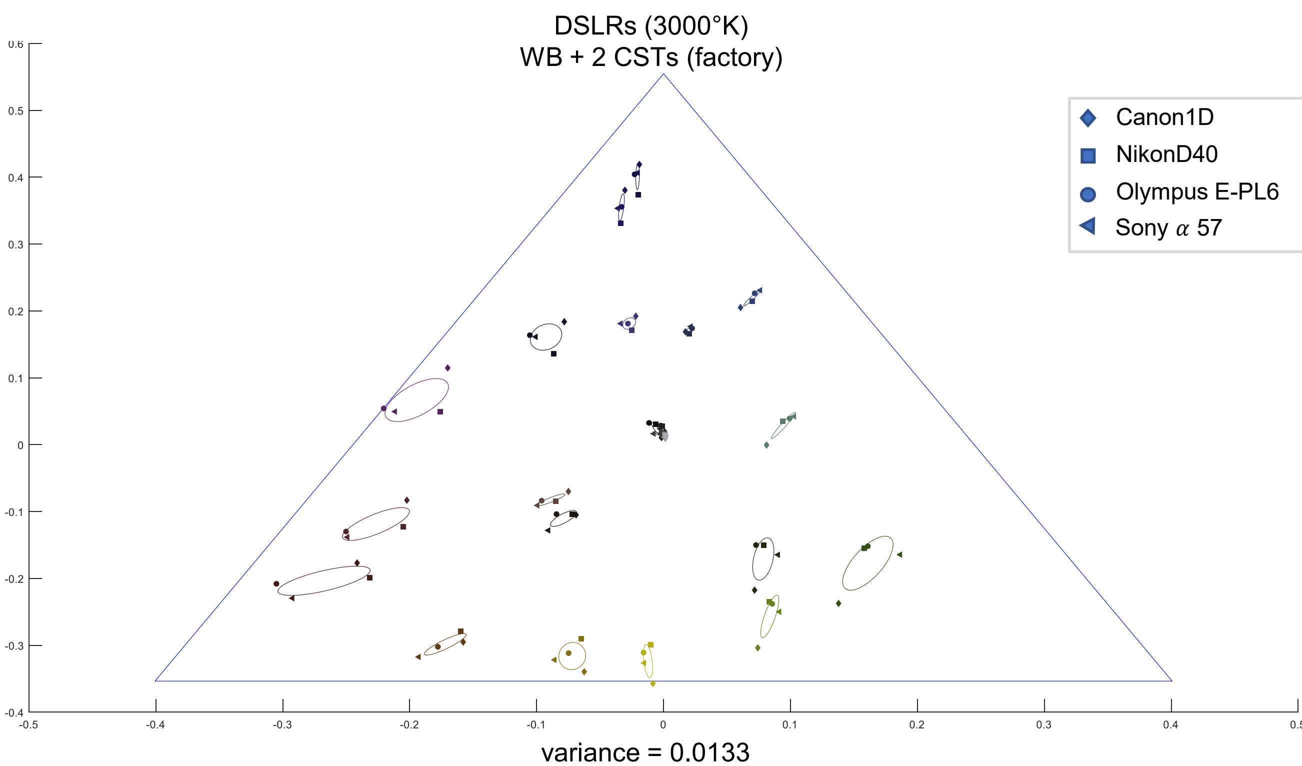

Figure 25. WB + CSTs (factory) consistency among DSLR cameras capturing the same scene under illumination 3000°K.

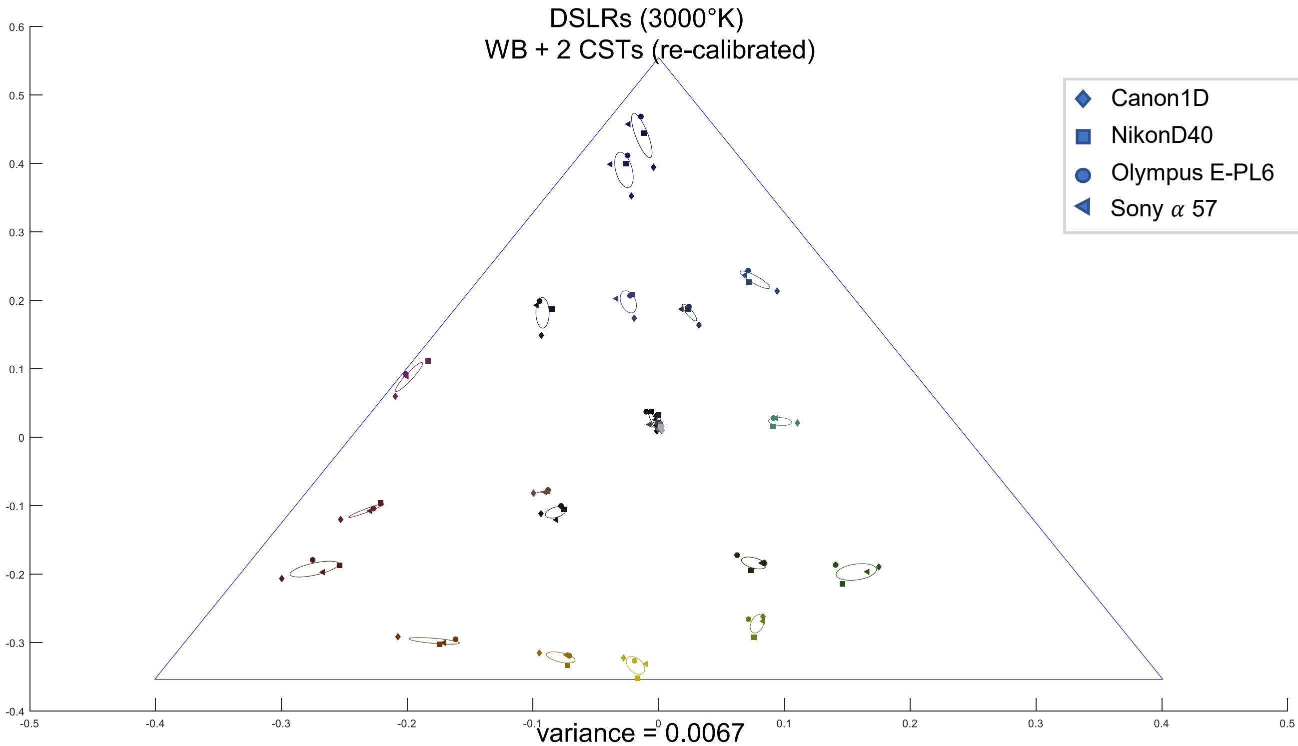

Figure 26. WB + CSTs (re-calibrated) consistency among DSLR cameras capturing the same scene under illumination 3000°K.

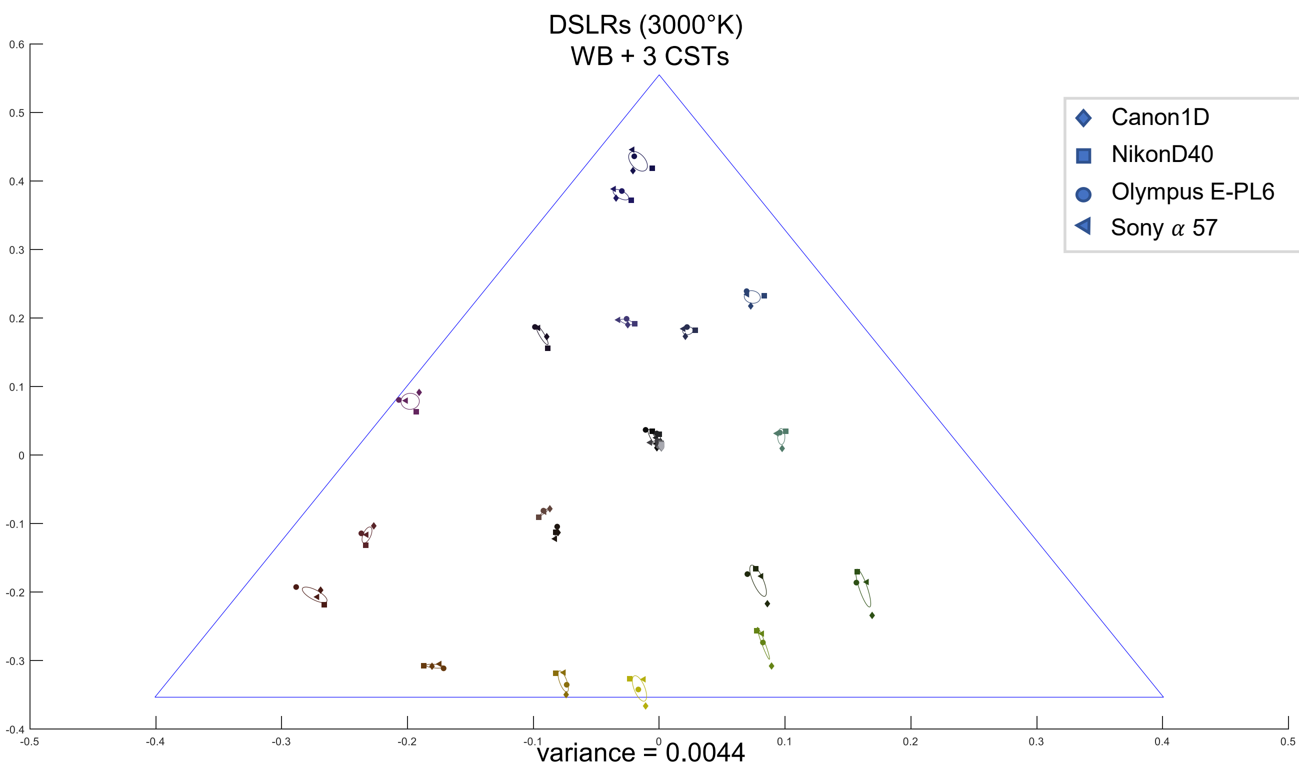

Figure 27. WB + 3 CSTs consistency among DSLR cameras capturing the same scene under illumination 3000°K.

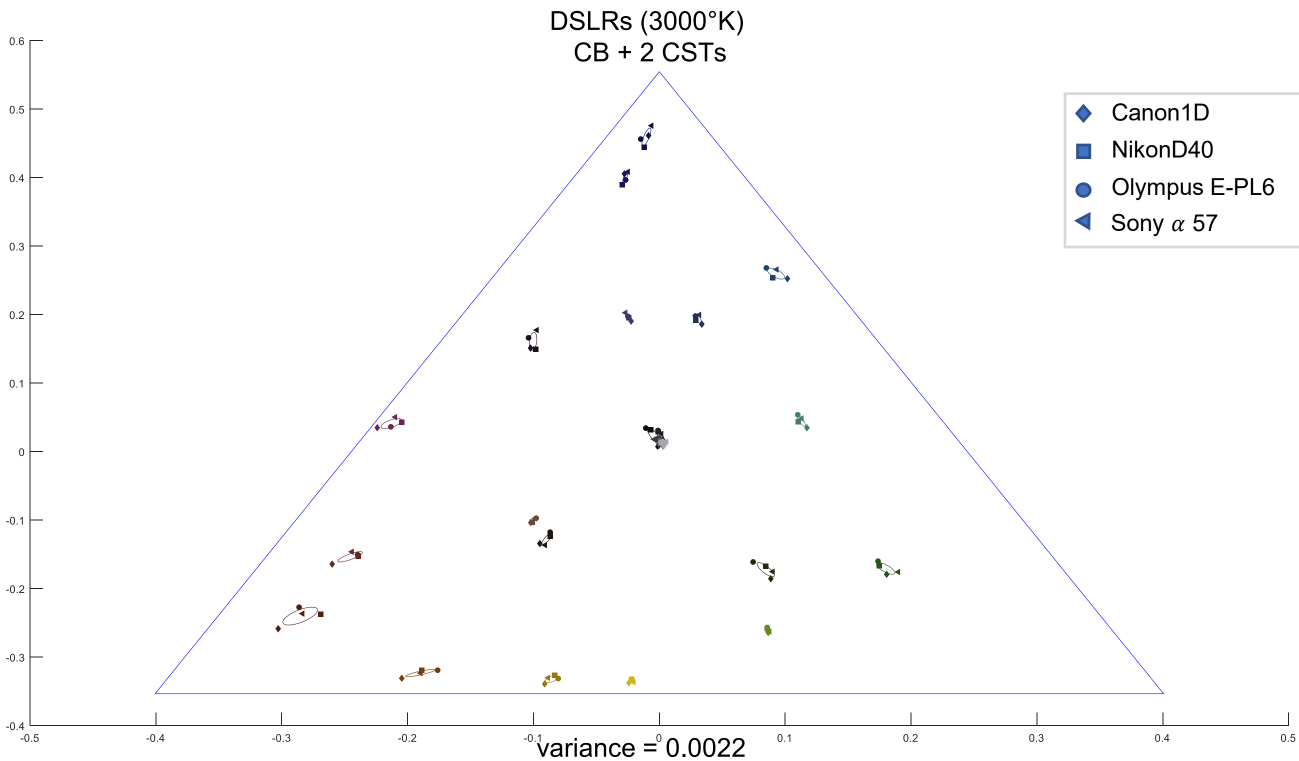

Figure 28. CB + 2 CSTs consistency among DSLR cameras capturing the same scene under illumination 3000°K.

