



ICtCp colour representation: Observations and Findings

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Introduction

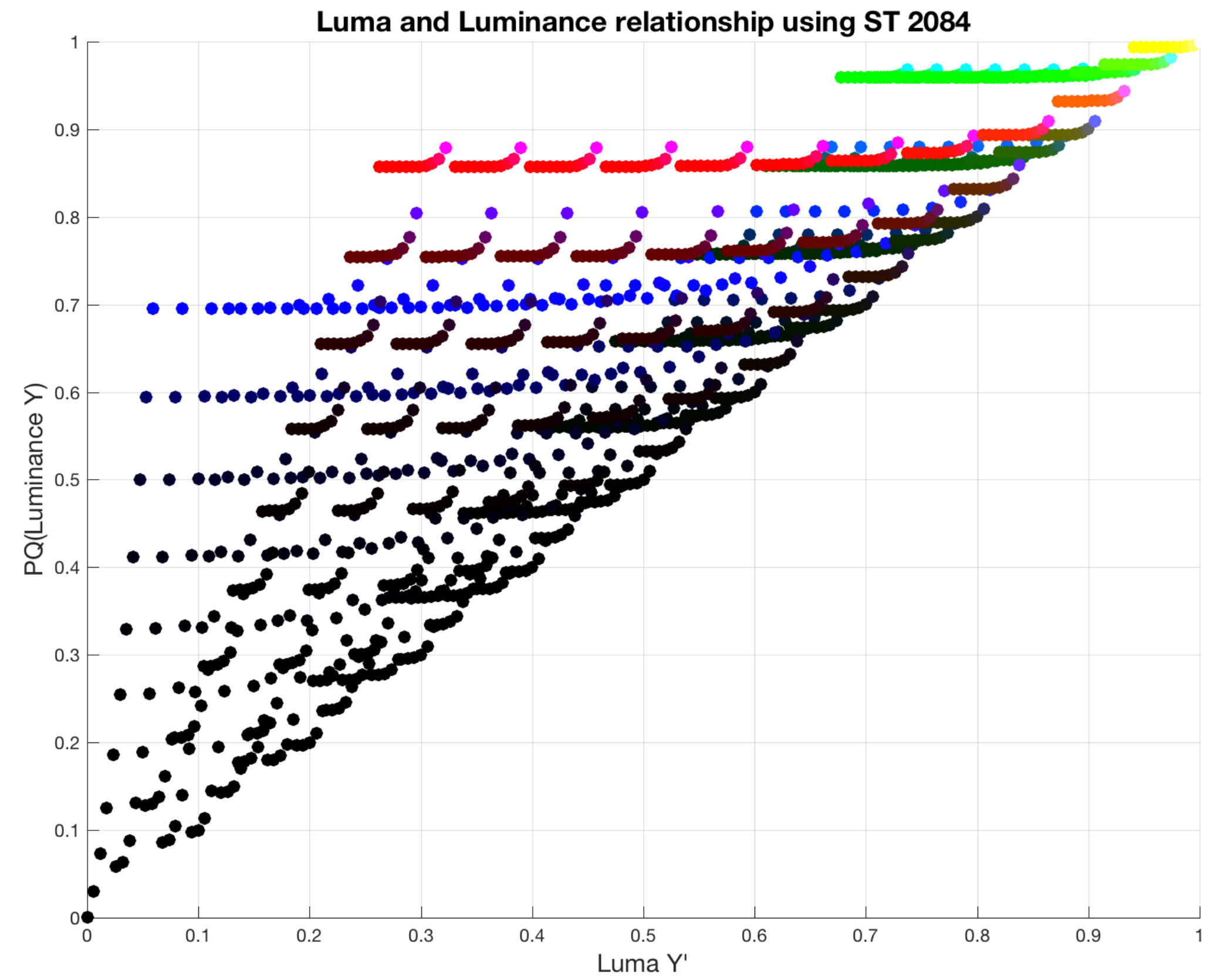
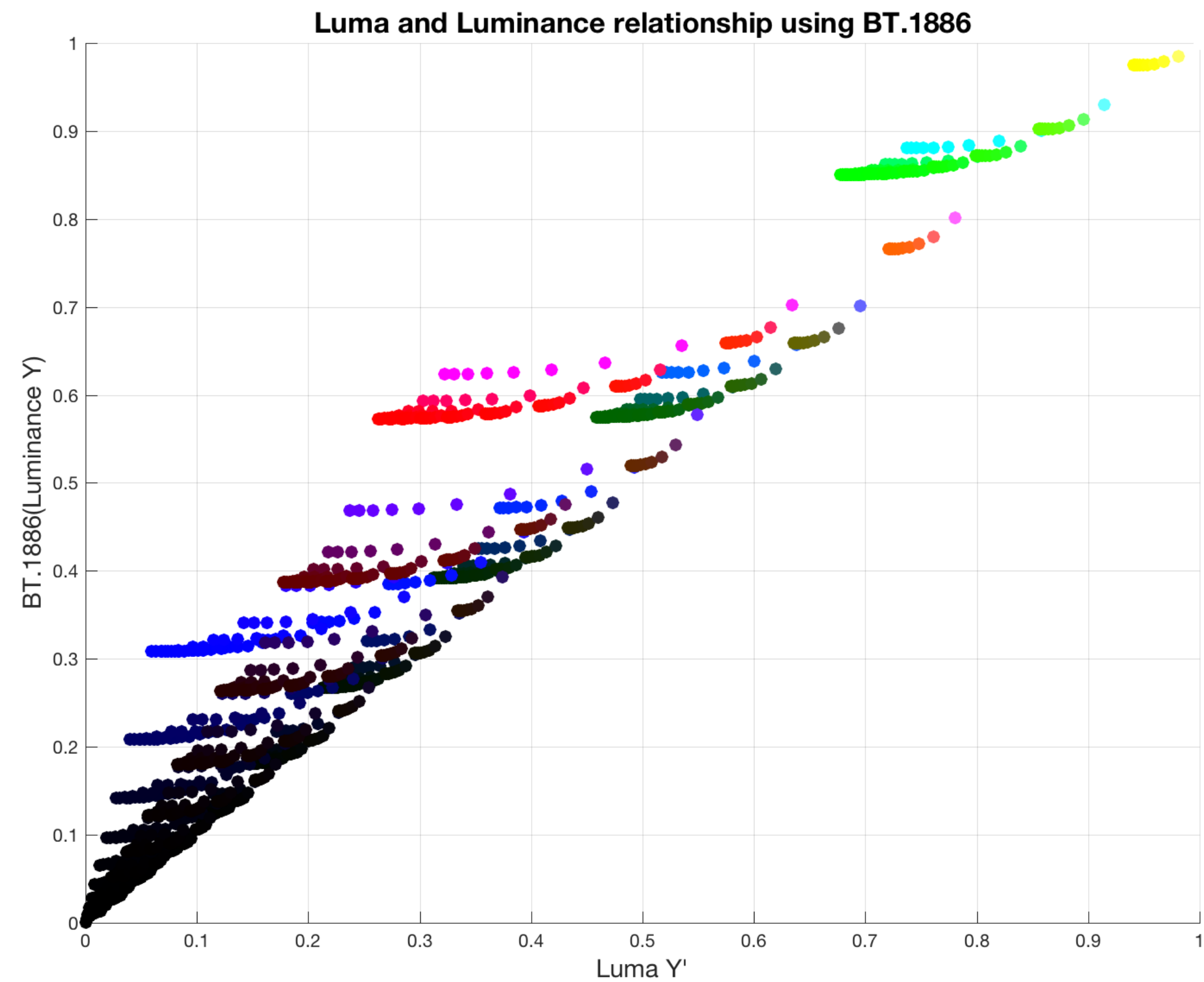
- A new colour representation was introduced in the HEVC, AVC, and CICP specifications (from ITU-R BT.[HDR])
 - ICtCp
- Claims to resolve several issues that have been observed in NCL YCbCr
 - Chroma leakage (especially for 4:2:0 applications)
 - Reduced banding/Improved codeword representation
 - Hue Linearity
 - Better performance for larger colour volumes

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \frac{1}{4096} \times \begin{bmatrix} 1688 & 2146 & 262 \\ 683 & 2951 & 462 \\ 99 & 309 & 3688 \end{bmatrix} \begin{bmatrix} R_{2020} \\ G_{2020} \\ B_{2020} \end{bmatrix}$$

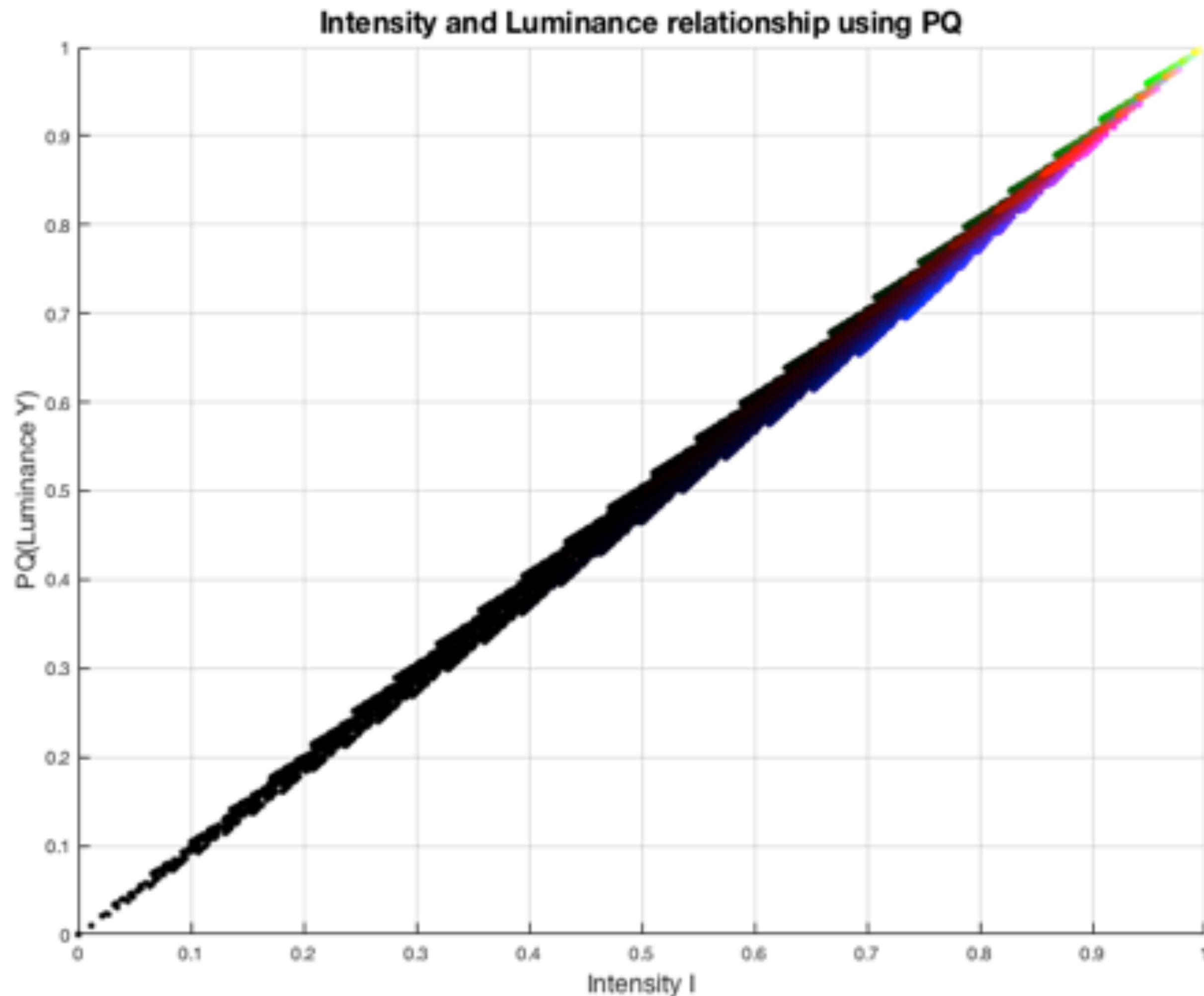
$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.359283259012122 & 0.697605114777950 & -0.035891593232029 \\ -0.192080846370499 & 1.100476797037432 & 0.075374865851912 \\ 0.007079784460748 & 0.074839666218637 & 0.843326545389877 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\begin{bmatrix} I \\ Ct \\ Cp \end{bmatrix} = \frac{1}{4096} \times \begin{bmatrix} 2048 & 2048 & 0 \\ 6610 & -13613 & 7003 \\ 17933 & -17390 & -543 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

