CHAPTER 5

RESULTS AND DISCUSSION

According to the experimental setup, it should be noted that the apparatus stability is around $\Delta E_{rms} \approx 1 \sim 2$ for both types of printer model. Especially the inkjet printer produces the printout that fades rapidly. Therefore the measuring is done immediately after each printing.

In the experiment, when the input data is loaded into the model, the obtained printout is measured by a spectrophotometer into *CIEXYZ* color space. This is converted again to be the color into *sRGB* color space. The results of *LUT data* here appear the minus sign of *sRGB* color values, It means that some parts of the *Printer gamut boundary* of the *Real Model* exceed the *sRGB gamut boundary.*

These out of range colors, however, are not denied in the coefficient calculation process, because it is better to use all possible *LUT data* to be *Coefficient Partition* for approximating the *Real Model.* However, the *Target Partition* can be only the intersection boundary of *sRGB* and *Printer gamut boundary.*

Figure 5-1 shows the *Printer Gamut boundary* of the Canon Bubble Jet BJC8500 and Canon Color Laser Copier CLC1120 side by side for each plan of the *sRGB* color space. It's clearly that *sRGB* color space doesn't cover all of *Printer gamut boundary*, even it's bigger.

It should be noted that the *Printer gamut boundary* is generated based on *sRGB* value of *LUT data.* Hence, there are two types for each *Real Model*; *7x7x7 base* and *9x9x9 base Printer gamut boundary.*