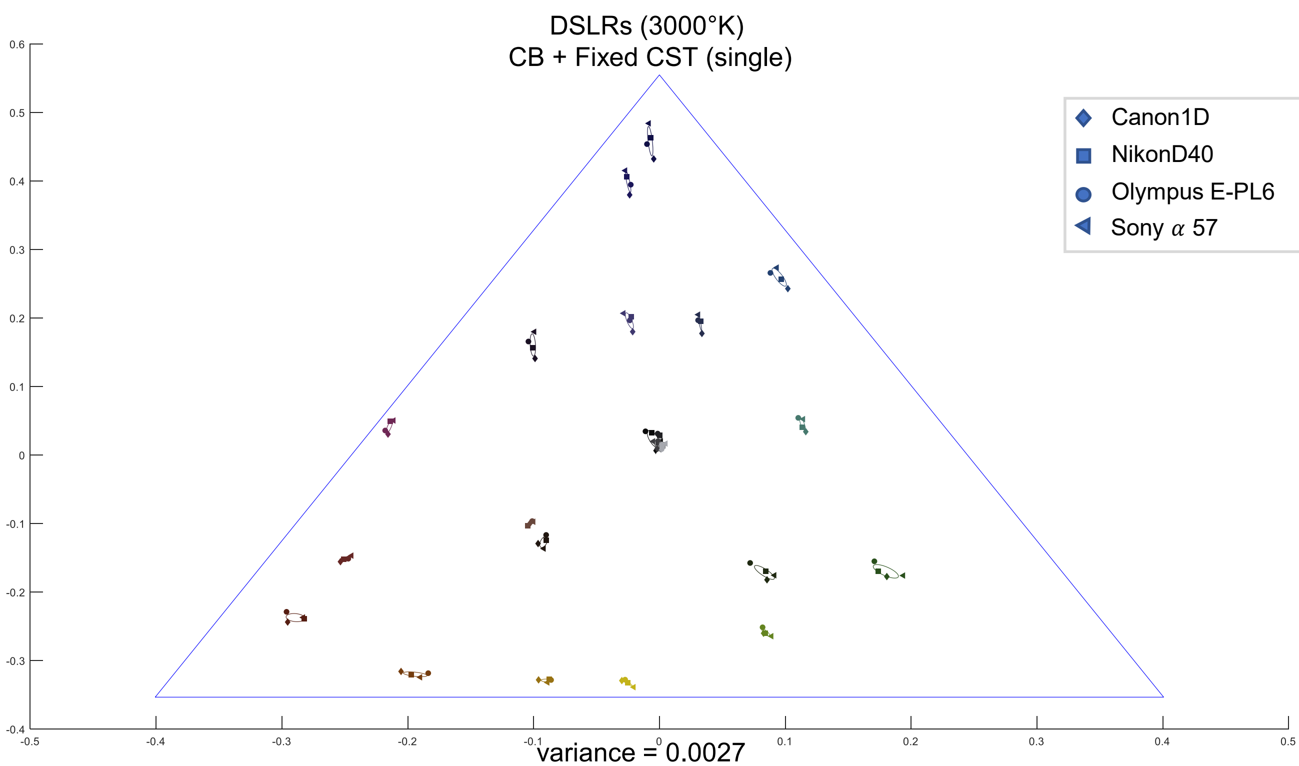

Figure 29. CB + Fixed CST (single) consistency among DSLR cameras capturing the same scene under illumination 3000°K.

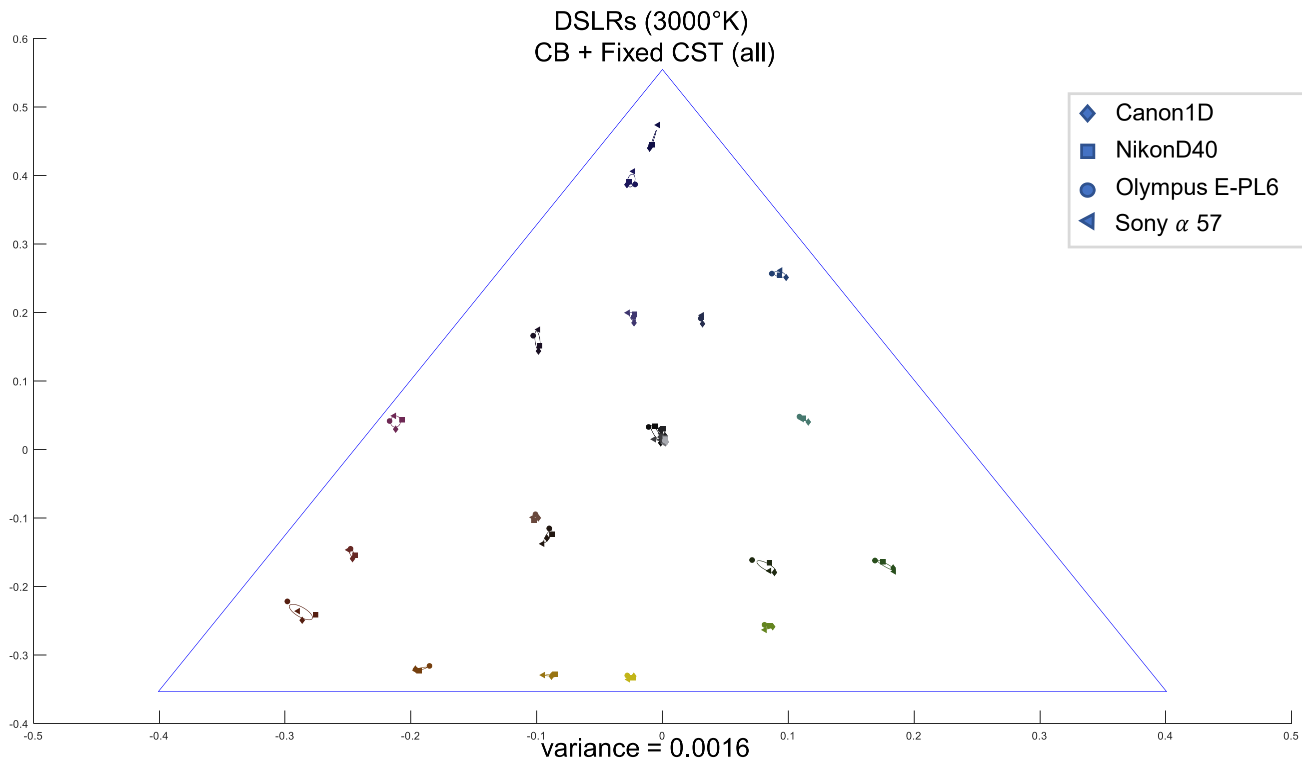

Figure 30. CB + Fixed CST (all) consistency among DSLR cameras capturing the same scene under illumination 3000°K.

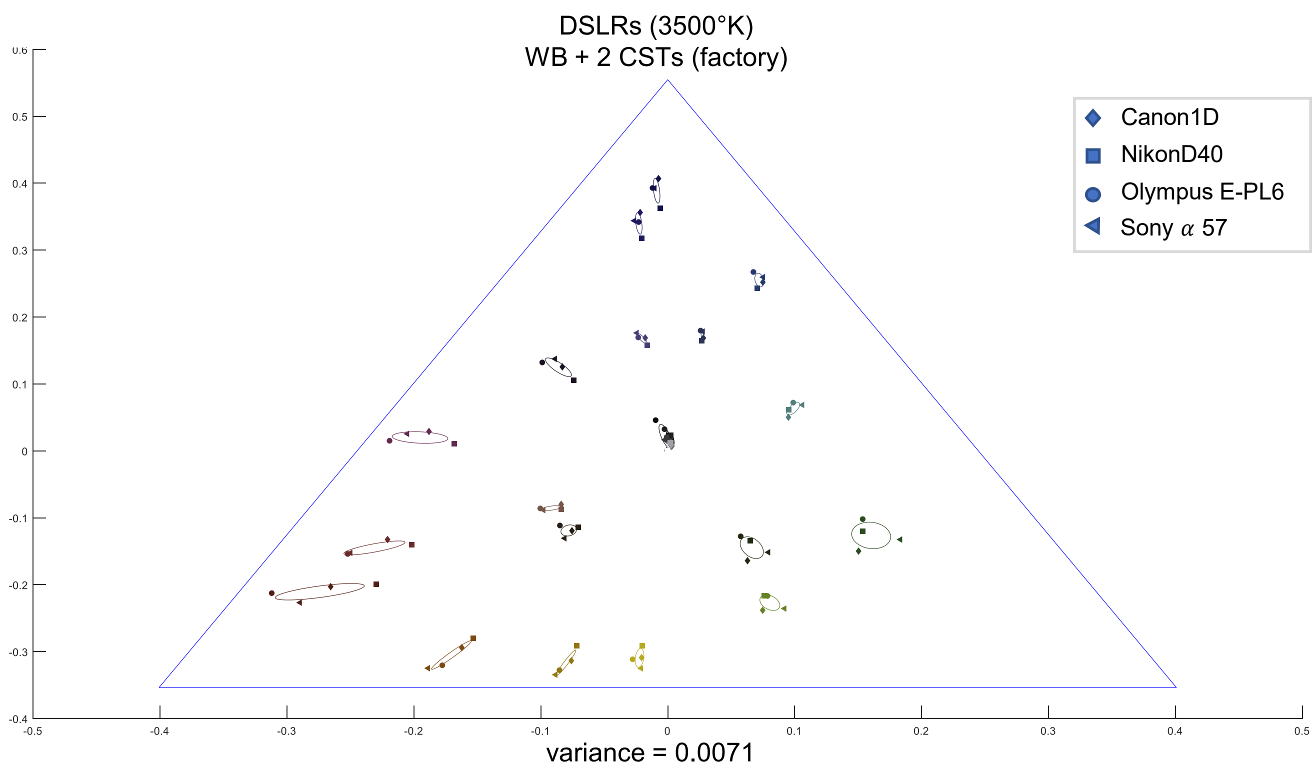

Figure 31. WB + CSTs (factory) consistency among DSLR cameras capturing the same scene under illumination 3500°K.