Isoluminance in YCbCr

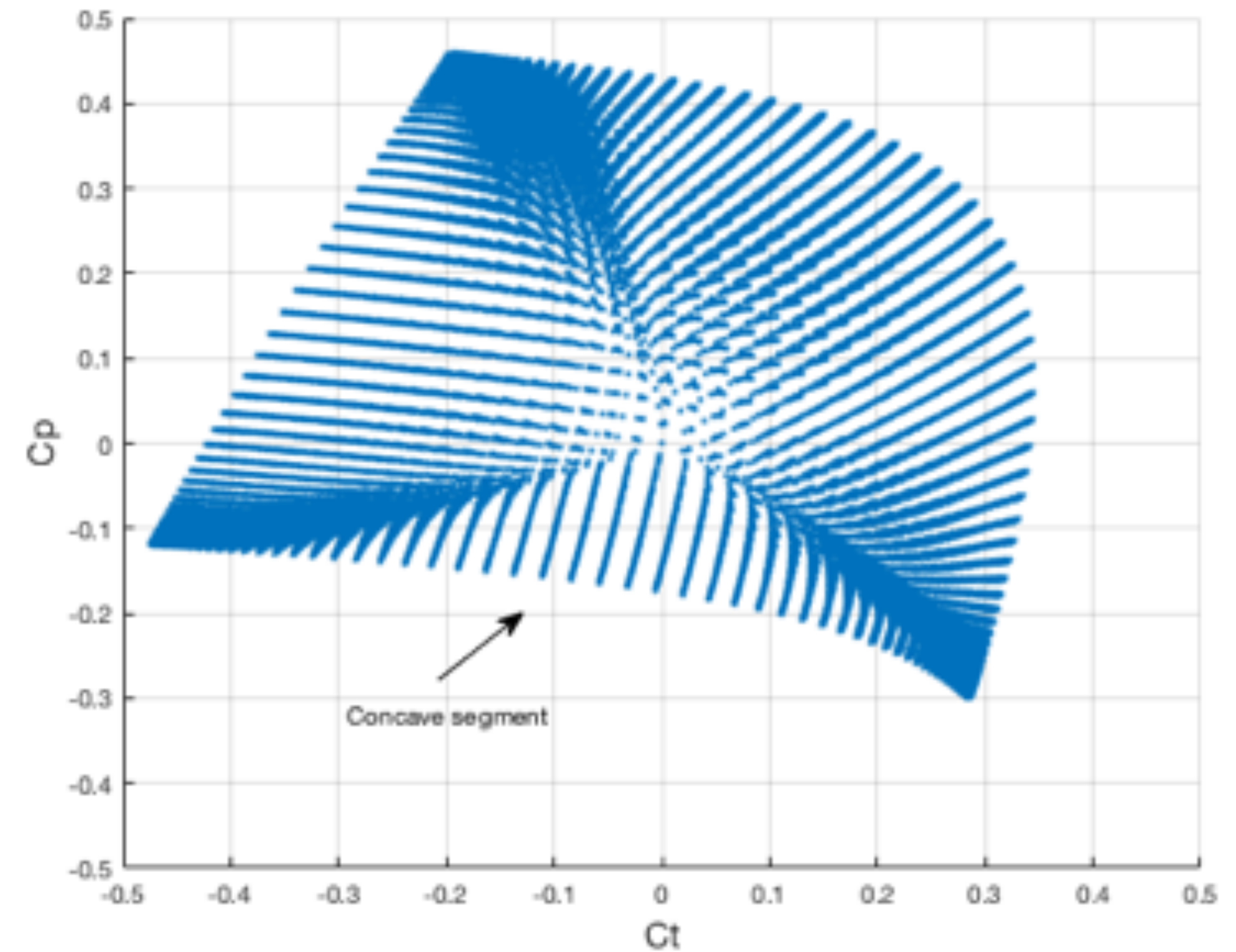
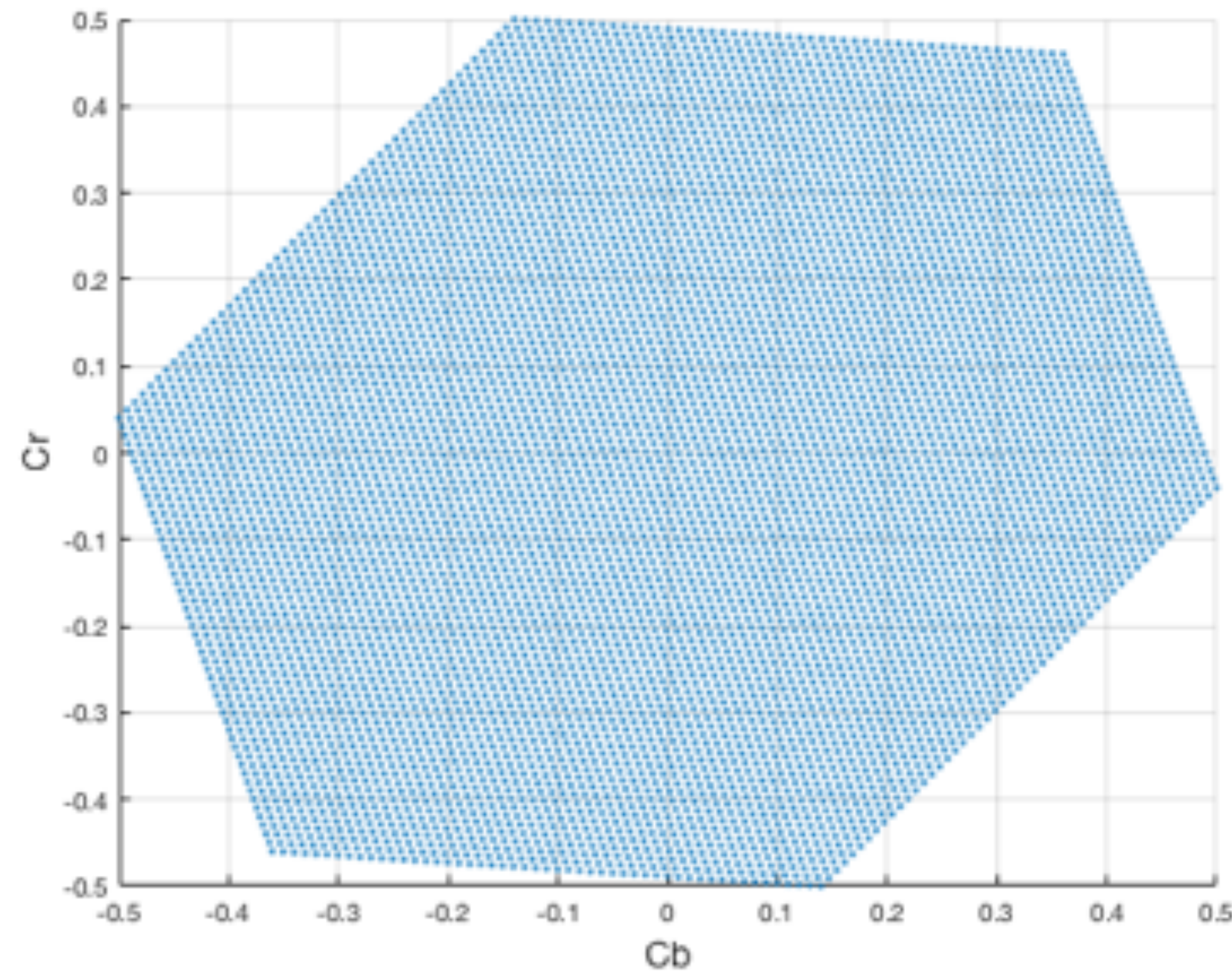


Isoluminance behavior for ICtCp



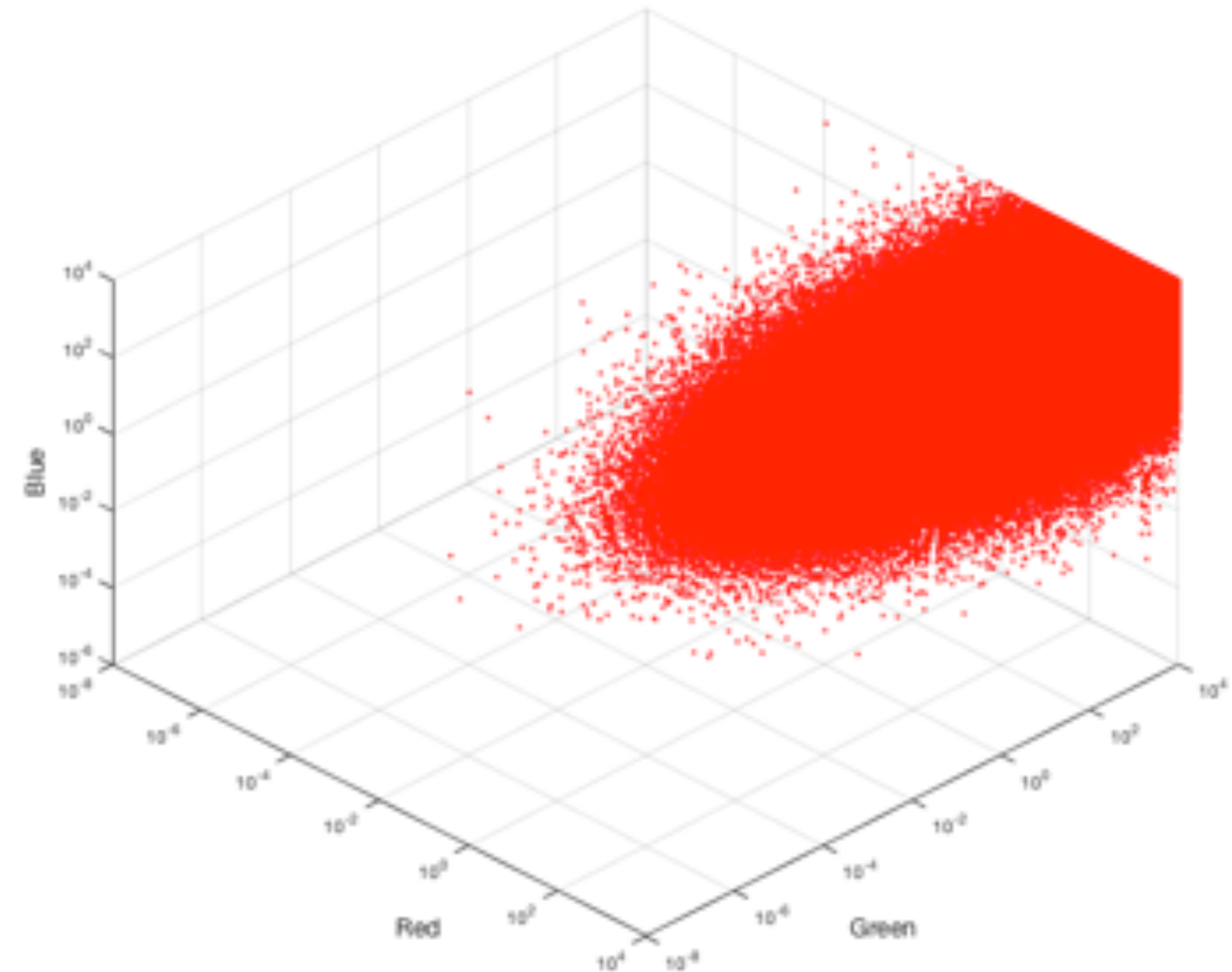
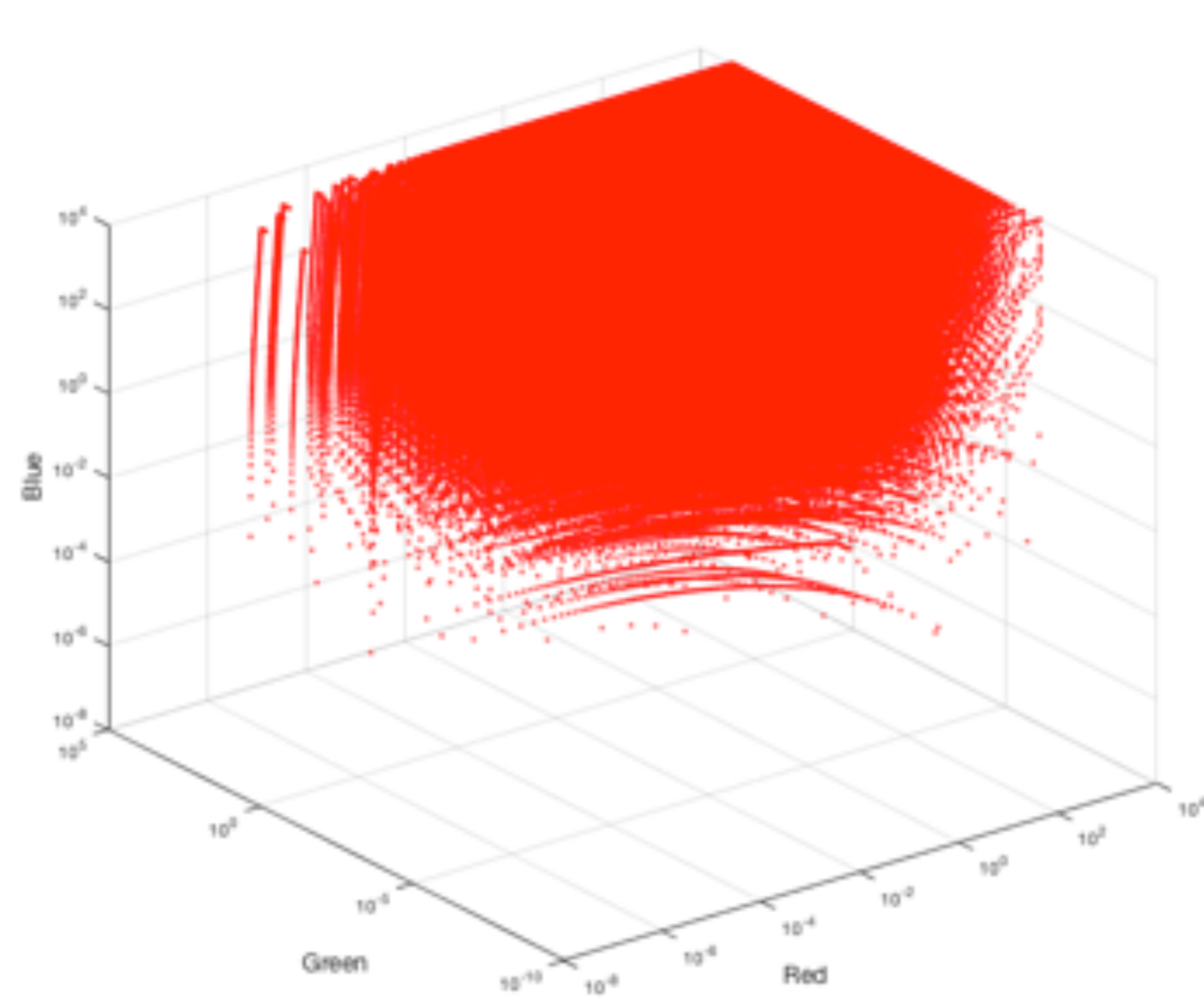
- I in ICtCp closer to Luminance compared to YCbCr
- However it is still not perfect
- Also, Luminance is not the only component of importance
- If we cared more about luminance then constant luminance methods would be preferred