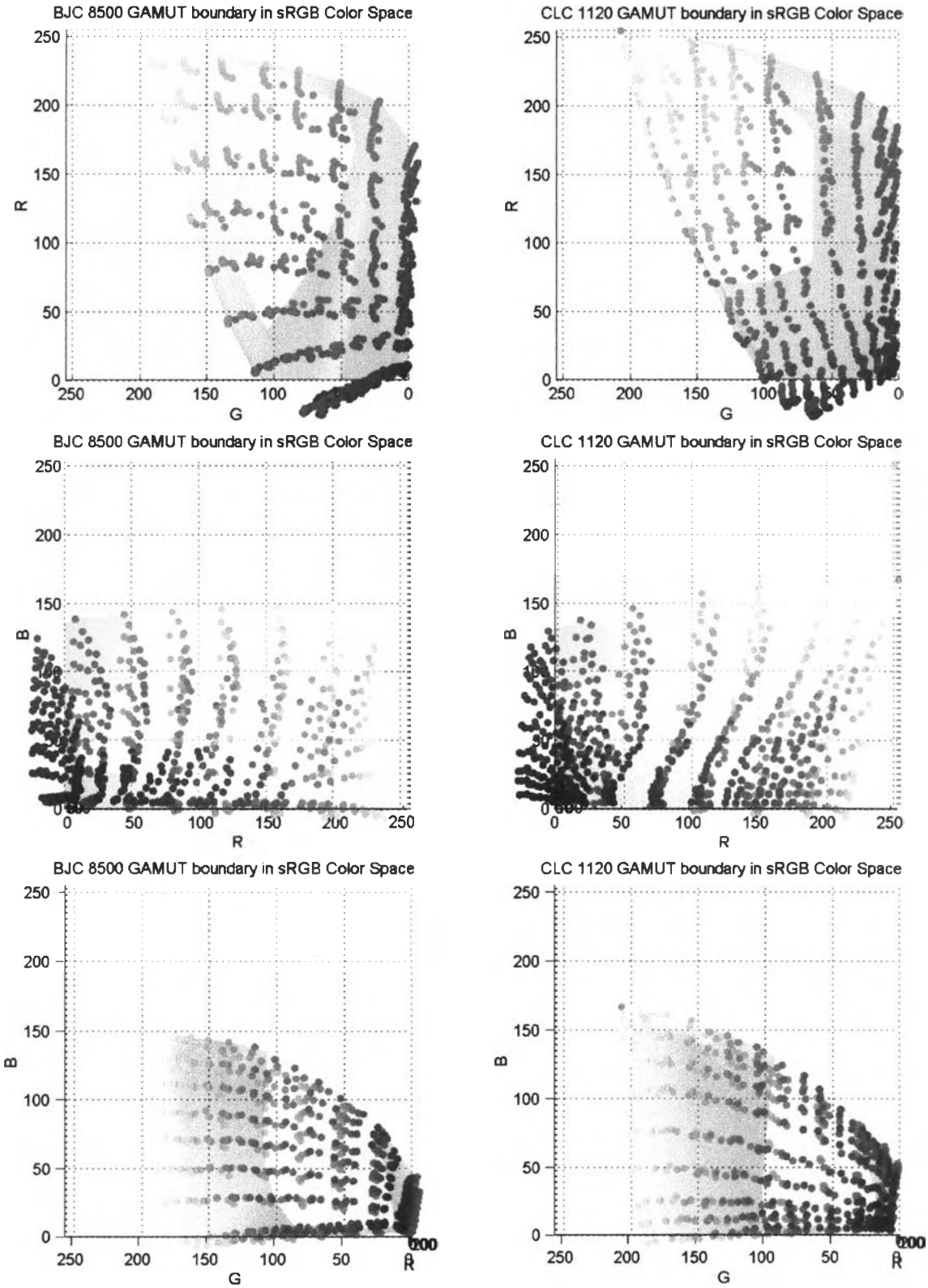


Figure 5-1 The *Printer Gamut boundary* of printer model BJC8500 and CLC1120

The algorithm, to generate the *Printer gamut boundary*, is *Convex Hull* technique. This algorithm does not highly produce in accurate *Printer gamut boundary*, especially for the printer that is highly nonlinear with small *LUT data size.*

Most of T_{uni} data, which uniformly distribute around *sRGB* color space, are out of *Printer gamut boundary*, so they were chosen only the inner by intersection. Thus, the numbers of residual data are different among the intersection between *Printer gamut boundary* that is created from *7x7x7 base* and *9x9x9 base*. For the printer model BJC8500, It has 498 residual data for *7x7x7 base* and 497 residual data for *9x9x9 base Printer gamut boundary*. And also for the printer model CLC1120, It has 497 residual data for *7x7x7 base* and 501 residual data for *9x9x9 base Printer gamut boundary*. Nonetheless, these differences of the number of *Testing data* $[T_{uni}]$ can be ignored when it is used to evaluate the approximated accuracy.

5.1 Effect of Model, LUT data size, Partition method and Degree of Regression Model

Many of parameters were used to evaluate the approximated accuracy. All of the parameters can be concluded as follow:

5.1.1 Model of Printer

- Canon Bubble Jet BJC8500
- Canon Color Laser Copier CLC1120

5.1.2 LUT data size

- 7x7x7 *LUT data*
- 9x9x9 *LUT data*

5.1.3 Partition method

- Whole space
- Tetrahedral method divided by plane $R+G+B=383$ with 50 unit Overlapping

5.1.4 Degree of Regression Model

- 1st Order with 4 Terms of Coefficient
- 2nd Order with 11 Terms of Coefficient
- 3rd Order with 14 Terms of Coefficient and 20 Terms of Coefficient

5.1.5 Testing data

- Canon Bubble Jet BJC8500

  -7x7x7 LUT data

  T_{uni} : 498-color patch

  T_{lut} : 343-color patch

  T_{glo} : 841-color patch

  -9x9x9 LUT data

  T_{uni} : 497-color patch

  T_{lut} : 729-color patch

  T_{glo} : 1226-color patch

- Canon Color Laser Copier CLC1120

  -7x7x7 LUT data

  T_{uni} : 497 color patch

  T_{lut} : 343 color patch

T_{glo} : 840 color patch

-9x9x9 LUT data

T_{uni} : 501 color patch

T_{lut} : 729 color patch

T_{glo} : 1230 color patch

The approximated accuracy of each parameter is shown in Table 5-1 through Table 5-4. Table 5-1 and Table 5-2 are the results of printer model Canon Bubble Jet BJC8500. Table 5-1 shows the approximated accuracy of *7x7x7 LUT data size* with both partition methods, which evaluated by T_{lut} 343, T_{lut} 498 and T_{lut} 841 testing data. Table 5-2 shows the approximated accuracy of *9x9x9 LUT data* size with both partition methods, which evaluated by T_{lut} 729, T_{lut} 497 and T_{lut} 1226 testing data.