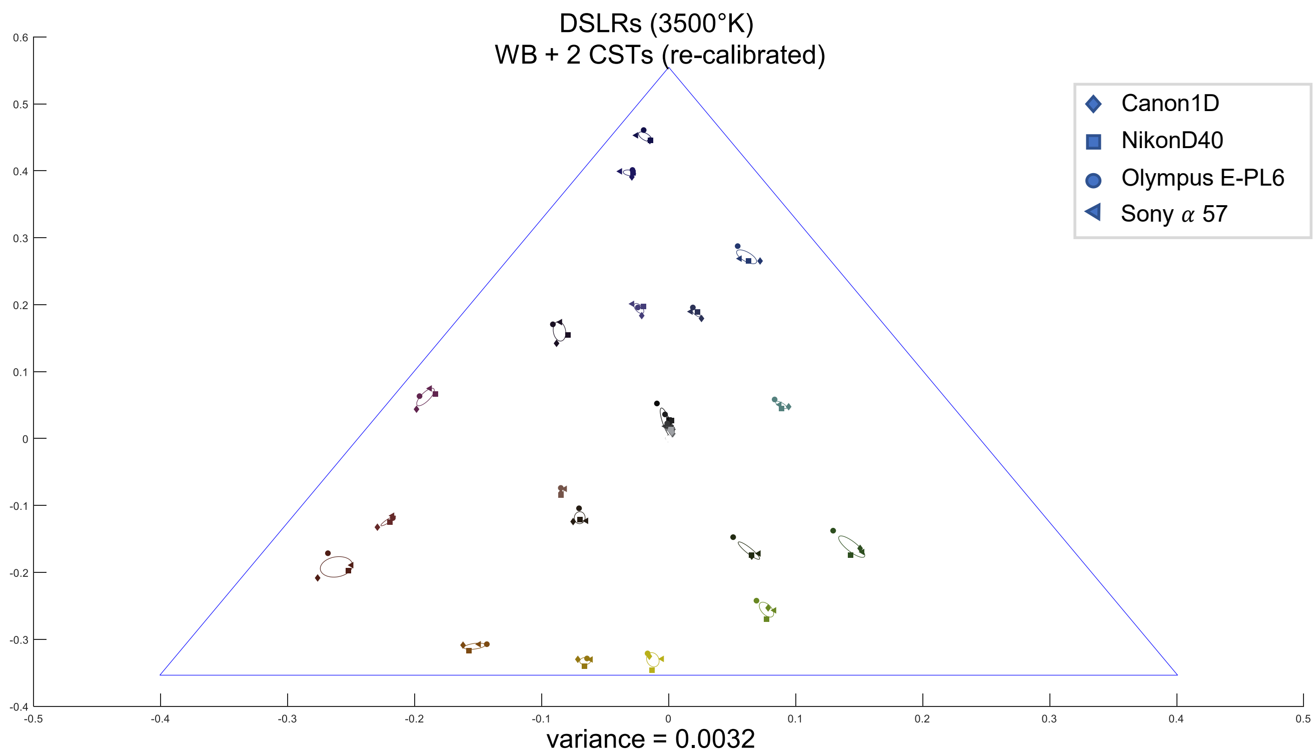

Figure 32. WB + CSTs (re-calibrated) consistency among DSLR cameras capturing the same scene under illumination 3500°K.

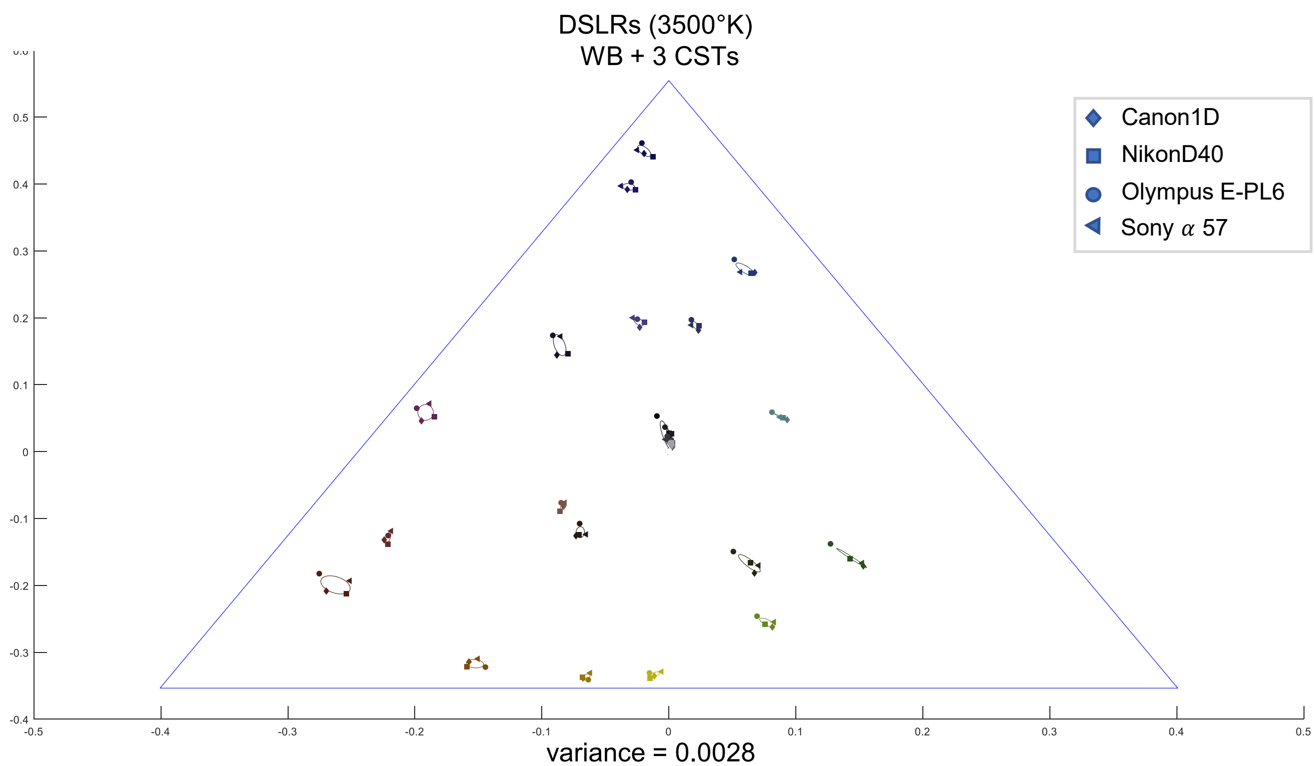

Figure 33. WB + 3 CSTs consistency among DSLR cameras capturing the same scene under illumination 3500°K.

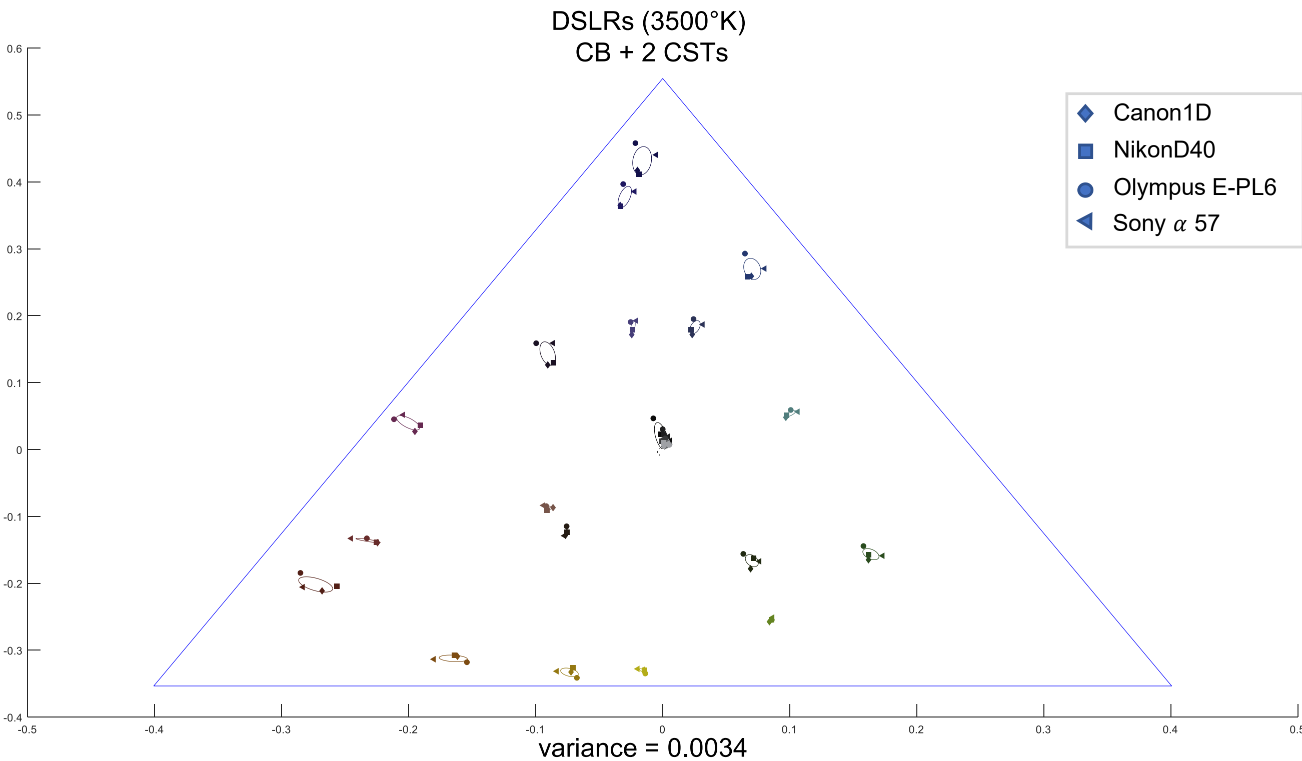

Figure 34. CB + 2 CSTs consistency among DSLR cameras capturing the same scene under illumination 3500°K.

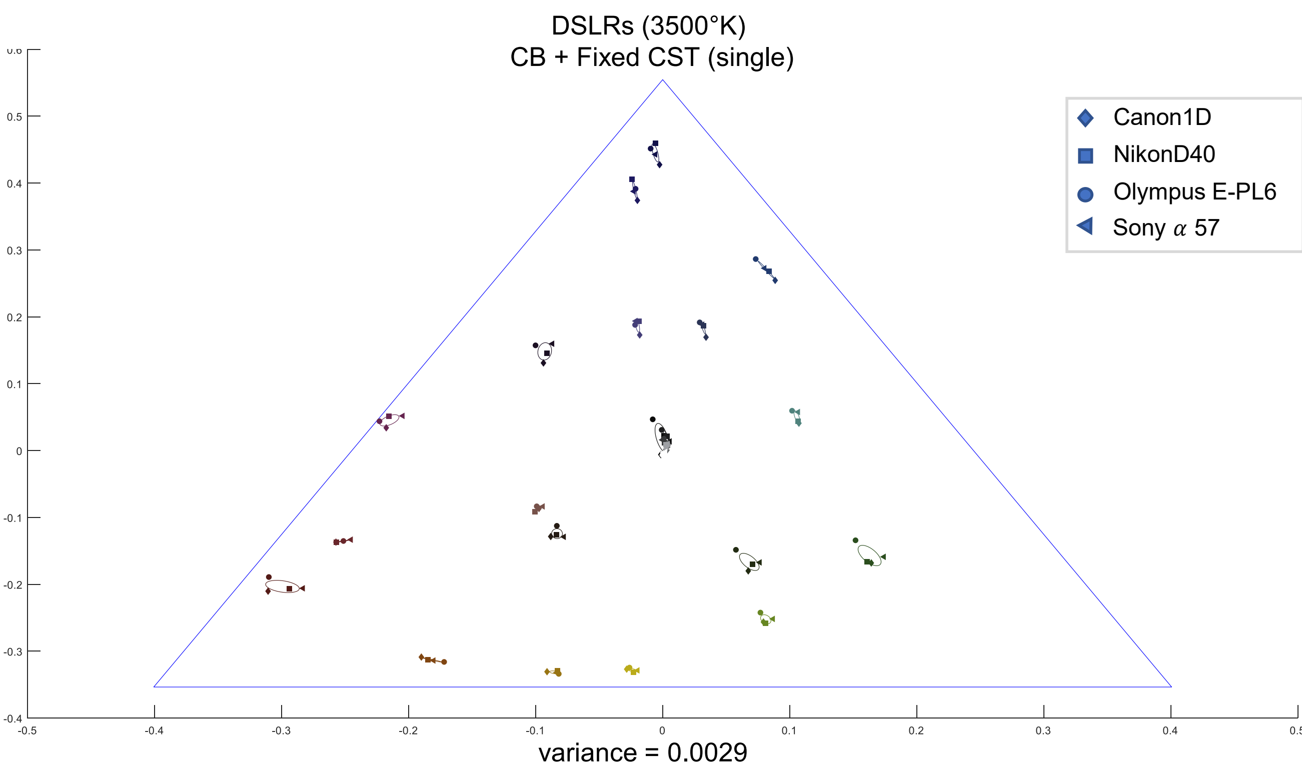

Figure 35. CB + Fixed CST (single) consistency among DSLR cameras capturing the same scene under illumination 3500°K.