Colour planes and behavior



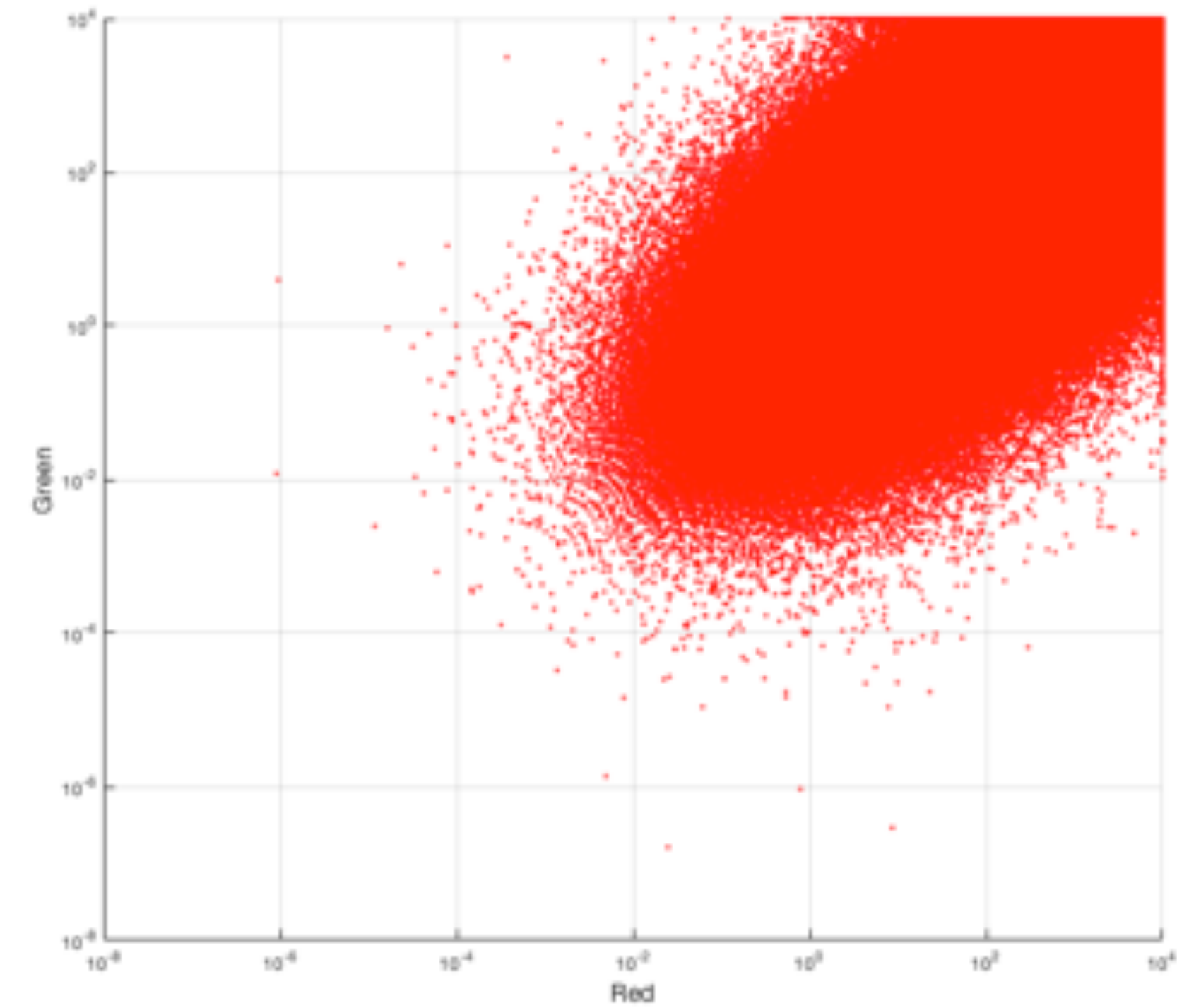
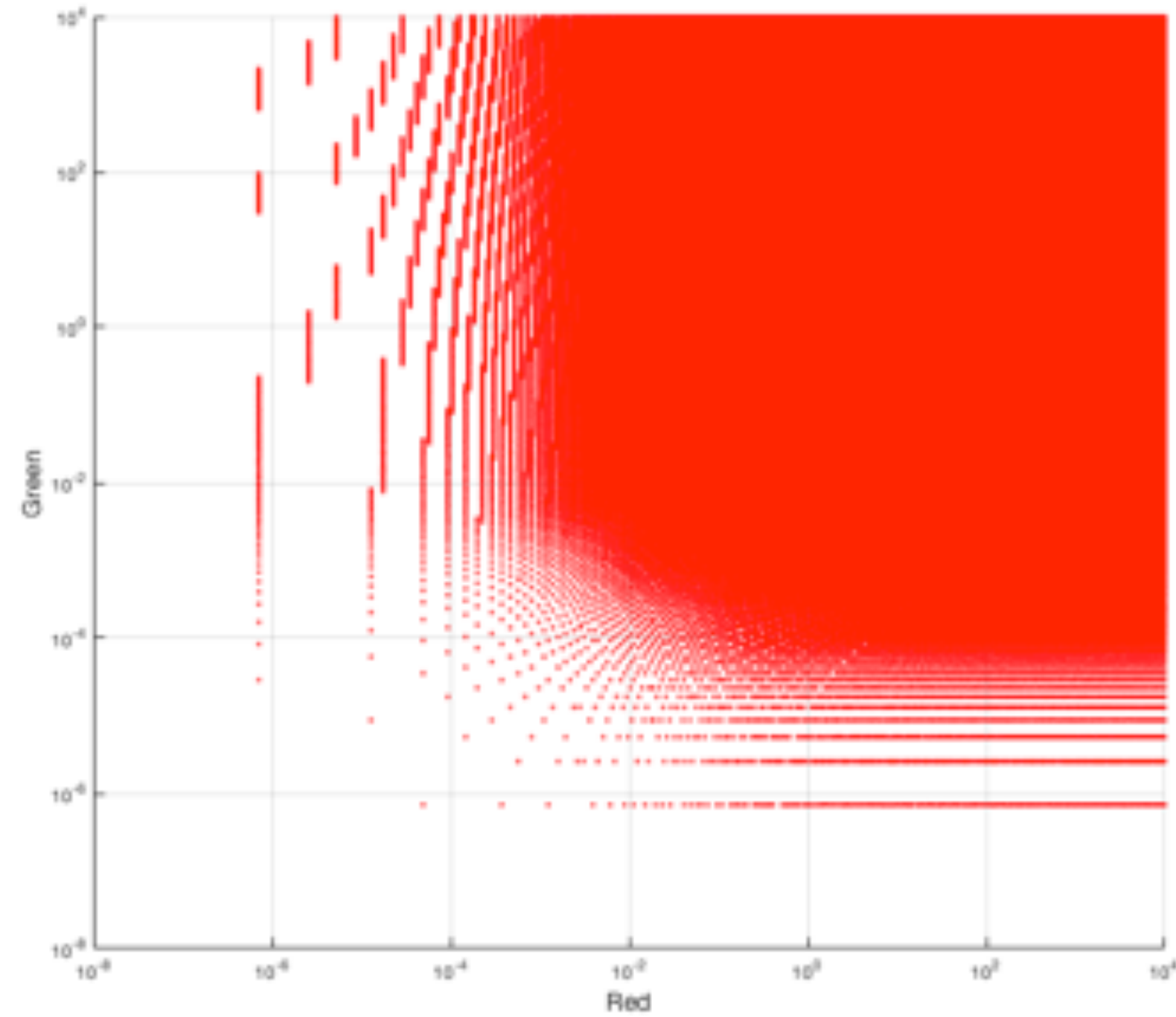
- Concave segment provides some concerns
 - If filtering is performed across two points on that segment, could this result in quality problems?
 - Filtering/Downsampling for example could result in out-of-gamut colours. Clipping may occur.

RGB Codeword volume allocation



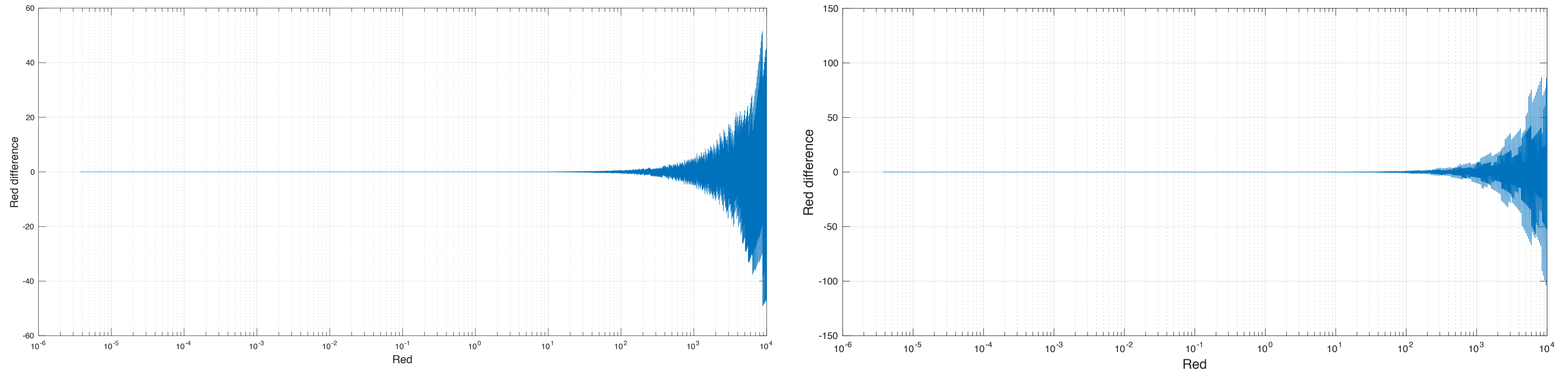
- In YCbCr codewords are more “uniformly” allocated.
- In ICtCp we observe codewords more densely allocated in ranges where there is good mix of colors
 - More sparse in areas where there is a lack of at least one colour and when the remaining colour presence is moderate to significant

RGB Codeword volume allocation - Red/Green view



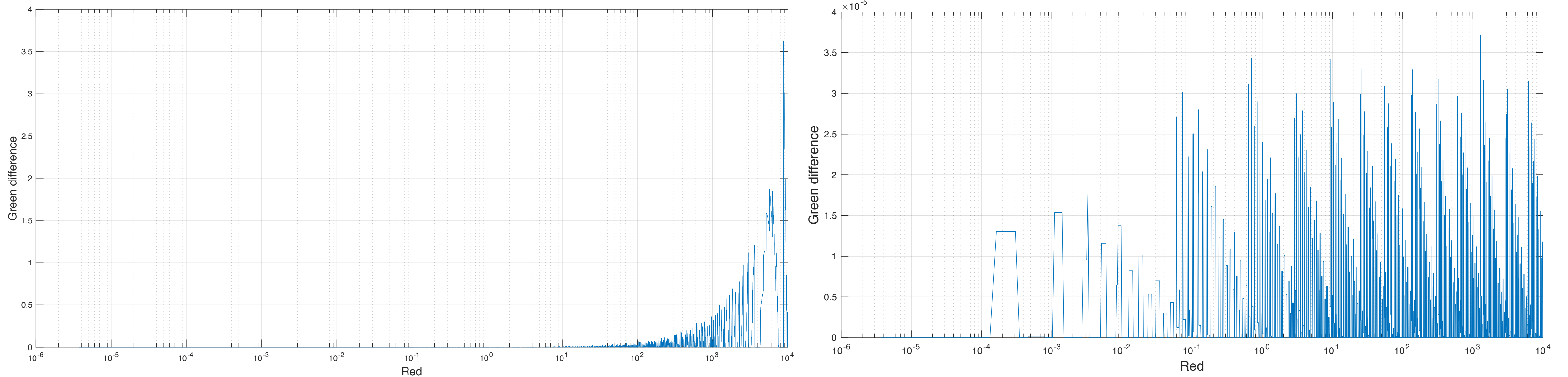
- Reduced precision of ICtCp in those areas could be a concern for some applications (colour accuracy)