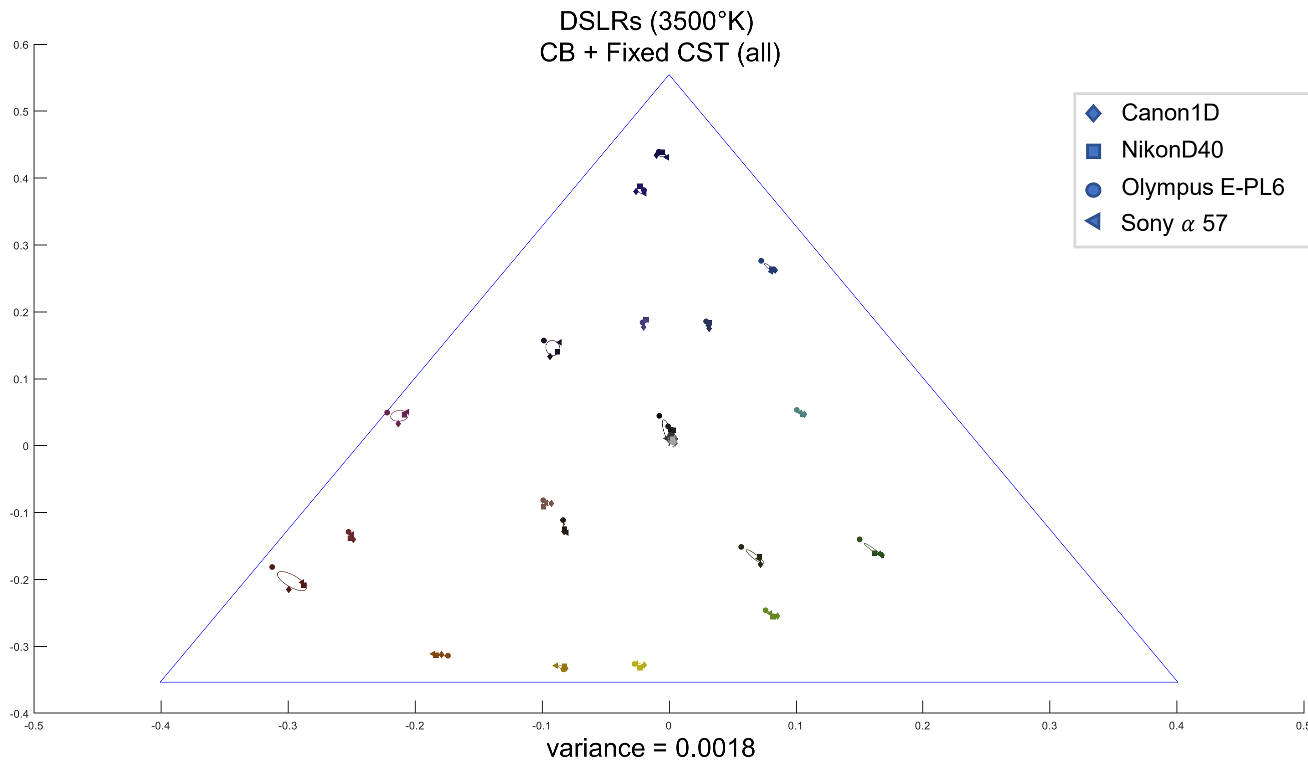

Figure 36. CB + Fixed CST (all) consistency among DSLR cameras capturing the same scene under illumination 3500°K.

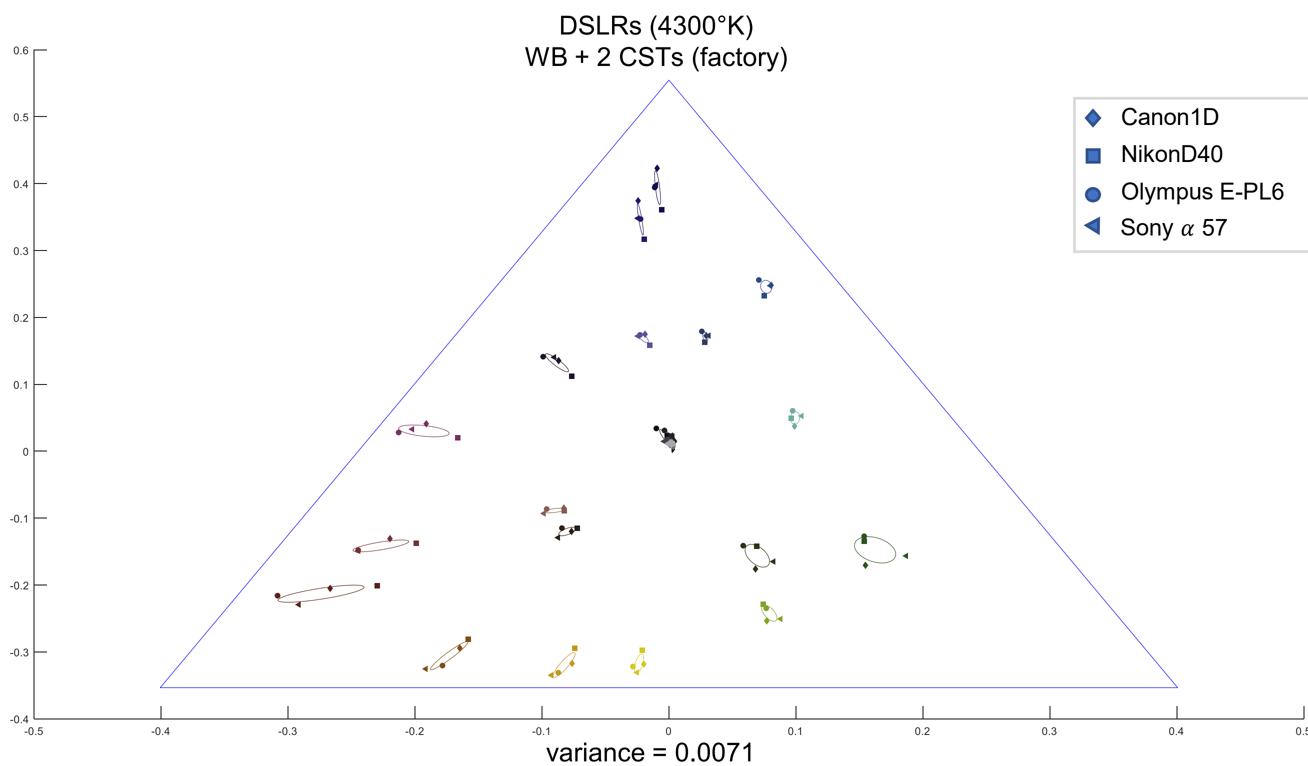

Figure 37. WB + CSTs (factory) consistency among DSLR cameras capturing the same scene under illumination 4300°K.

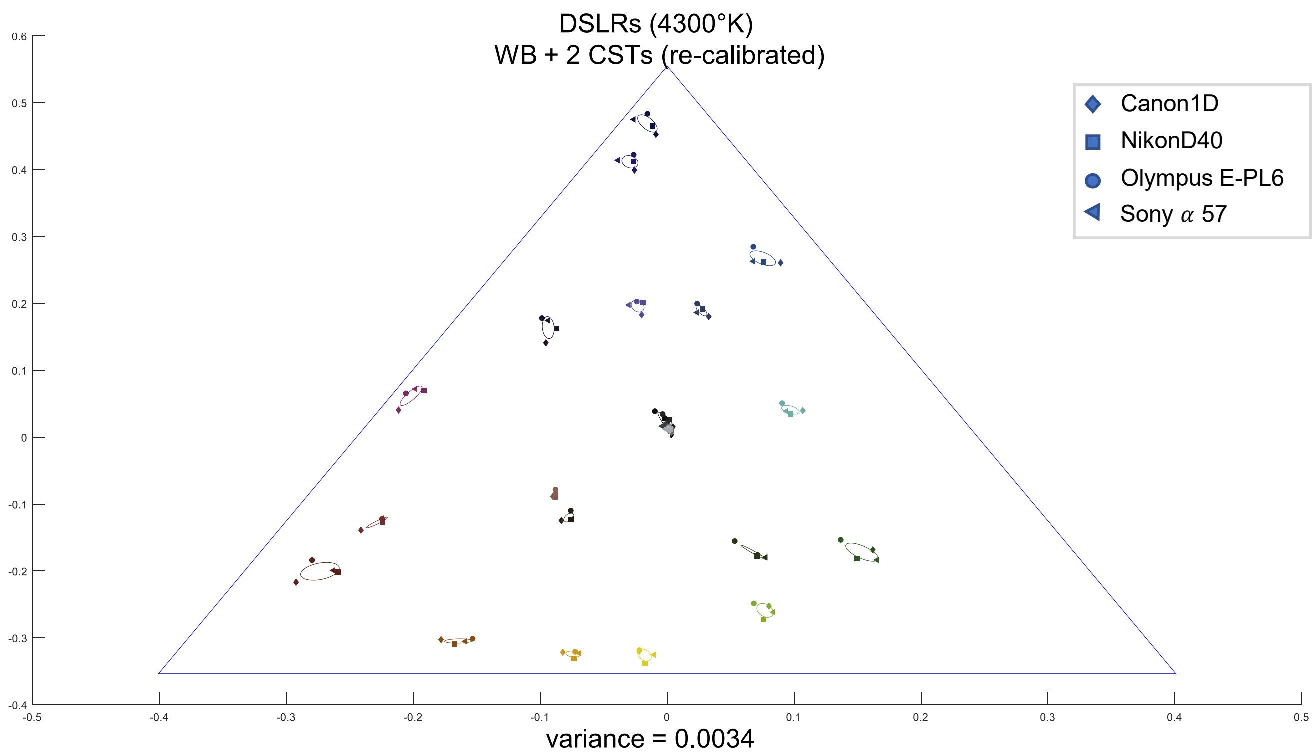

Figure 38. WB + CSTs (re-calibrated) consistency among DSLR cameras capturing the same scene under illumination 4300°K.