A more careful look: Quantized (10bit) Color Ramps



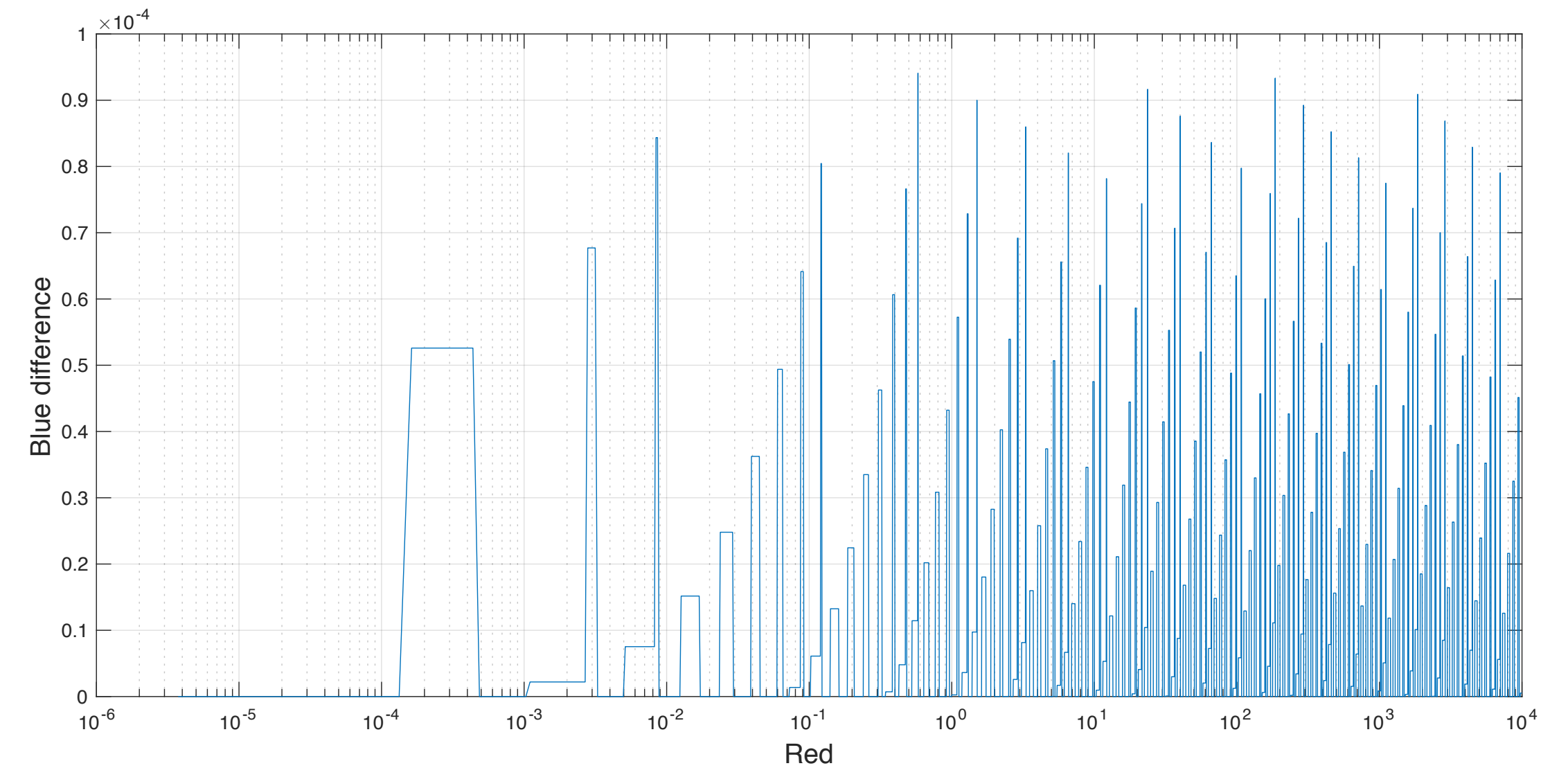
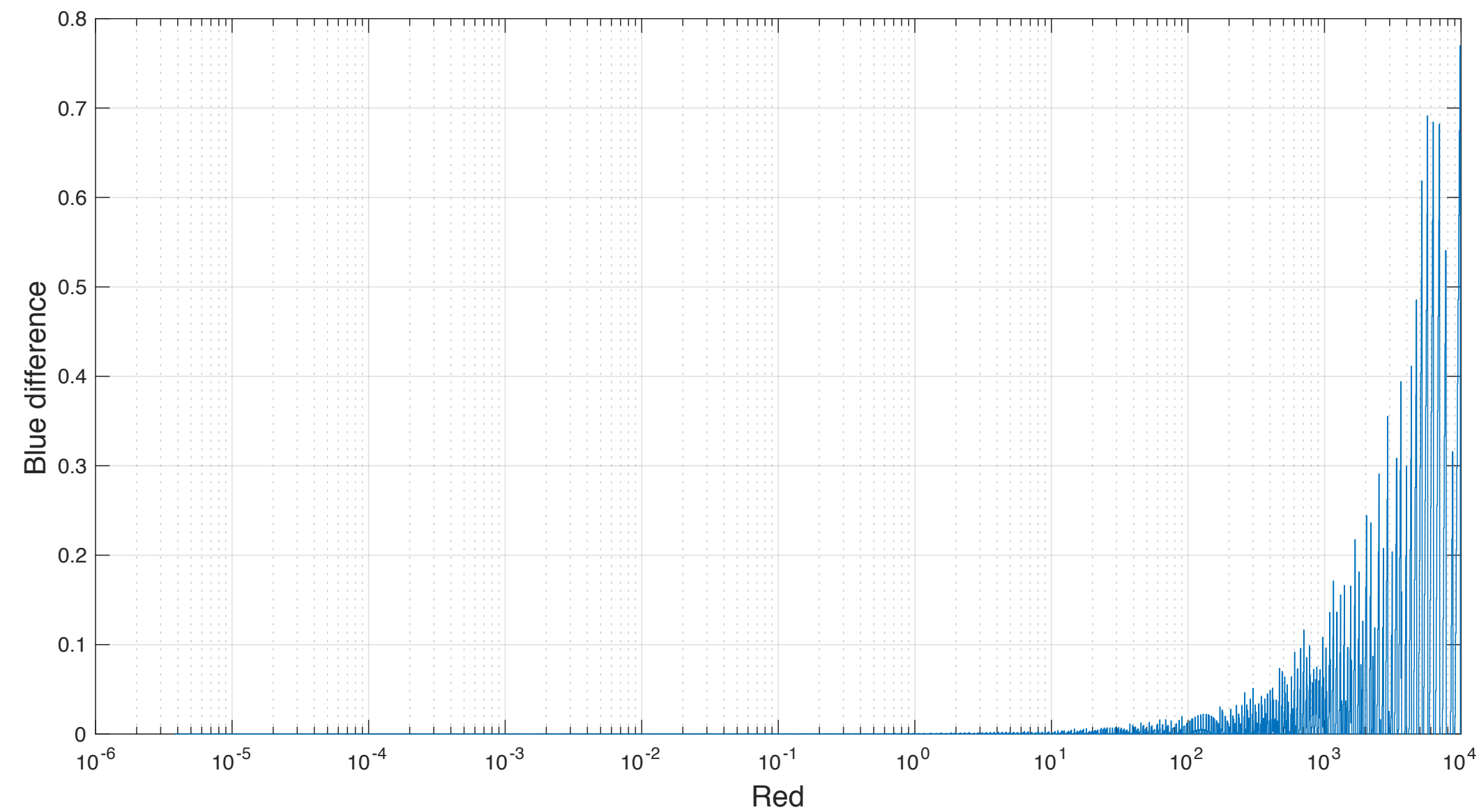
- ICtCp (left) vs YCbCr (right) differences for red only ramps
- YCbCr for some values may introduce much bigger distortion on the red component

A more careful look: Quantized (10bit) Color Ramps



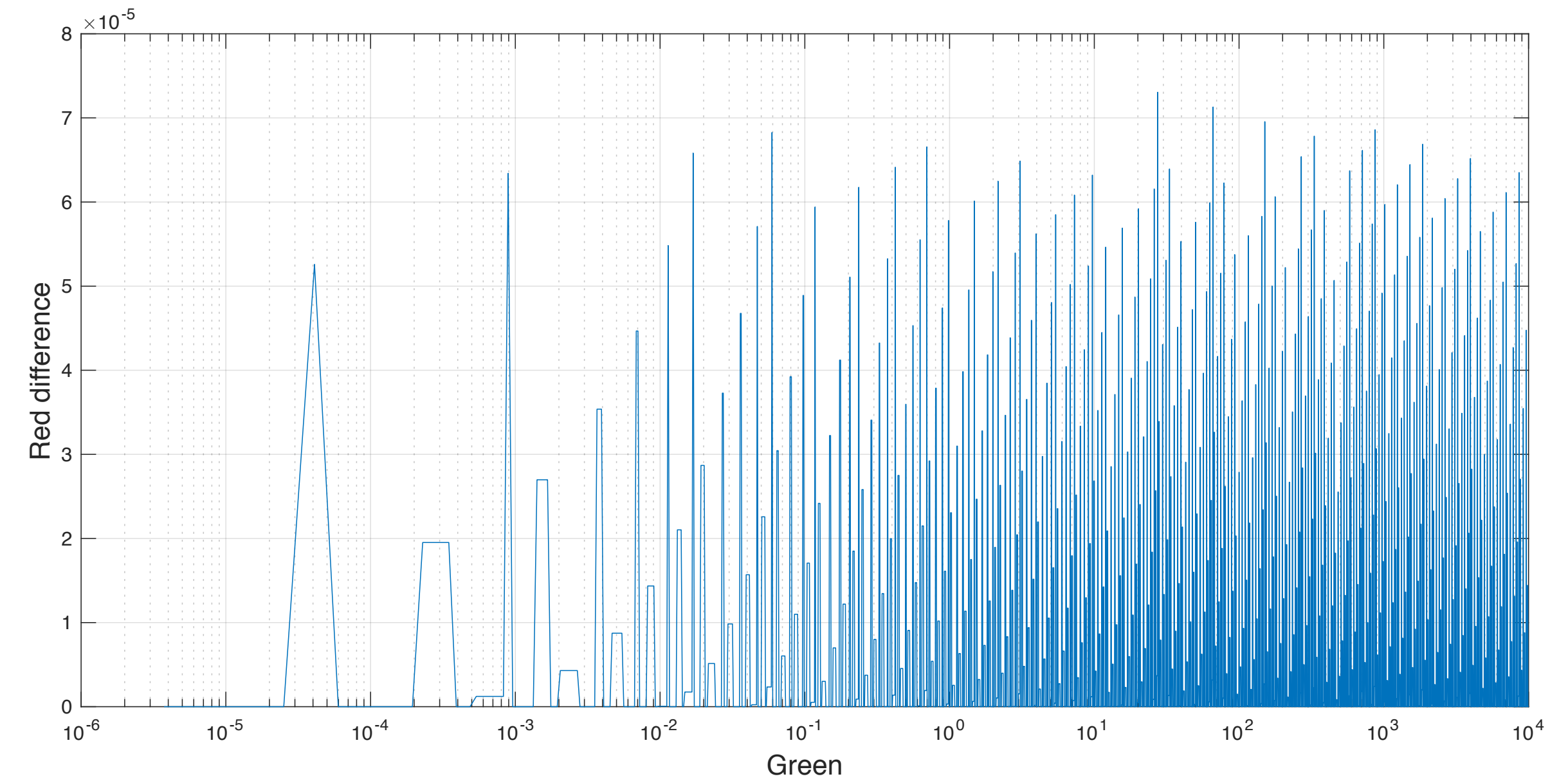
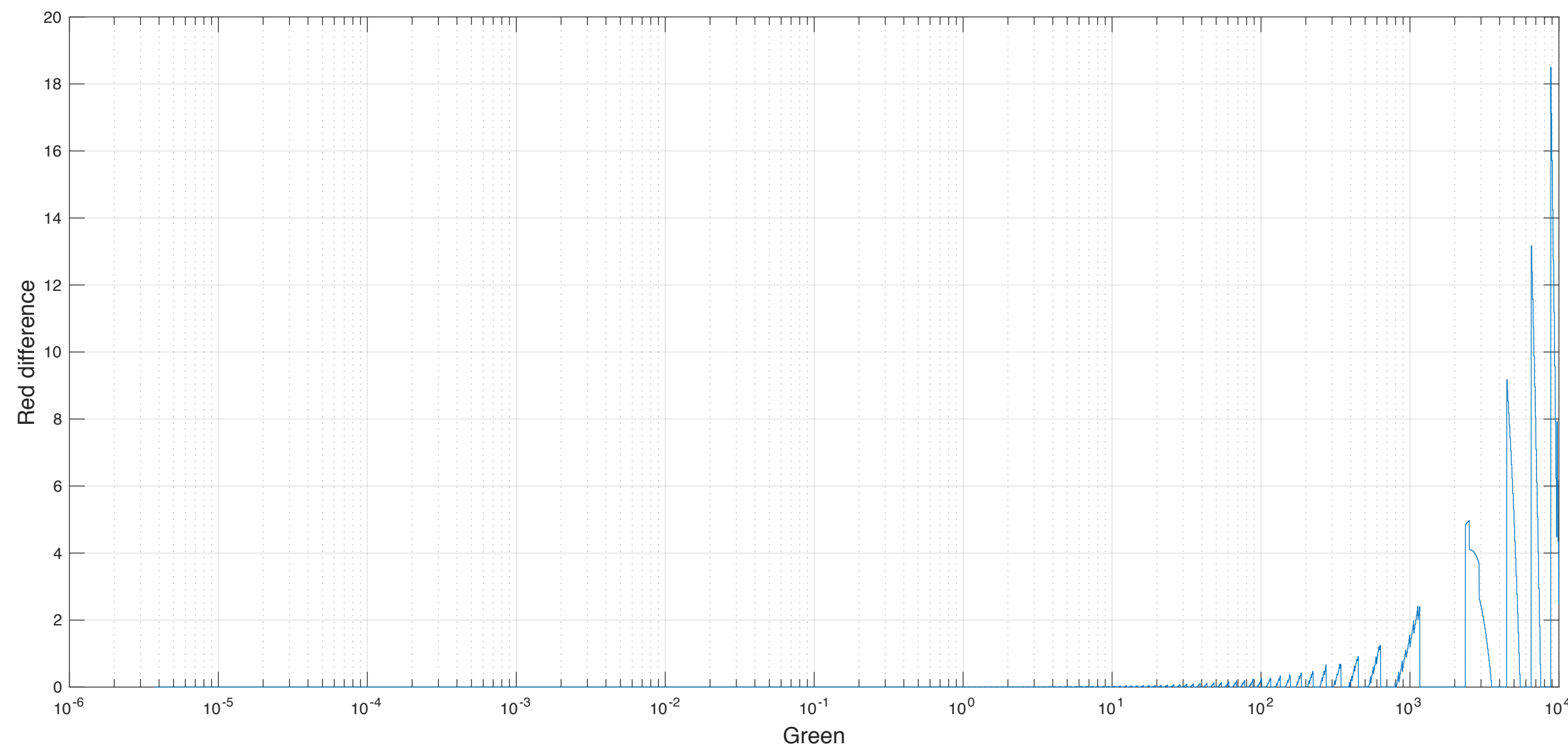
- ICtCp (left) vs YCbCr (right) differences for red only ramps
- However, distortion in the other two components tends to be much smaller in the other two components