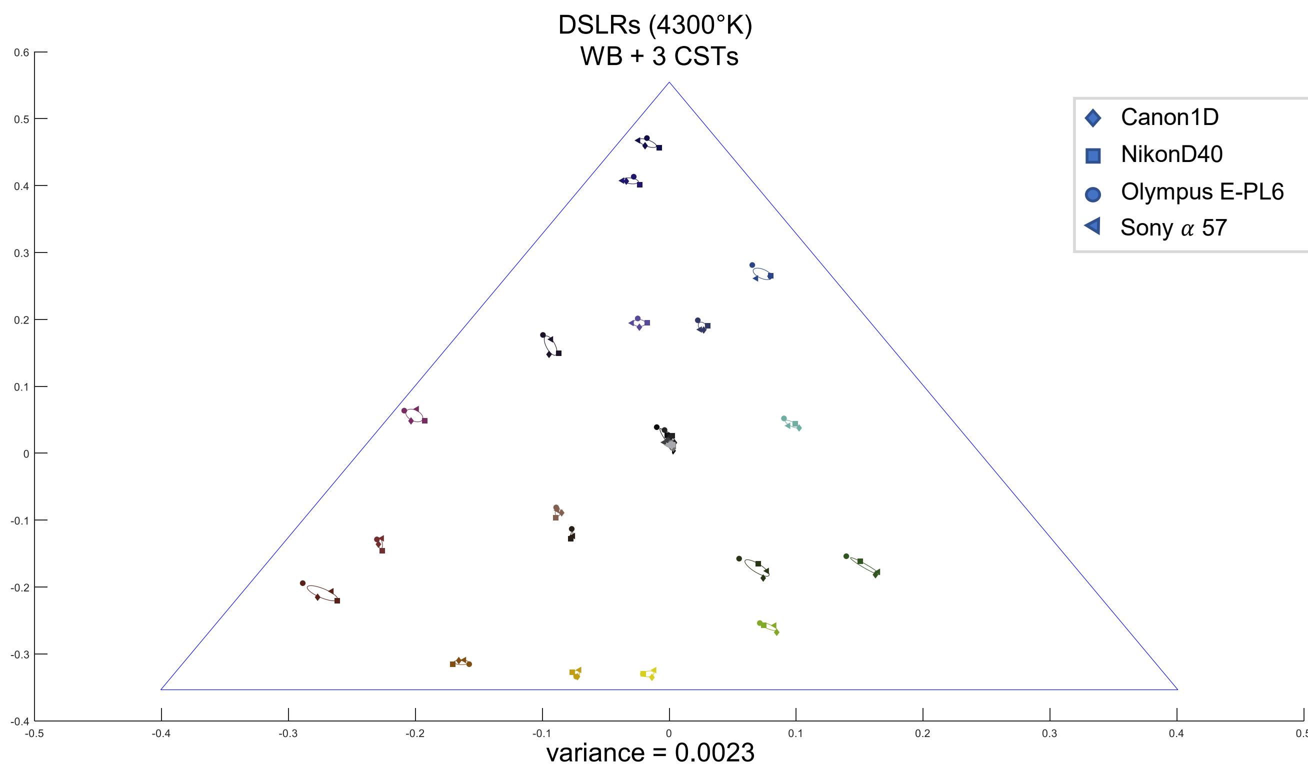

Figure 39. WB + 3 CSTs consistency among DSLR cameras capturing the same scene under illumination 4300°K.

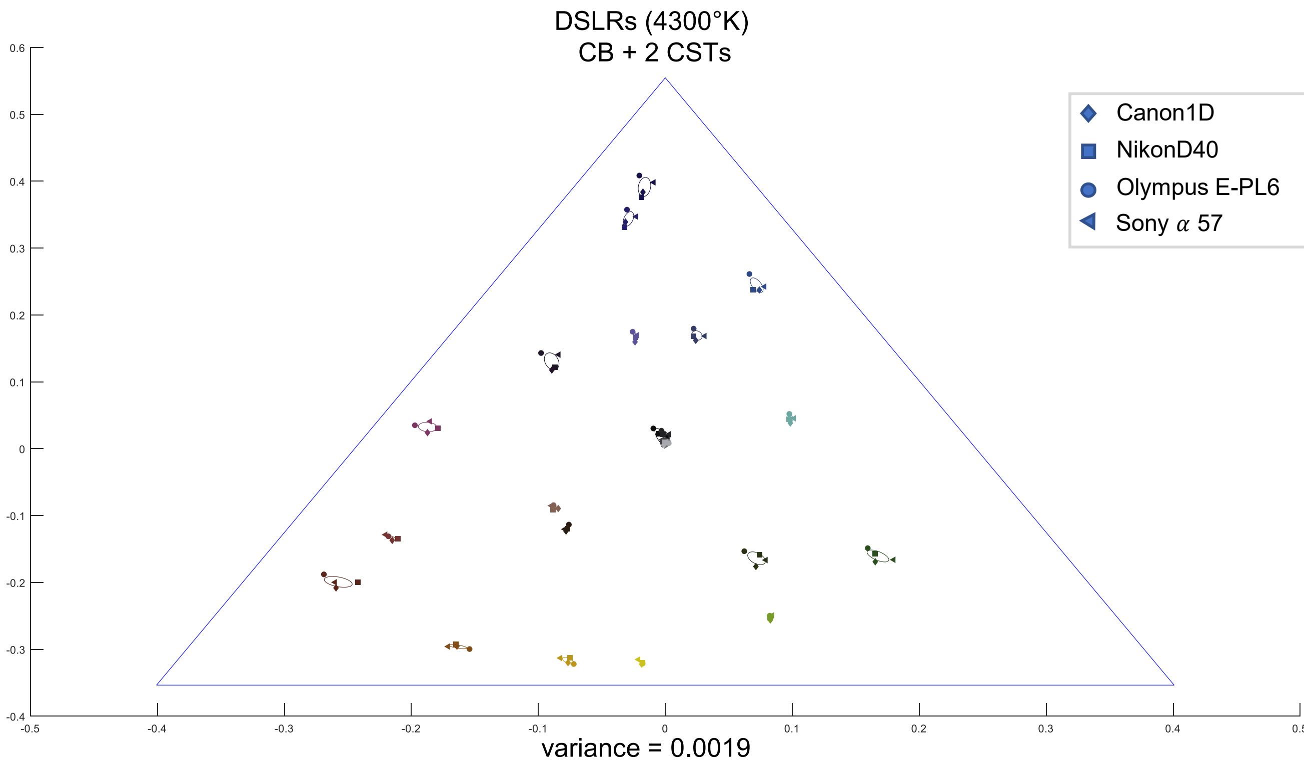

Figure 40. CB + 2 CSTs consistency among DSLR cameras capturing the same scene under illumination 4300°K.

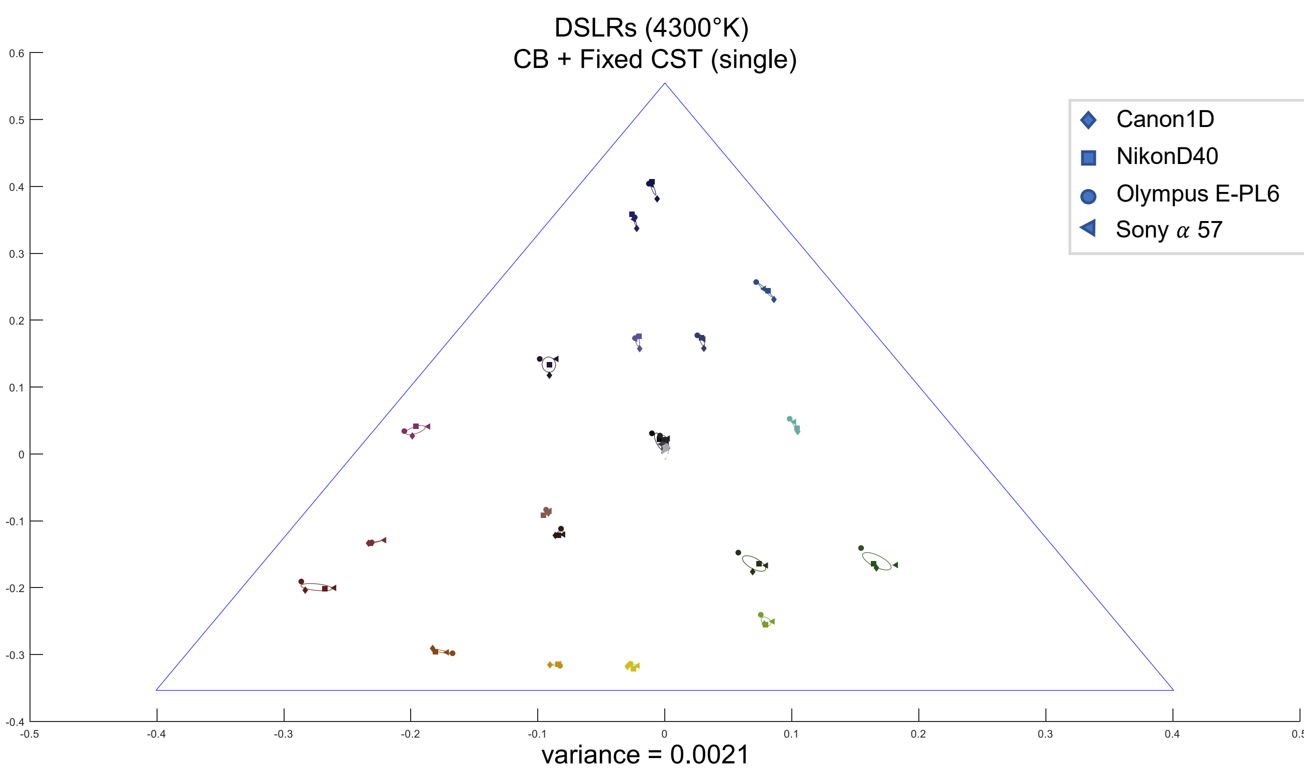

Figure 41. CB + Fixed CST (single) consistency among DSLR cameras capturing the same scene under illumination 4300°K.

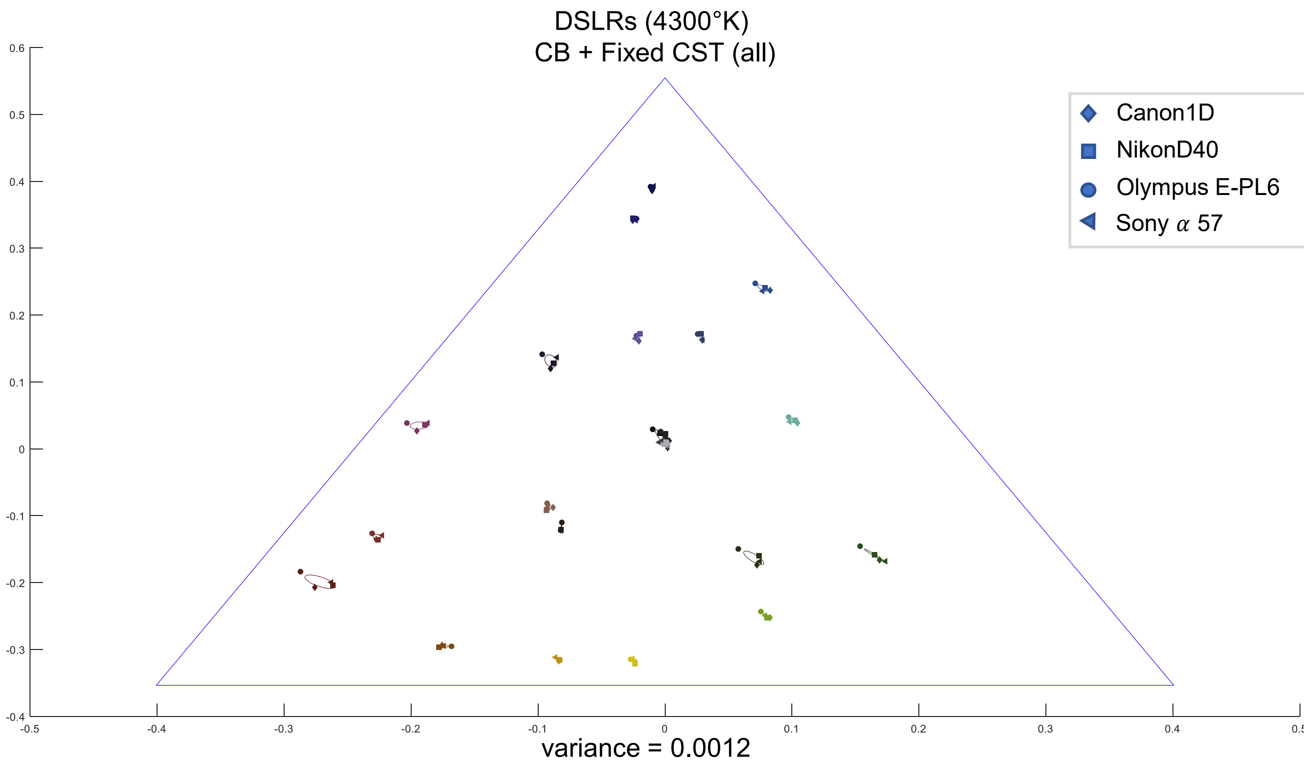

Figure 42. CB + Fixed CST (all) consistency among DSLR cameras capturing the same scene under illumination 4300°K.