A more careful look: Quantized (10bit) Color Ramps



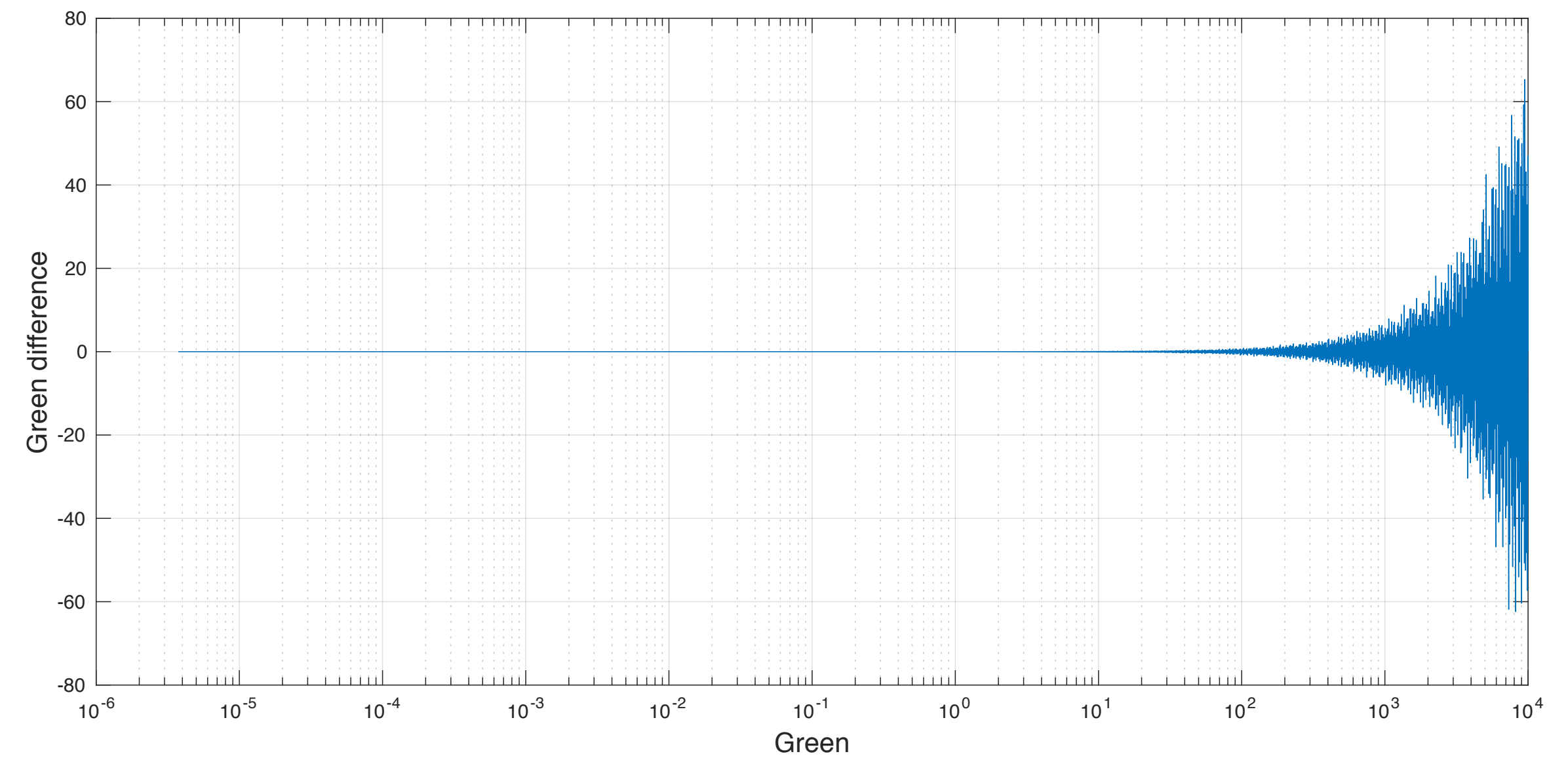
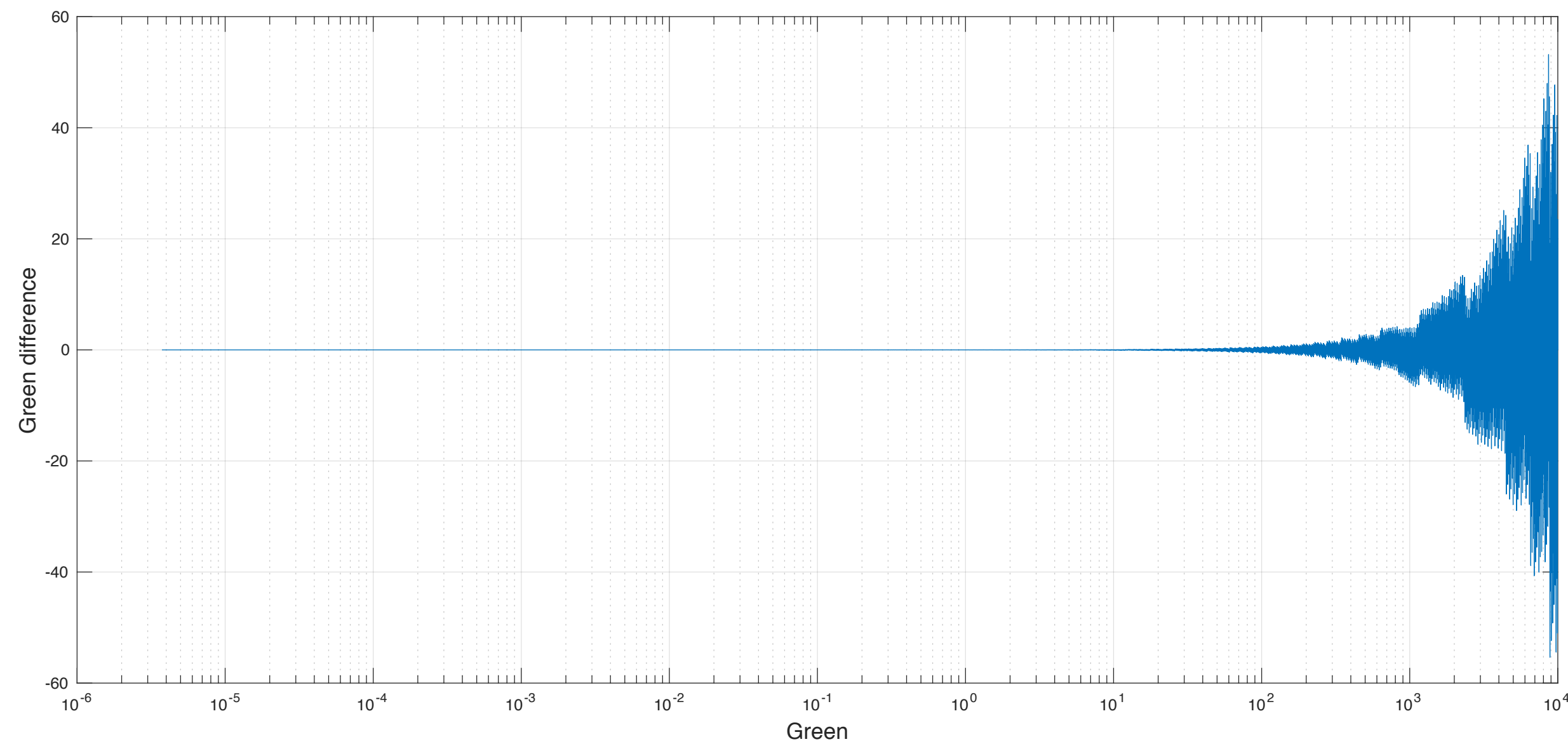
- ICtCp (left) vs YCbCr (right) differences for red only ramps
- YCbCr for some values may introduce much bigger distortion on the red component

A more careful look: Quantized (10bit) Color Ramps



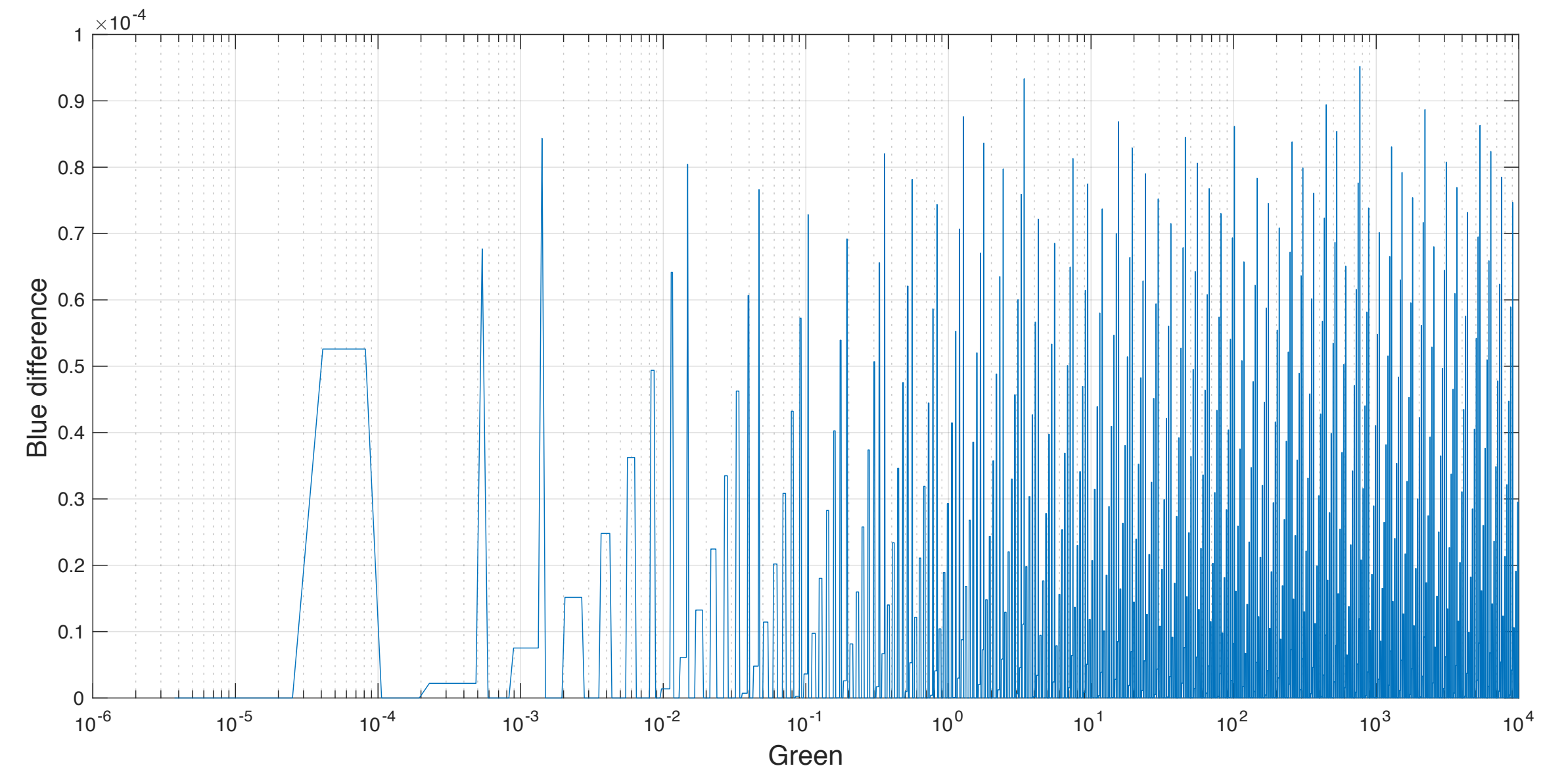
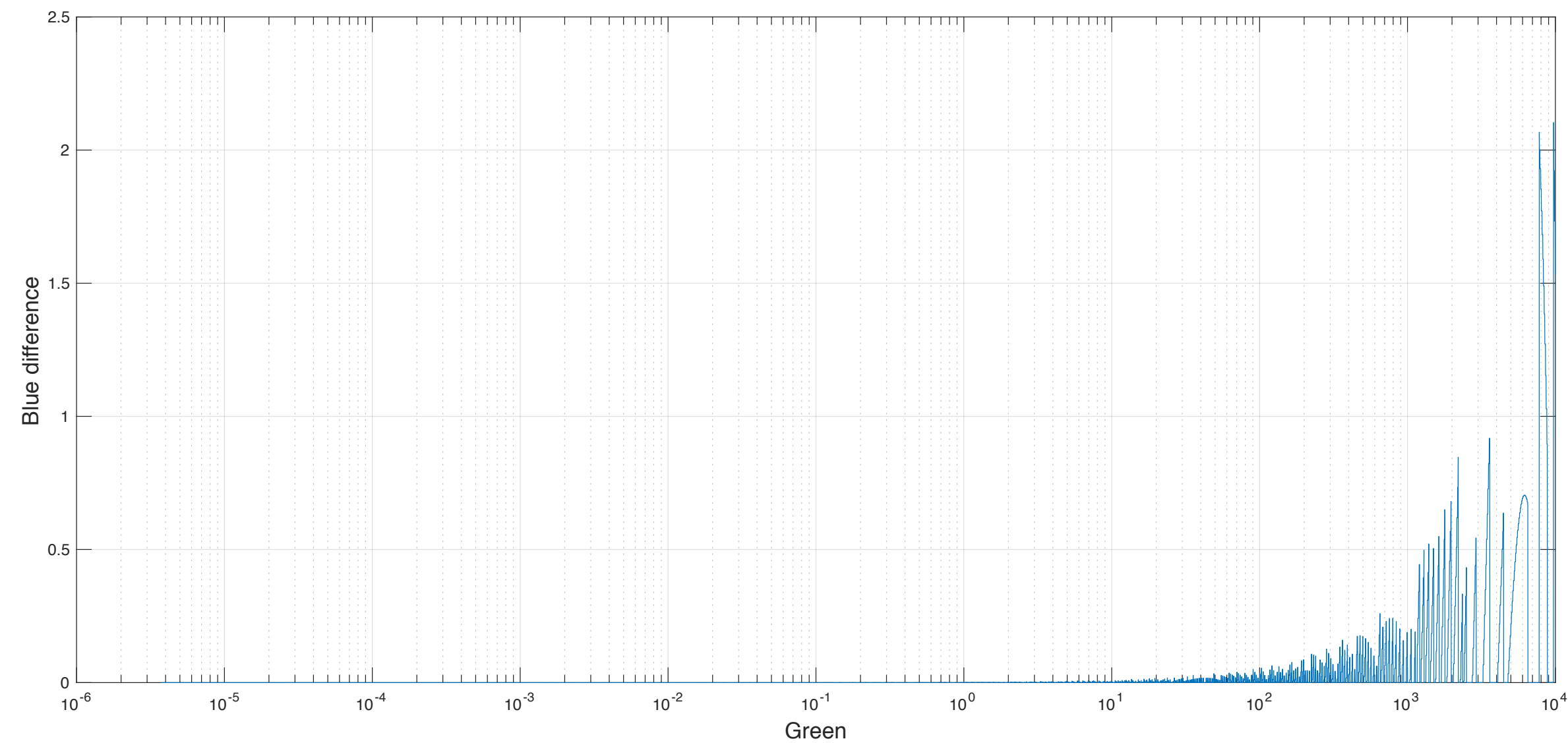
- ICtCp (left) vs YCbCr (right) differences for green only ramps
- Distortion is again smaller in green and blue components for YCbCr

A more careful look: Quantized (10bit) Color Ramps



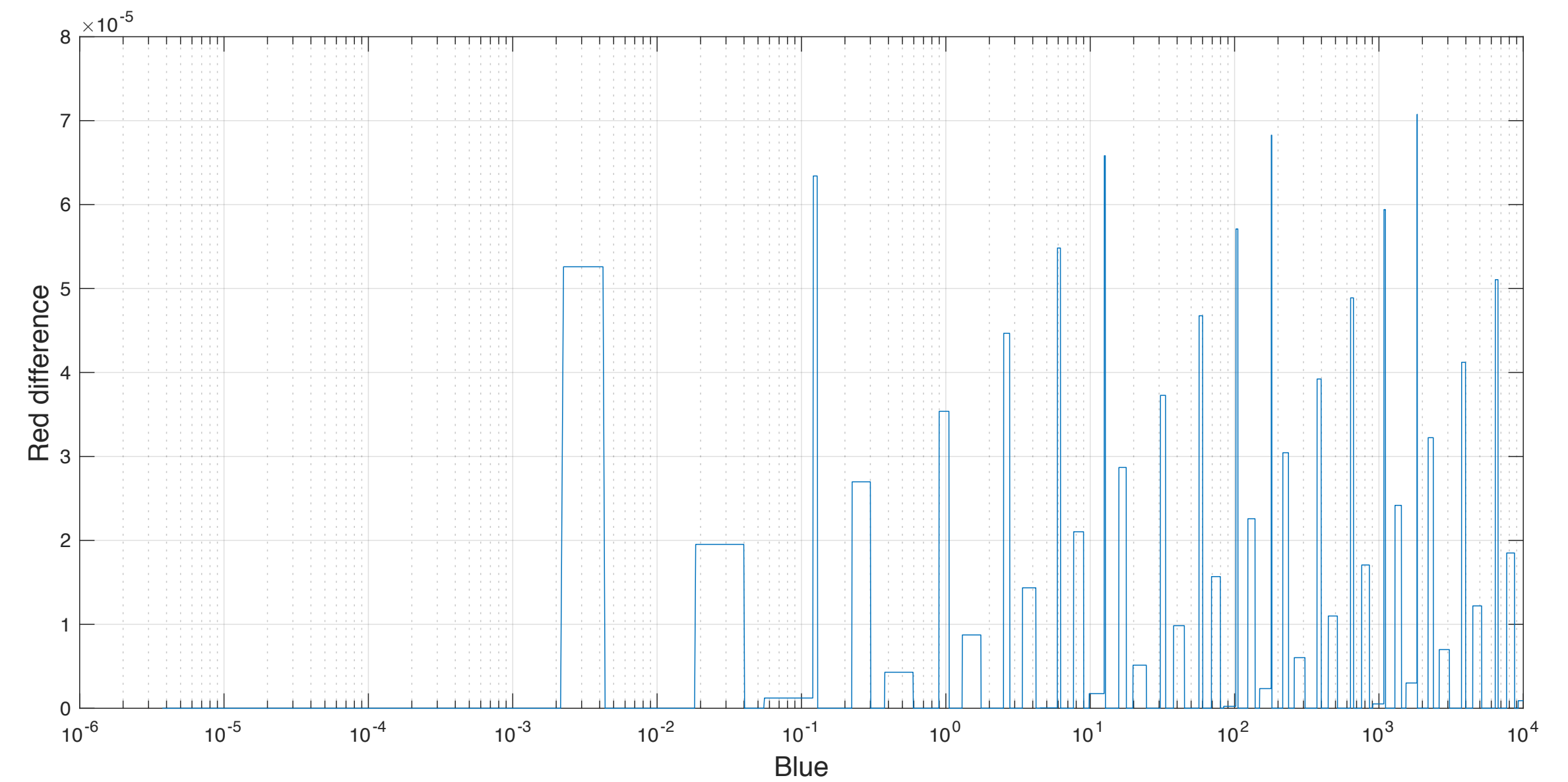
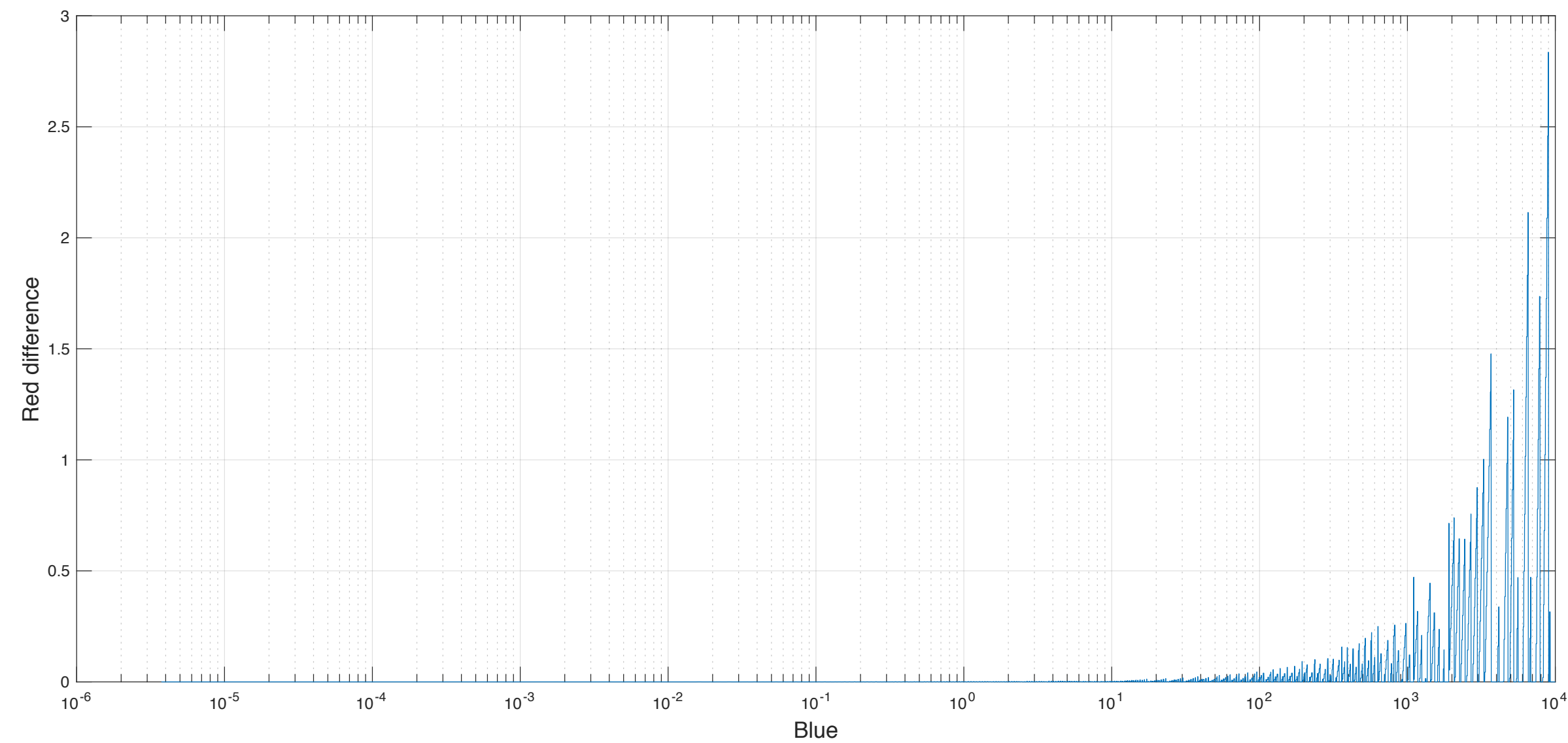
- ICtCp (left) vs YCbCr (right) differences for green only ramps

A more careful look: Quantized (10bit) Color Ramps



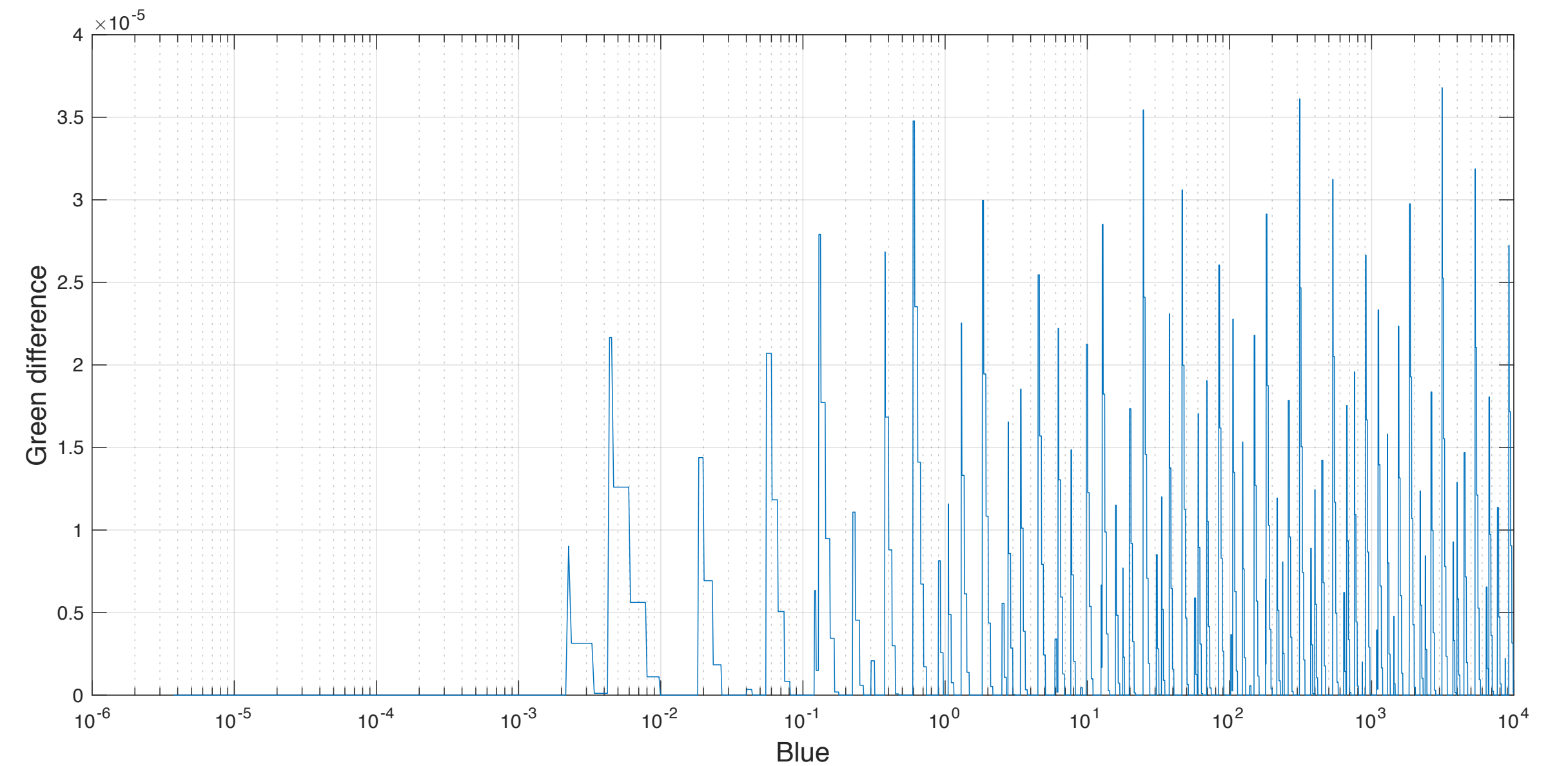
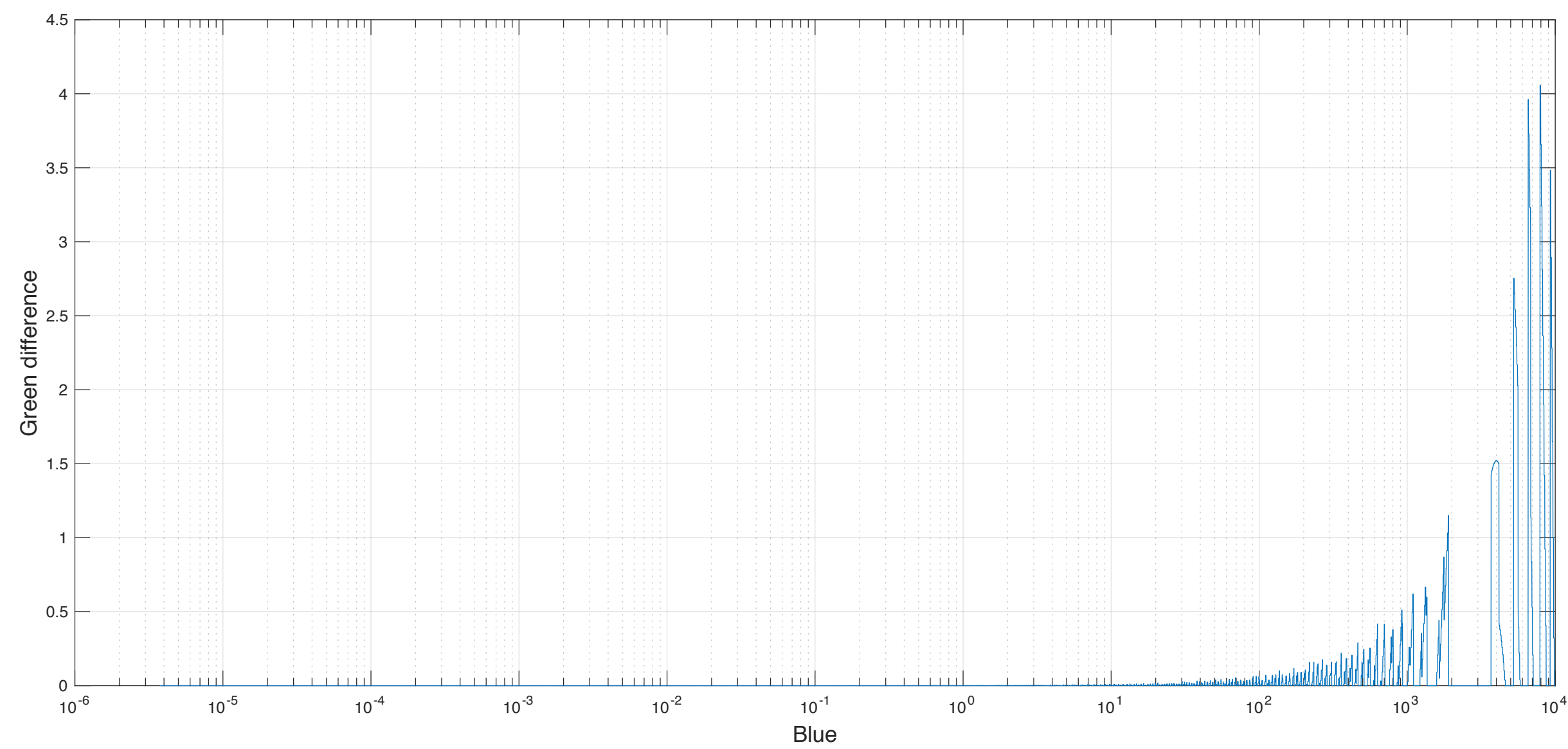
- ICtCp (left) vs YCbCr (right) differences for green only ramps