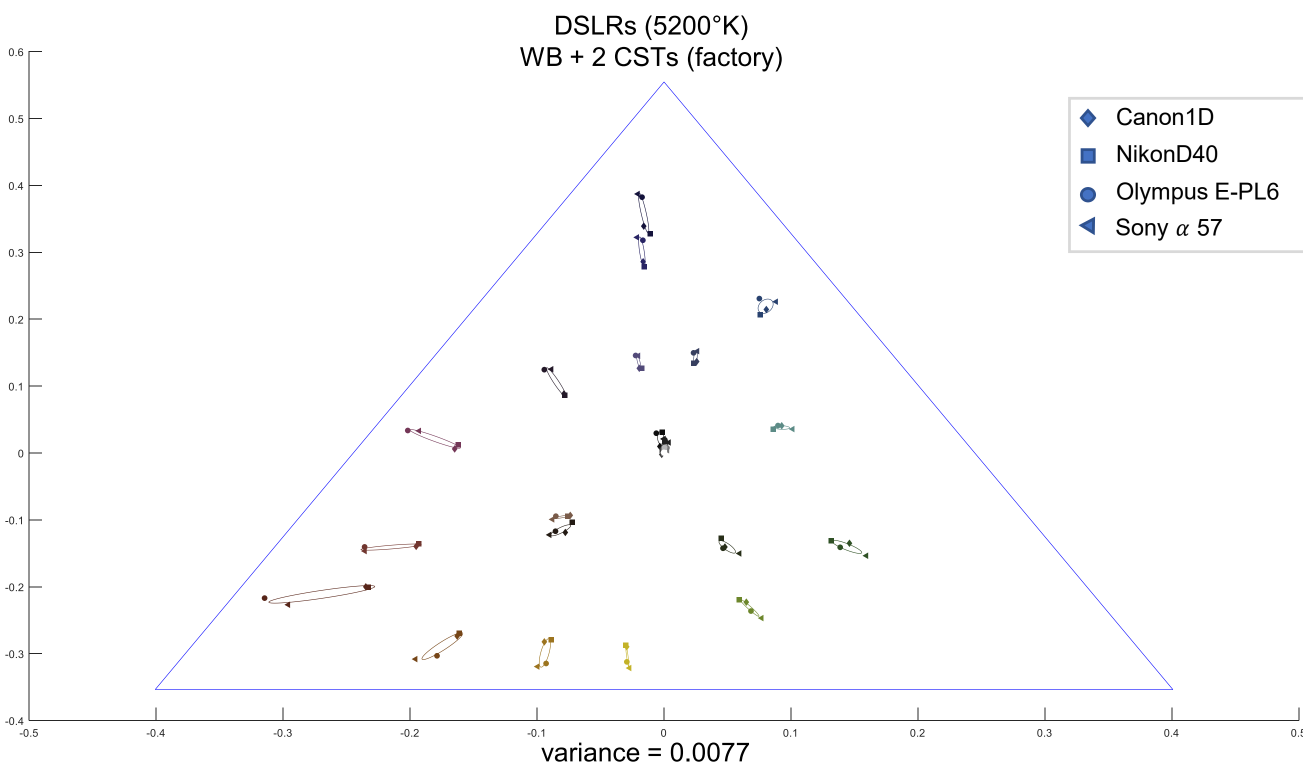

Figure 43. WB + CSTs (factory) consistency among DSLR cameras capturing the same scene under illumination 5200°K.

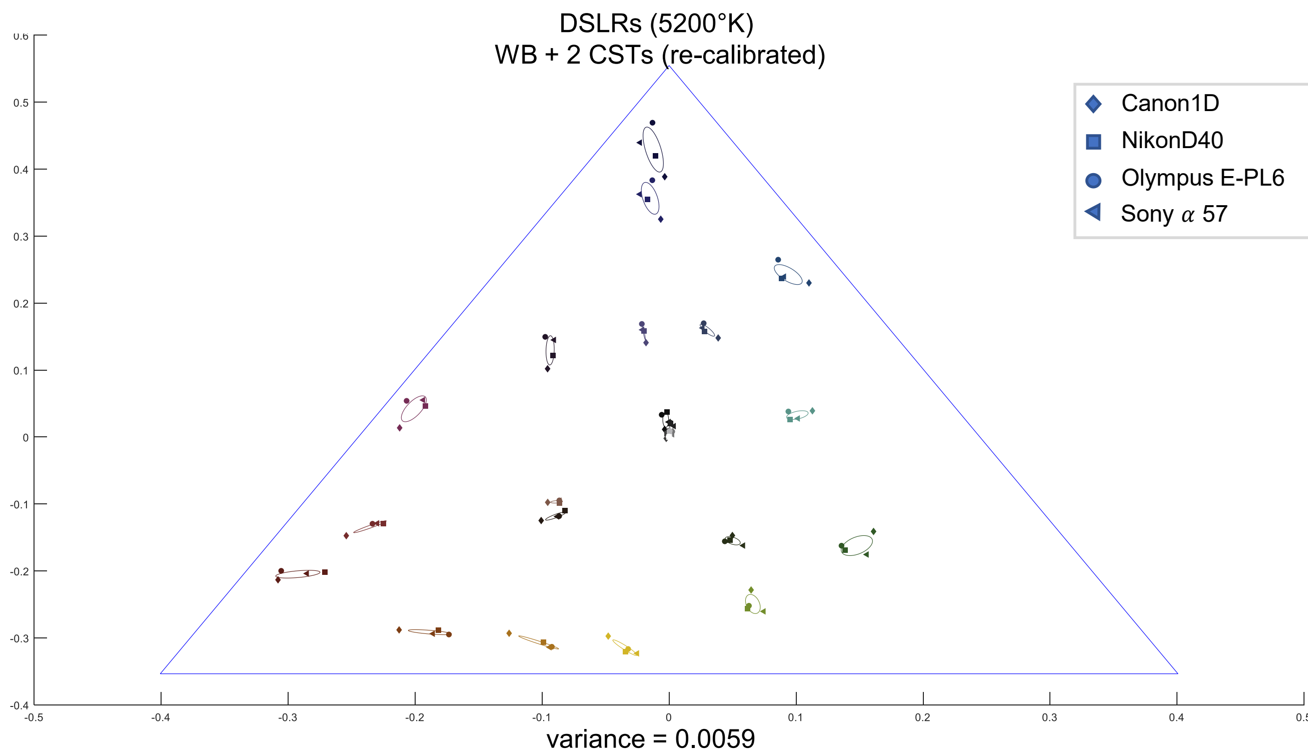

Figure 44. WB + CSTs (re-calibrated) consistency among DSLR cameras capturing the same scene under illumination 5200°K.

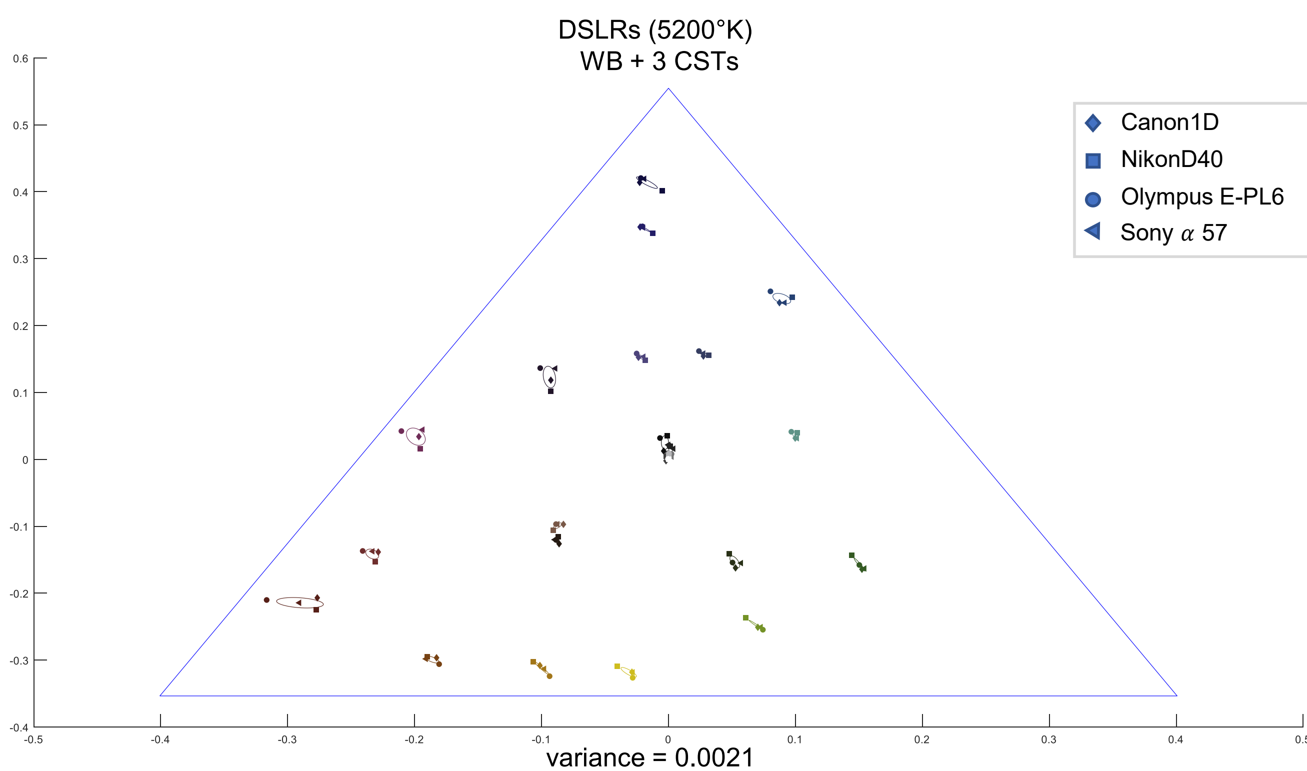

Figure 45. WB + 3 CSTs consistency among DSLR cameras capturing the same scene under illumination 5200°K.

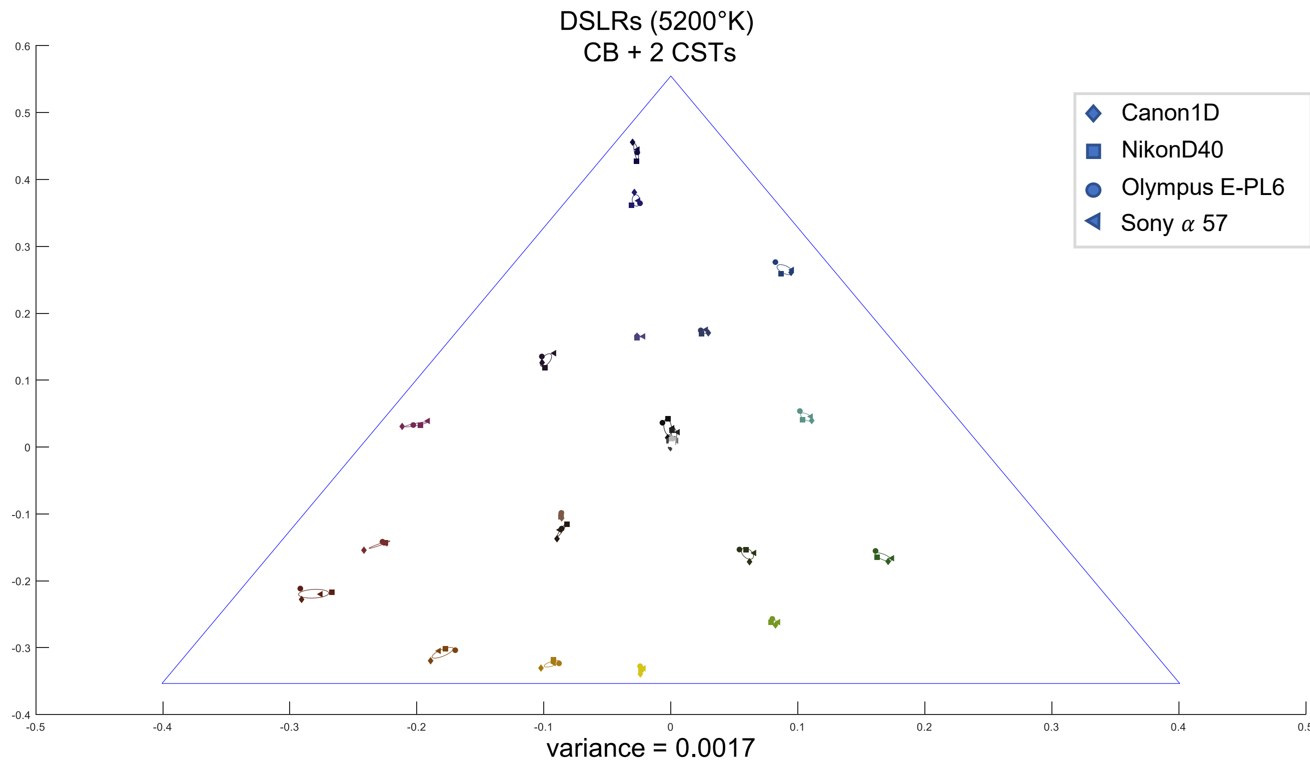

Figure 46. CB + 2 CSTs consistency among DSLR cameras capturing the same scene under illumination 5200°K.

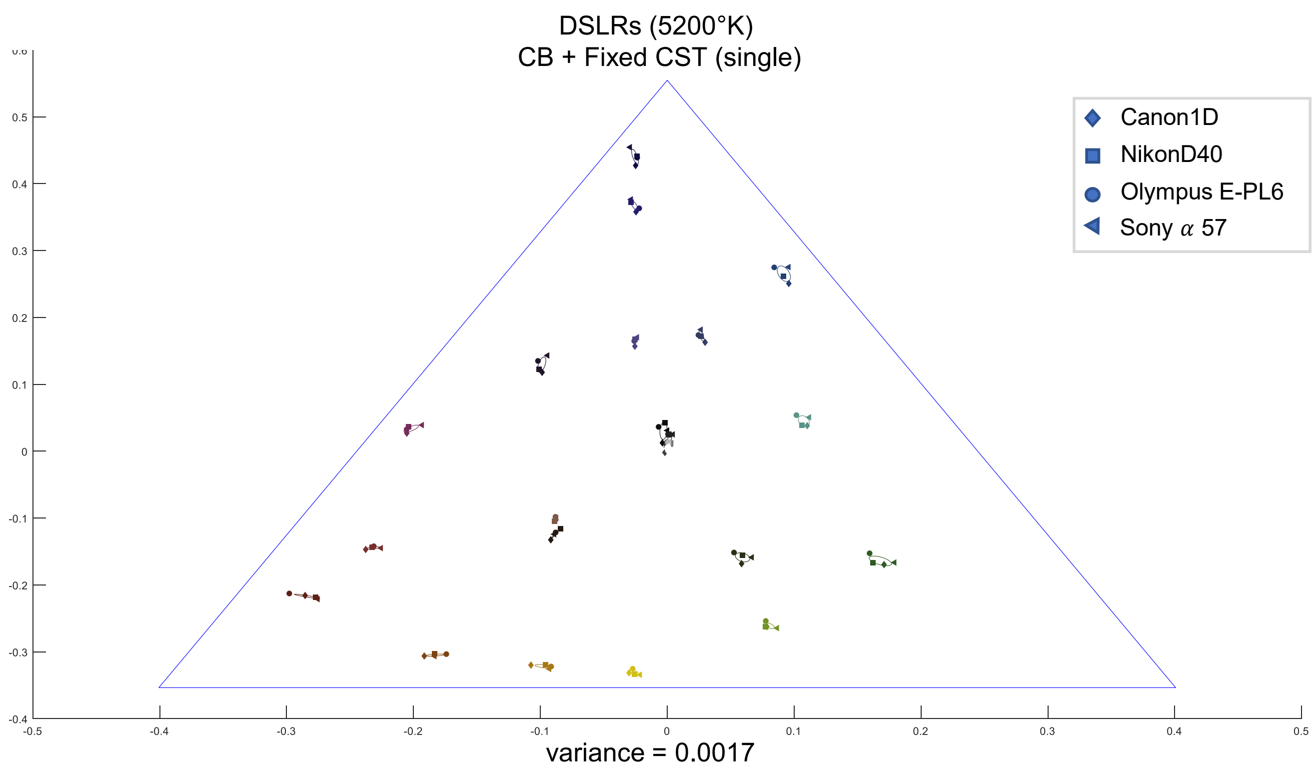

Figure 47. CB + Fixed CST (single) consistency among DSLR cameras capturing the same scene under illumination 5200°K.

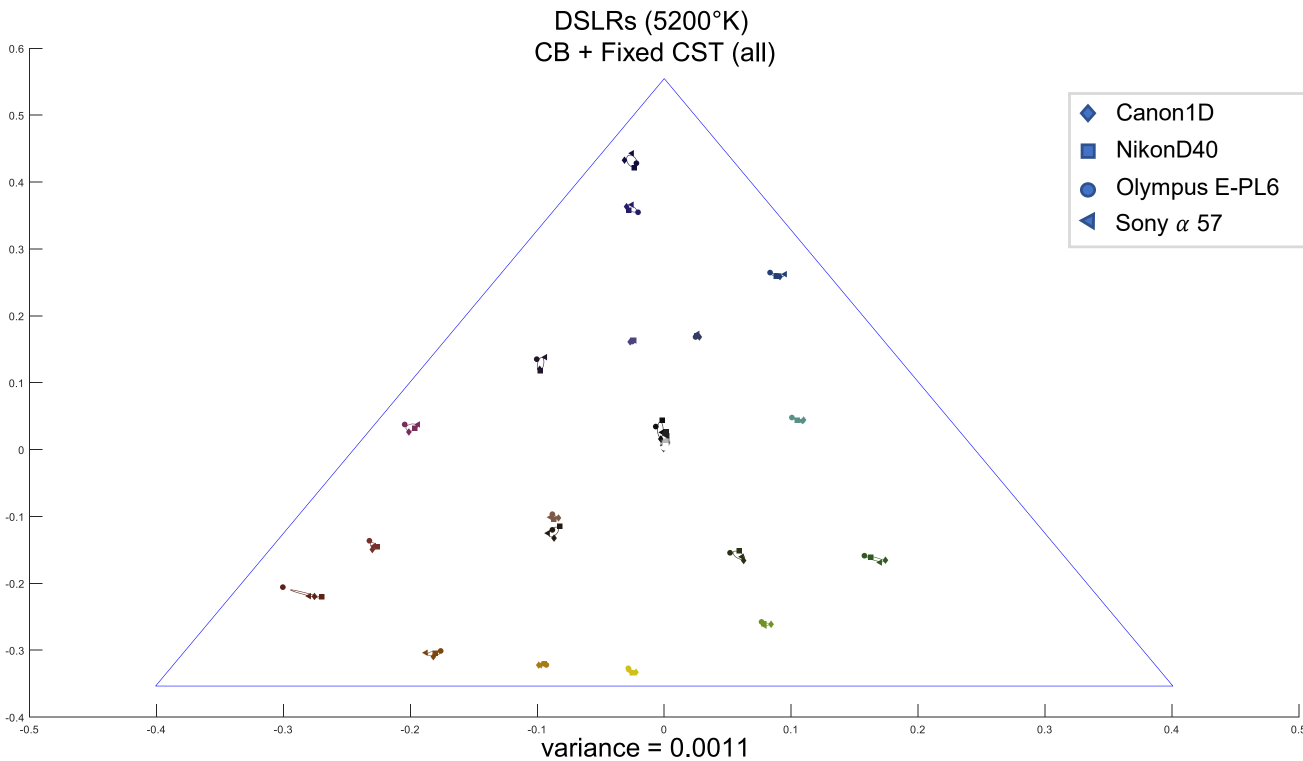

Figure 48. CB + Fixed CST (all) consistency among DSLR cameras capturing the same scene under illumination 5200°K.

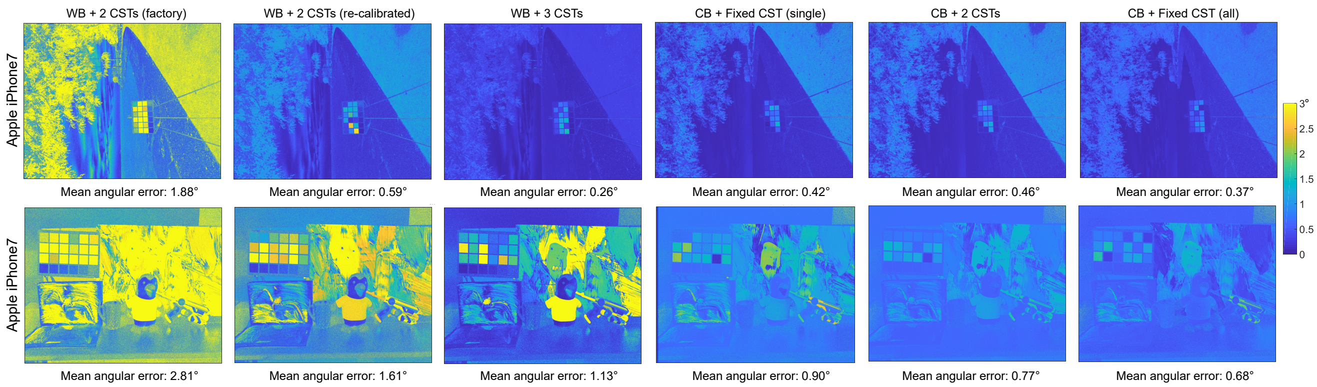

Figure 49. Visual comparison for the Apple iPhone7.