A more careful look: Quantized (10bit) Color Ramps



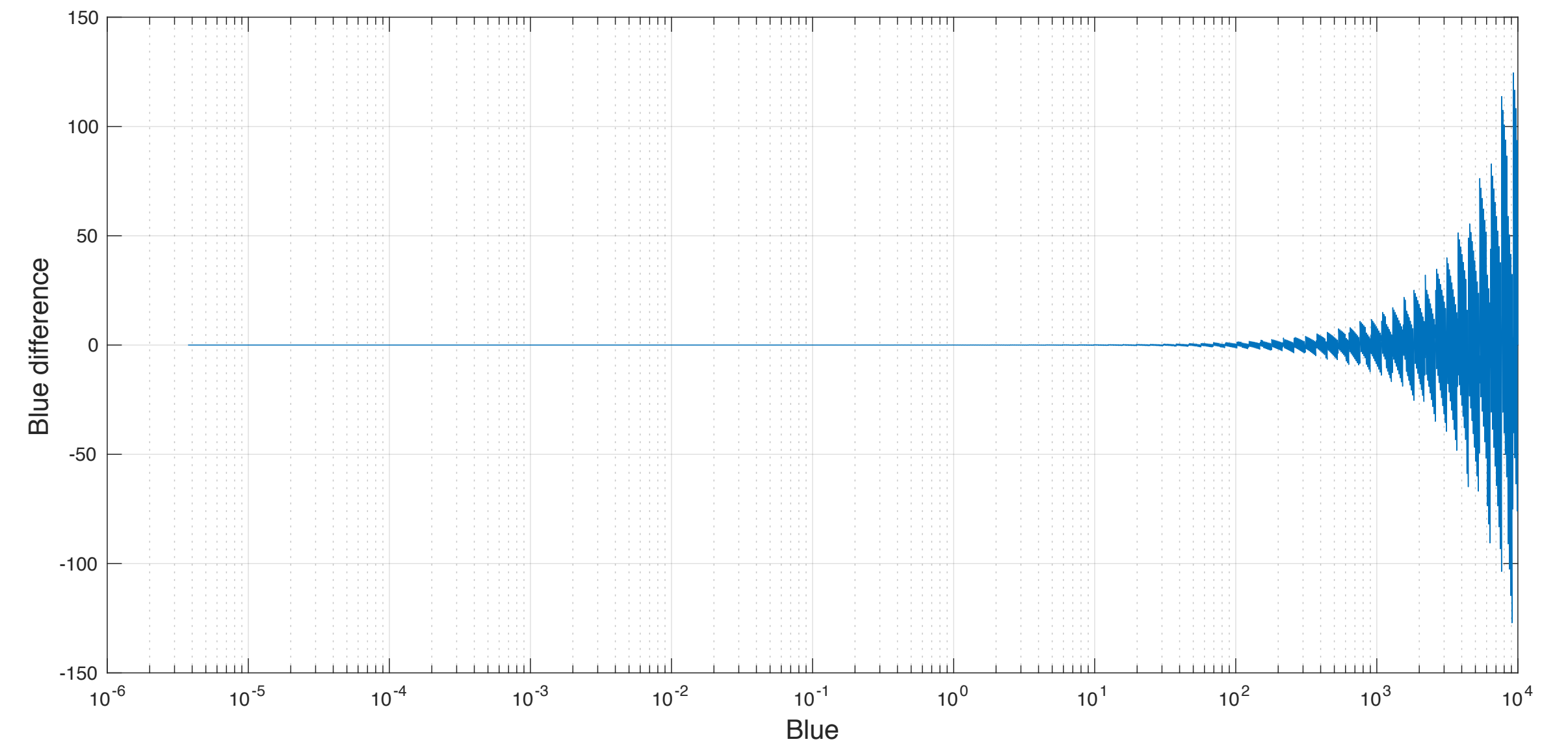
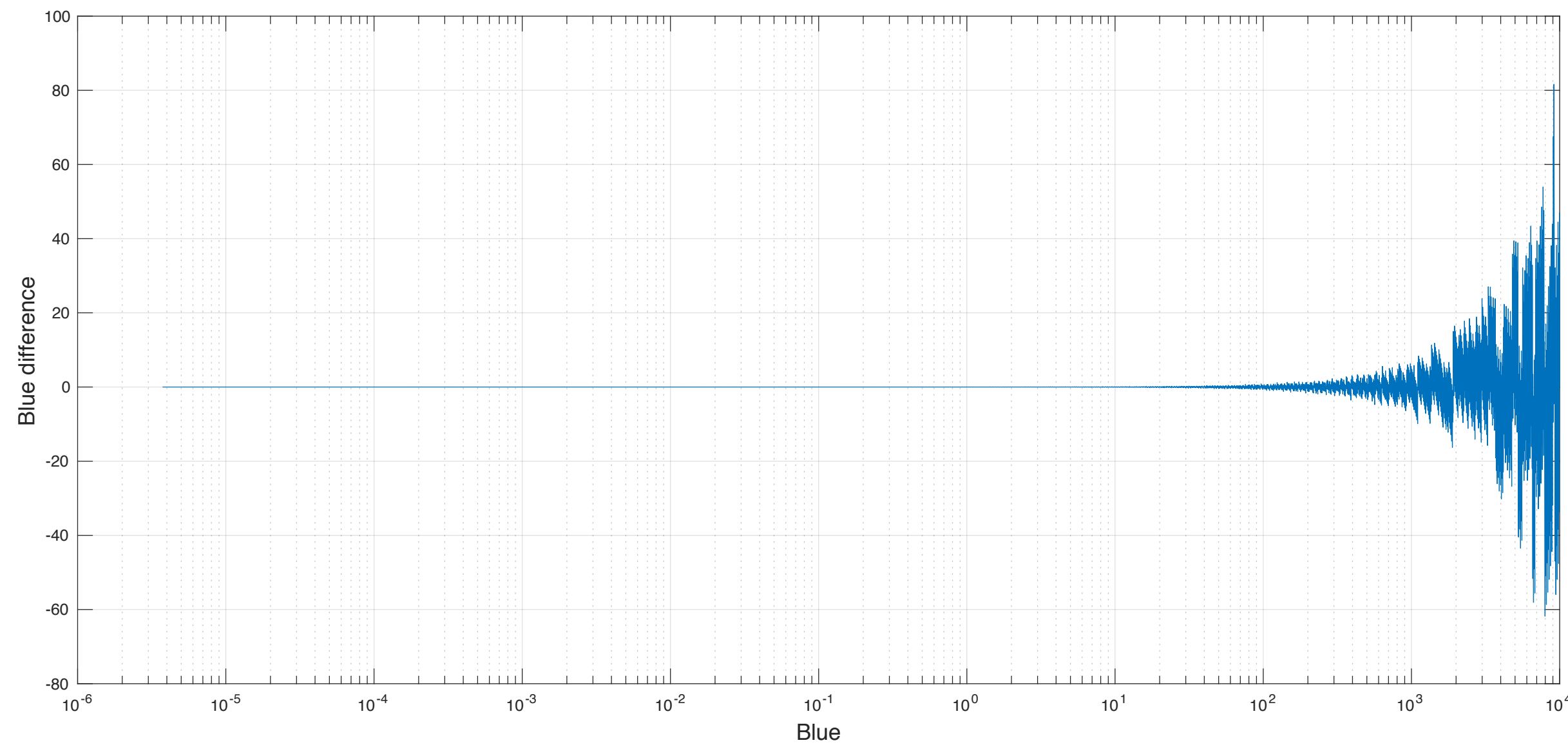
- ICtCp (left) vs YCbCr (right) differences for blue only ramps

A more careful look: Quantized (10bit) Color Ramps



- ICtCp (left) vs YCbCr (right) differences for blue only ramps

A more careful look: Quantized (10bit) Color Ramps

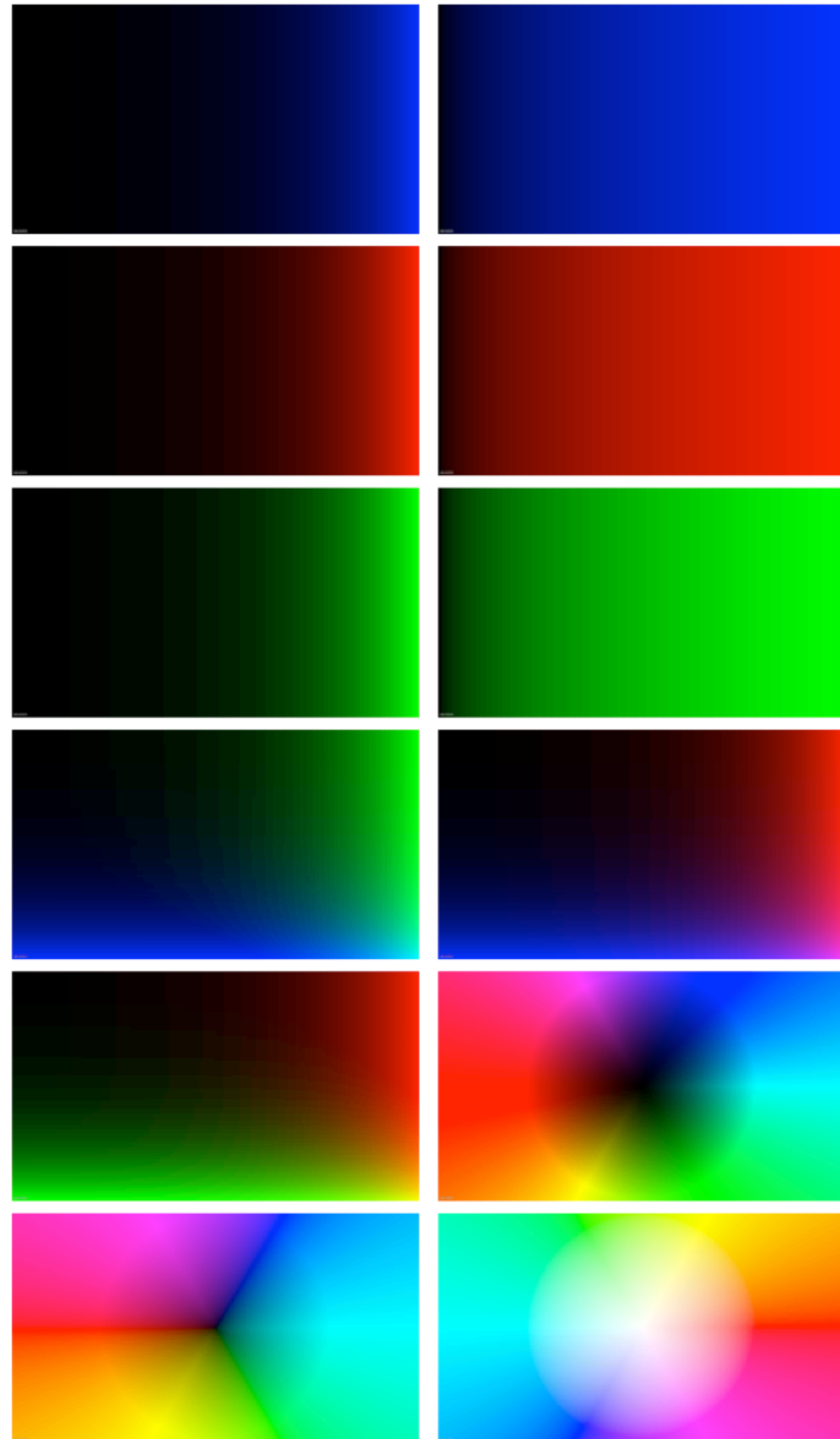


- ICtCp (left) vs YCbCr (right) differences for blue only ramps

Observation

- Single Colour ramps (4:4:4 10 bit conversions):
 - ICtCp seems to bound the max distortion on the original colour primary a bit more
 - At the same time, introduces “non-insignificant” distortion in the other primaries
 - The impact seems to relate to bit depth used.
Distortion expected to reduce substantially at a higher precision
- Is this colour distortion an issue?
- Can this also lead to other issues during, for example, downsampling and blending?

Test patterns



- mix frame :
a special column wise mix of
alternating (dark to bright and
bright to dark) ramps

Analysis on test patterns

- YCbCr vs ICtCp vs YcIcBcCr (4:4:4) 10 bit

		PSNR			tPSNR								t-oPSNR	DE2000	
		R	G	B	R	G	B	RGB	X	Y	Z	XYZ	XYZ	DE0100	L0100
YCbCr	blue_mix	263.17	263.17	58.86	263.17	263.17	50.43	55.20	53.57	55.68	50.47	52.27	53.05	21.50	34.77
	blue	263.17	263.17	58.86	263.17	263.17	50.43	55.20	53.57	55.68	50.47	52.27	53.05	21.50	34.77
	bluexgreen	263.17	58.82	54.46	263.17	50.11	47.28	50.02	55.48	55.04	51.27	53.38	55.62	16.99	23.83
	colorimage	56.09	58.53	50.38	56.23	55.90	53.07	54.64	66.65	69.03	54.84	58.53	60.85	14.75	22.95
	cyan	263.17	54.87	48.10	263.17	69.24	62.56	66.49	66.46	69.30	63.14	65.58	61.95	13.68	20.49
	green_mix	263.17	58.90	263.17	263.17	50.43	263.17	55.20	53.87	51.07	57.28	52.97	53.75	19.40	24.18
	green	263.17	58.90	263.17	263.17	50.43	263.17	55.20	53.87	51.07	57.28	52.97	53.75	19.40	24.18
	magenta	54.15	263.17	48.28	68.65	263.17	62.75	66.52	69.37	69.46	62.97	66.11	62.41	14.39	24.08
	red_mix	58.90	263.17	263.17	50.45	263.17	263.17	55.22	51.20	52.76	263.17	53.61	54.41	20.22	28.30
	red	58.90	263.17	263.17	50.45	263.17	263.17	55.22	51.20	52.76	263.17	53.61	54.41	20.22	28.30
	redxblue	58.52	263.17	54.88	49.55	263.17	47.28	49.89	55.05	56.61	47.28	50.85	51.31	17.64	27.43
	redxgreen	56.24	58.34	263.17	48.07	49.43	263.17	50.41	53.80	54.83	56.40	54.78	56.07	16.30	22.78
	yellow	50.17	53.71	263.17	64.51	68.23	263.17	67.75	66.06	69.37	69.16	67.92	63.86	12.24	19.42
		151.69	152.39	150.22	151.30	151.75	150.22	56.69	57.70	58.67	88.22	56.53	56.50	17.56	25.81

Analysis on test patterns

- YCbCr vs ICtCp vs YcIcBcCr (4:4:4) 10 bit

		R	G	B	R	G	B	RGB	X	Y	Z	XYZ	XYZ	DE0100	L0100
ICtCp	blue_mix	88.17	82.32	57.47	26.51	23.99	49.73	26.32	52.86	55.09	49.73	51.59	52.37	20.75	34.37
	blue	88.17	82.32	57.47	26.51	23.99	49.73	26.32	52.86	55.09	49.73	51.59	52.37	20.75	34.37
	bluexgreen	69.67	58.66	57.27	18.46	41.30	41.77	22.78	56.13	55.05	53.35	54.57	56.73	17.86	23.82
	colorimage	52.91	54.81	53.13	19.26	25.19	28.26	22.61	65.39	66.06	53.93	57.54	59.47	14.62	19.85
	cyan	64.41	54.65	53.51	15.06	69.16	67.11	19.83	68.34	69.35	67.45	68.31	64.49	15.49	20.48
	green_mix	69.95	58.66	88.36	18.62	50.40	26.39	22.52	52.46	51.12	55.60	51.88	52.48	19.10	24.20
	green	69.95	58.66	88.36	18.62	50.40	26.39	22.52	52.46	51.12	55.60	51.88	52.48	19.10	24.20
	magenta	54.65	75.31	53.55	69.12	18.46	67.76	23.23	69.22	69.51	67.99	68.86	65.16	15.96	24.13
	red_mix	58.83	84.26	102.62	50.34	23.38	37.04	27.32	51.10	52.74	32.81	34.27	35.86	20.14	28.35
	red	58.83	84.26	102.62	50.34	23.38	37.04	27.32	51.10	52.74	32.81	34.27	35.86	20.14	28.35
	redxblue	58.78	80.63	57.36	43.15	21.98	46.62	25.92	54.95	56.62	45.06	49.13	52.43	18.29	27.44
	redxgreen	57.95	58.64	86.79	36.55	40.30	25.53	27.71	54.52	54.85	49.25	50.92	54.52	17.55	22.78
	yellow	53.25	54.61	81.39	68.06	69.08	21.68	26.45	68.61	69.35	65.19	67.32	63.80	14.87	19.43
		65.04	68.29	72.30	35.43	37.00	40.39	24.68	57.69	58.36	52.19	53.24	53.69	18.05	25.52

Analysis on test patterns

- YCbCr vs ICtCp vs YcIcCbCr (4:4:4) 10 bit

		PSNR			tPSNR								t-oPSNR	DE2000	
YcIcCbCr	blue_mix	263.17	76.38	50.76	263.17	21.86	46.70	26.15	49.92	52.76	46.72	48.79	49.35	17.43	32.05
	blue	263.17	76.38	50.76	263.17	21.86	46.70	26.15	49.92	52.76	46.72	48.79	49.35	17.43	32.05
	bluexgreen	79.76	58.75	52.34	20.91	40.14	47.26	24.69	55.25	55.07	51.23	53.30	55.38	16.28	23.80
	colorimage	51.33	54.24	49.73	19.45	19.01	53.38	20.95	64.78	66.44	50.80	54.88	57.66	12.93	20.42
	cyan	74.64	54.83	46.41	16.56	69.20	61.65	21.33	66.16	69.39	62.19	64.94	61.10	12.59	20.50
	green_mix	80.30	58.77	263.17	21.21	50.51	263.17	25.52	53.90	51.16	57.36	53.03	53.77	19.33	24.13
	green	80.30	58.77	263.17	21.21	50.51	263.17	25.52	53.90	51.16	57.36	53.03	53.77	19.33	24.13
	magenta	49.61	63.19	49.03	64.85	16.28	63.01	21.05	65.46	66.67	63.41	64.97	61.38	13.52	22.80
	red_mix	54.29	66.39	263.17	47.85	16.30	263.17	20.96	48.80	51.91	26.42	30.15	29.17	16.76	27.69
	red	54.29	66.39	263.17	47.85	16.30	263.17	20.96	48.80	51.91	26.42	30.15	29.17	16.76	27.69
	redxblue	54.14	66.56	52.28	48.03	16.96	47.26	21.48	53.11	55.49	42.73	46.89	50.62	15.46	26.51
	redxgreen	54.10	57.82	263.17	40.35	33.94	263.17	37.74	53.53	54.85	43.44	46.88	51.78	15.26	22.77
	yellow	54.56	54.70	263.17	68.96	69.22	263.17	70.85	69.15	69.34	70.15	69.53	65.93	16.54	19.43
		93.36	62.55	148.49	72.58	34.01	149.61	27.95	56.36	57.61	49.61	51.18	51.42	16.12	24.92

Analysis on test patterns

- YCbCr vs ICtCp vs YcIcCbCr (4:2:0) 10 bit

		PSNR			tPSNR								t-oPSNR	DE2000	
		R	G	B	R	G	B	RGB	X	Y	Z	XYZ	XYZ	DE0100	L0100
YCbCr	blue_mix	53.03	51.46	23.43	19.28	19.14	19.66	19.34	21.32	22.66	19.62	20.98	23.20	4.44	22.09
	blue	263.17	263.17	58.79	263.17	263.17	48.49	53.26	52.43	54.92	48.42	50.87	52.98	21.49	34.75
	bluexgreen	263.17	58.81	54.51	263.17	43.50	41.29	43.89	55.38	55.04	50.38	52.81	55.64	17.09	23.83
	colorimage	55.81	58.38	49.37	46.06	44.52	44.98	45.10	65.37	68.90	48.22	52.73	60.27	14.83	22.96
	cyan	263.17	54.87	48.04	263.17	69.32	62.39	66.36	66.39	69.38	62.96	65.47	61.98	13.71	20.50
	green_mix	44.43	48.49	44.43	18.66	44.11	18.70	20.39	44.05	44.91	36.71	39.41	45.73	13.21	24.04
	green	263.17	58.97	263.17	263.17	50.40	263.17	55.17	53.84	51.04	57.26	52.94	53.72	19.44	24.23
	magenta	54.12	263.17	48.38	68.12	263.17	61.80	65.66	69.05	69.23	61.97	65.33	62.27	14.42	24.08
	red_mix	36.30	45.73	51.35	25.60	18.69	19.12	20.10	26.11	27.24	18.93	22.21	24.51	10.34	23.23
	red	58.98	263.17	263.17	50.22	263.17	263.17	54.99	50.99	52.61	263.17	53.43	54.33	20.23	28.32
	redxblue	58.53	263.17	55.01	43.50	263.17	41.31	43.90	55.04	56.60	41.18	45.55	50.81	17.69	27.43
	redxgreen	56.46	58.39	263.17	43.28	41.42	263.17	43.91	53.75	54.82	51.40	51.93	55.87	16.54	22.78
	yellow	50.20	53.73	263.17	64.52	68.24	263.17	67.75	66.08	69.38	69.16	67.93	63.89	12.25	19.44
		116.96	118.58	114.31	110.15	111.69	108.49	46.14	52.29	53.59	63.80	49.35	51.17	15.05	24.44

Analysis on test patterns

- YCbCr vs ICtCp vs YcIcCbCr (4:4:4) 10 bit

		PSNR			tPSNR								t-oPSNR	DE2000	
		R	G	B	R	G	B	RGB	X	Y	Z	XYZ	XYZ	DE0100	L0100
ICtCp	blue_mix	46.54	41.00	21.88	12.25	12.39	31.59	13.83	35.73	39.32	31.86	34.59	34.86	4.41	21.02
	blue	88.32	82.25	57.45	26.59	24.03	45.07	26.36	49.57	52.53	44.94	47.80	52.10	20.77	34.37
	bluexgreen	69.81	58.67	57.34	18.73	40.02	38.24	23.01	56.13	55.04	52.77	54.33	56.75	17.92	23.82
	colorimage	52.78	54.78	53.00	19.48	25.41	28.60	22.84	65.02	65.99	47.24	51.75	59.05	14.69	19.84
	cyan	64.40	54.64	53.50	15.06	68.28	66.41	19.83	65.29	69.18	66.68	66.77	64.26	15.49	20.48
	green_mix	31.72	35.79	32.80	10.39	46.00	11.36	12.60	37.78	49.46	28.68	32.83	34.31	7.16	18.54
	green	69.95	58.68	88.34	18.64	49.86	26.44	22.54	49.72	51.06	50.02	47.76	52.20	19.11	24.21
	magenta	54.66	75.30	53.56	65.66	18.47	62.79	23.24	65.98	69.23	62.88	65.29	64.91	15.97	24.14
	red_mix	27.18	36.28	40.79	39.14	11.32	11.86	13.32	40.50	46.12	11.67	16.41	15.02	5.79	24.26
	red	58.82	84.22	101.79	47.68	23.38	36.37	27.30	48.68	50.78	32.55	34.23	35.82	20.14	28.35
	redxblue	58.79	80.87	57.42	40.61	22.32	38.39	26.19	54.93	56.62	38.29	42.70	51.36	18.32	27.44
	redxgreen	57.99	58.66	87.04	36.39	38.29	25.90	27.97	54.50	54.85	48.40	50.19	54.53	17.64	22.78
	yellow	53.24	54.61	81.40	67.97	69.05	21.71	26.48	68.53	69.36	54.35	58.83	63.27	14.87	19.43
		56.48	59.67	60.49	32.20	34.52	34.21	21.96	53.26	56.12	43.87	46.42	49.11	14.79	23.74

Analysis on test patterns

■ YCbCr vs ICtCp vs YcICbCr (4:4:4) 10 bit

		PSNR			tPSNR								t-oPSNR	DE2000	
		R	G	B	R	G	B	RGB	X	Y	Z	XYZ	XYZ	DE0100	L0100
YcICbCr	blue_mix	61.59	42.16	20.71	20.53	11.60	30.29	15.62	32.67	39.31	30.51	32.85	32.47	3.40	31.43
	blue	263.17	76.36	50.76	263.17	21.91	44.39	26.18	48.43	51.41	44.30	46.92	49.15	17.45	32.07
	bluexgreen	79.76	58.76	52.51	20.91	38.64	40.47	24.69	55.26	55.05	50.19	52.66	55.47	16.46	23.80
	colorimage	51.27	54.21	49.76	19.45	19.05	45.06	20.97	64.00	66.31	46.64	51.16	57.31	13.08	20.42
	cyan	74.64	54.83	46.41	16.56	69.21	61.49	21.33	66.06	69.38	62.00	64.80	61.04	12.59	20.50
	green_mix	46.74	49.83	46.42	15.01	50.27	18.78	17.92	48.09	51.15	37.87	41.62	47.44	13.64	24.13
	green	80.30	58.77	263.17	21.21	50.50	263.17	25.52	53.89	51.15	57.36	53.03	53.77	19.33	24.13
	magenta	49.61	63.19	49.03	62.03	16.28	60.93	21.05	62.84	66.18	61.18	62.94	61.10	13.52	22.79
	red_mix	26.85	35.24	52.17	39.31	11.02	19.38	15.09	40.31	46.13	16.81	21.53	20.72	4.99	26.29
	red	54.26	66.42	263.17	46.35	16.32	263.17	20.97	47.37	50.12	26.44	30.15	29.18	16.76	27.69
	redxblue	54.17	66.62	52.42	42.59	17.08	40.47	21.60	53.11	55.50	40.12	44.43	50.20	15.56	26.54
	redxgreen	54.24	57.87	263.17	40.10	34.03	263.17	37.79	53.55	54.85	43.59	47.01	51.96	15.47	22.77
	yellow	54.56	54.70	263.17	68.92	69.23	263.17	70.83	69.12	69.33	70.16	69.51	65.92	16.54	19.43
		73.17	56.84	113.30	52.01	32.70	108.76	26.12	53.44	55.84	45.17	47.59	48.90	13.75	24.77

Observations

- Surprisingly, YCbCr 4:4:4-10 seems to perform the best
- For some patterns ICtCp objective performance seems to be the worst
- Constant luminance (based on original BT.2020 with unequal scaling) seems to behave a bit better than ICtCp but still has issues
- 4:2:0 drops performance of YCbCr considerably (Luma adjustment used)
 - Mostly for the “color mix” patterns
- ICtCp and YcIcBcCr also drop further

Subjective evaluation

- Evaluation on a Sim2 difficult for these patterns:
 - Patterns exercise full BT.2020 gamut
 - Display has a variety of issues (uniformity, precision/accuracy, color etc)
 - Most issues seem to happen outside BT.709 gamut
 - Visible but not objectionable
- Evaluation on a Sony BVM X300 (P3 capable display, however limited to $\sim 1000\text{cd/m}^2$)
 - Artifacts quite visible and objectionable
 - However, also limitations with this display and its interface
 - **Interface was 4:2:2 YCbCr 10 !!!**
 - **Artifacts could be a cascade of the two processes**
 - We need a better subjective evaluation process (not adequate)

Subsampling effect on the mix frame (original)



Subsampling effect on the mix frame (YCbCr)



Subsampling effect on the mix frame (ICtCp)

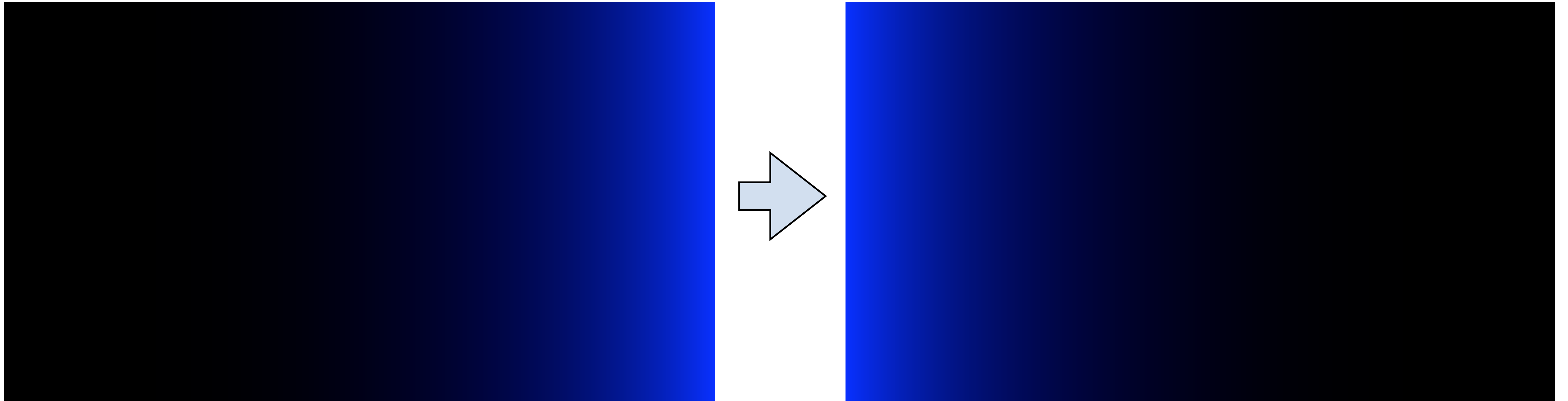


Subsampling effect on the mix frame (original)



Blending

- Perform a blend from a forward to an inverse blue ramp:



Blending in ICtCp (0)



Blending in ICtCp (1)



Blending in ICtCp (2)



Blending in ICtCp (3)



Blending in ICtCp (4)



Comments on blending

- Blending in lCtCp domain for this pattern appeared objectionable on the Sony monitor
- Colorfulness/saturation seems to be impacted
- In this case, we cannot blame the 4:2:2 interface

Conclusion (if any)

- In this contribution we are providing some information relating to the ICtCp space
 - Space might not always behave as desired and there may be hidden issues with it
 - Quantization issues may exist for some colour values
 - Subsampling issues may also occur for some signals
 - Possibility of further issues near the concave segment in the CtCp diagram
 - Blending in ICtCp space in some cases did not result in acceptable results (however this may be purely subjective)
 - Other (unknown) issues may also exist
- We would encourage the community to perform further (and more careful) study of this new colour space
 - Use not only available (and limited in characteristics) content, but by creating appropriate test patterns
 - Better analyze the properties of this space through analytical/mathematical means and look carefully at different colour/brightness ranges, not just averages.