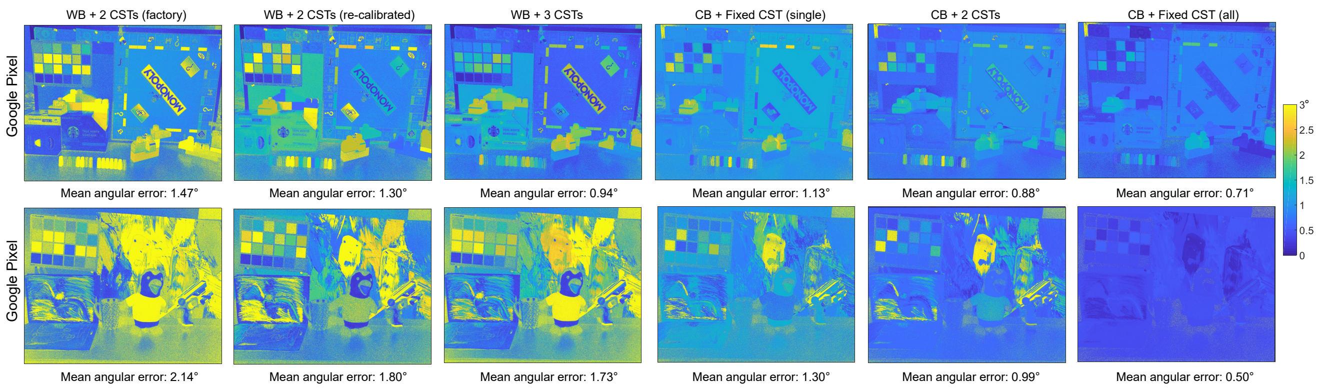

Figure 50. Visual comparison for the Google Pixel.

3. Additional visual results

As we stated in the main paper, we compute the T_{fixed} for method #2 in two ways. The first is to only use a single observation of the color chart image with CCT of 6500°K. The second approach is to consider all observations of the color rendition chart for each different illumination. In our experiments, we distinguish the results obtained with these two different approaches to estimate T_{fixed}. In this supplemental material we also present visual results for "Method 2 (extension)" shown as CB + 2 CSTs.

When using all observations, we use a standard 10-fold cross validation procedure that uses 90 images for estimating the T_{fixed} with Iteratively Re-weighted Least Squares(IRLS) [2] algorithm and the remaining 10 images for computing the error. The final error is the average error across the 10-fold cross validation.

Figures 49,50,51,52,53,54, and 55 show visual results on whole images for the Apple iPhone7, the Google Pixel, the LG-G4, the Canon1D, the NikonD40, the Sony α57 and the Olympus E-PL6 respectively. These results are accompanied by heat maps to reveal which parts of the images are being most affected by errors. For all figures, the corresponding sRGB (as rendered by the camera) is also provided.

References

[1] Adobe Systems Incorporated. *Digital Negative (DNG) Specification (Version 1.4.0.0)*, accessed November 20, 2017. https://www.adobe.com/support/downloads/detail.jsp?ftpID=5475. 2

[2] P. J. Huber and E. M. Ronchetti. *Robust statistics (2nd Edition)*. Wiley, 2009. 28

[3] G. Wyszecki and W. S. Stiles. *Color science (2nd Edition)*. Wiley, 2000. 2

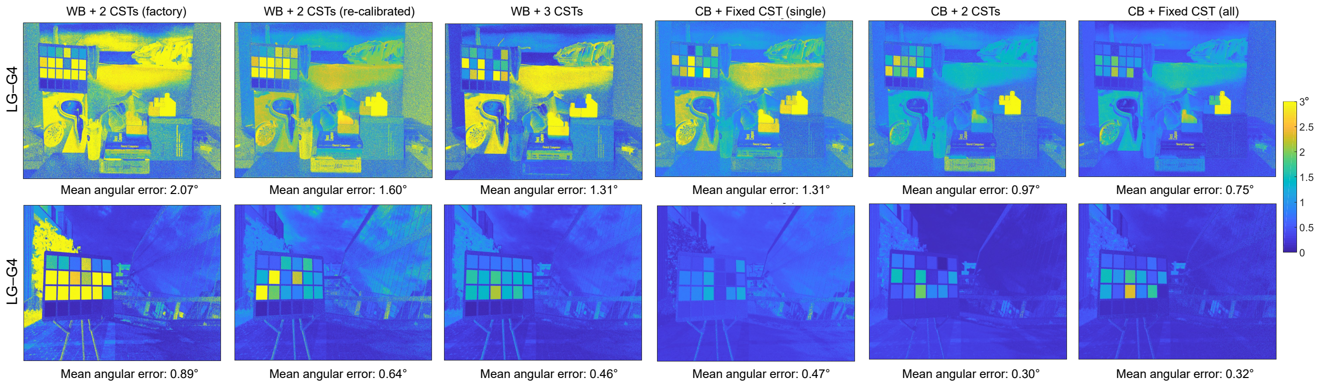

Figure 51. Visual comparison for the LG-G4.

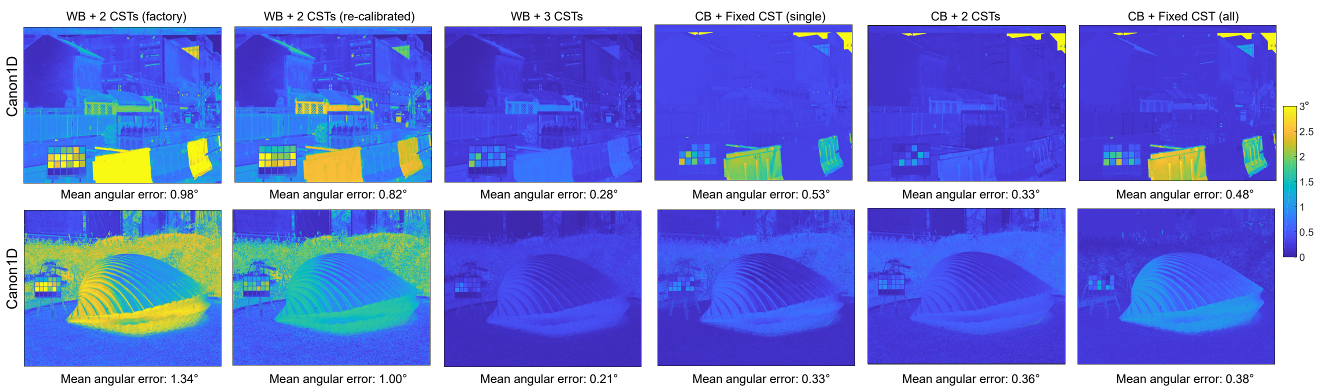

Figure 52. Visual comparison for the Canon1D.

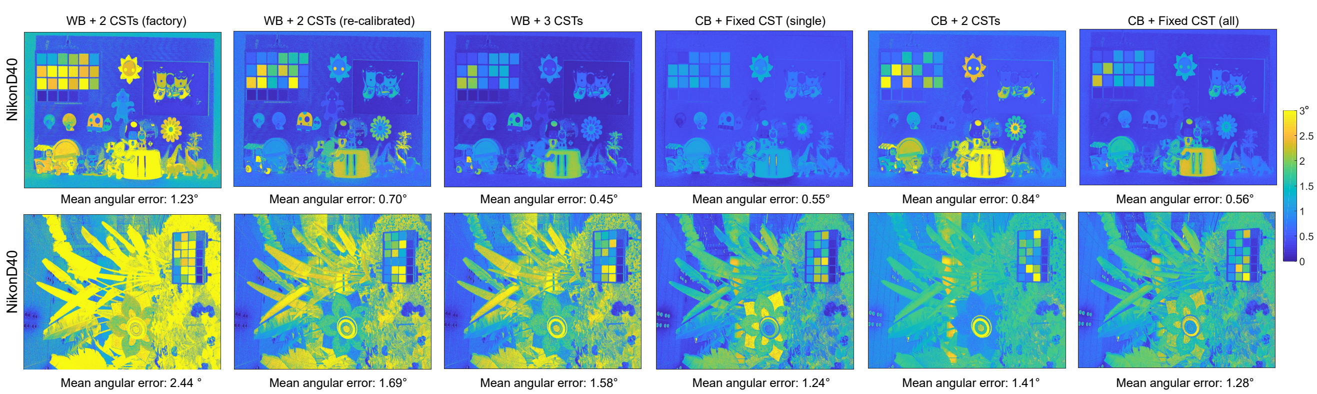

Figure 53. Visual comparison for the NikonD40.

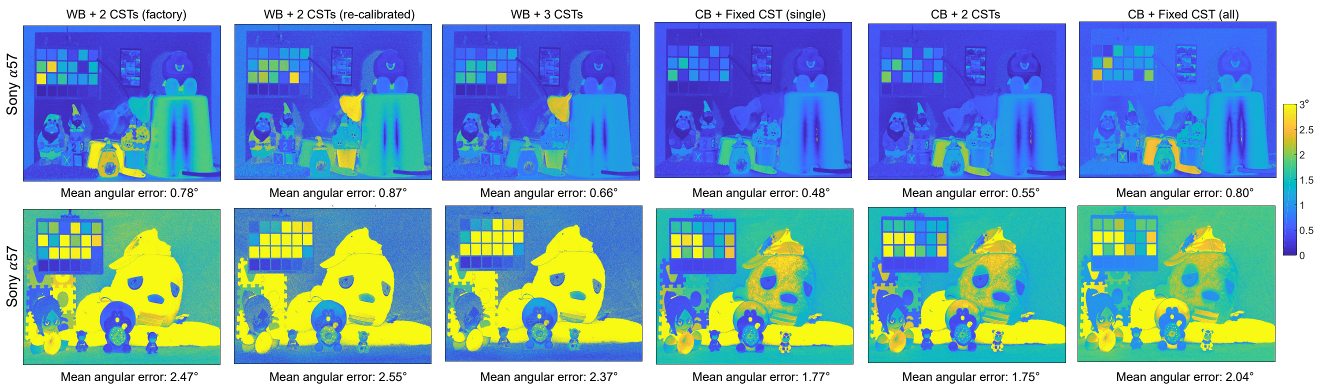

Figure 54. Visual comparison for the Sony α57.

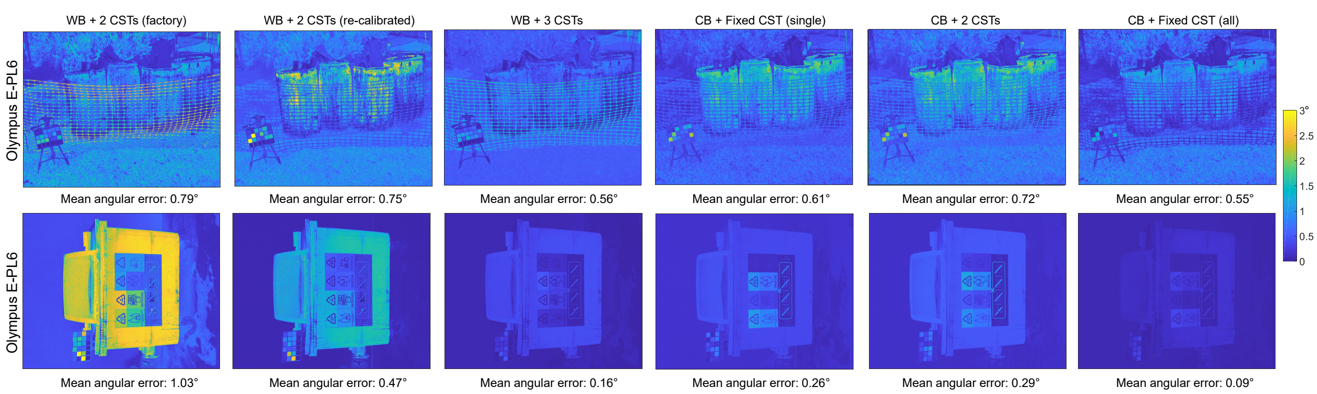

Figure 55. Visual comparison for the Olympus E-PL6.