Table 5-3 and Table 5-4 are the results of printer Canon Color Laser Copier CLC1120. Table 5-3 shows the approximated accuracy of *7x7x7 LUT data* size with both partition methods, which evaluated by T_{lut} 343, T_{lut} 497 and T_{lut} 840 testing data.

Table 5-4 shows the approximated accuracy of *9x9x9 LUT data size* with both partition methods, which evaluated by T_{lut} 729, T_{lut} 501 and T_{lut} 1230 testing data.

7x7x7 LUT data

		Whole			Tetra12		
		T-lut 343	T-uni 498	T-glo 841	T-lut 343	T-uni 498	T-glo 841
3x04	min	0.28	0.83	0.28	0.12	0.47	0.12
	max	38.87	30.64	38.87	19.58	27.06	27.06
	mean	12.17	8.80	10.49	6.77	5.66	6.22
	std	7.52	5.78	6.54	4.20	4.02	4.09
	rms	14.30	10.53	12.21	7.97	6.94	7.37
3x11	min	0.28	0.44	0.28	0.19	0.23	0.19
	max	20.20	25.71	25.71	17.62	21.10	21.10
	mean	7.21	5.95	6.58	5.17	4.09	4.63
	std	4.67	4.73	4.70	4.07	3.52	3.75
	rms	8.59	7.59	8.01	6.58	5.39	5.90
3x14	min	0.26	0.17	0.17	0.15	0.42	0.15
	max	18.05	16.67	18.05	16.12	14.74	16.12
	mean	6.19	4.99	5.59	4.33	3.63	3.98
	std	4.11	3.48	3.75	3.48	2.37	2.87
	rms	7.43	6.08	6.66	5.55	4.34	4.87
3x20	min	0.33	0.37	0.33	0.15	0.33	0.15
	max	17.75	15.75	17.75	16.04	13.41	16.04
	mean	5.50	4.57	5.03	4.05	3.39	3.72
	std	3.81	3.07	3.39	3.44	2.24	2.79
	rms	6.69	5.50	6.01	5.31	4.06	4.61

Table 5-1 The approximated accuracy of the Canon BJC8500 for 7x7x7 LUT data

9x9x9 LUT data

		Whole			Tetra12		
		T-lut 729	T-uni 497	T-glo 1226	T-lut 729	T-uni 497	T-glo 1226
3x04	min	0.43	0.32	0.32	0.21	0.46	0.21
	max	39.70	31.56	39.70	22.12	24.66	24.66
	mean	12.25	8.68	10.46	6.03	5.42	5.73
	std	8.28	5.66	7.33	3.90	3.55	3.76
	rms	14.78	10.36	13.17	7.18	6.47	6.90
3x11	min	0.67	0.41	0.41	0.10	0.23	0.10
	max	24.27	24.92	24.92	13.73	18.40	18.40
	mean	6.13	5.69	5.91	3.88	3.87	3.87
	std	4.04	4.27	4.13	2.42	3.07	2.70
	rms	7.34	7.11	7.25	4.57	4.93	4.72
3x14	min	0.13	0.26	0.13	0.12	0.16	0.12
	max	15.82	16.41	16.41	12.69	12.11	12.69
	mean	4.94	4.58	4.76	3.01	2.89	2.95
	std	3.18	3.19	3.18	1.89	2.05	1.96
	rms	5.87	5.58	5.76	3.56	3.54	3.55
3x20	min	0.23	0.35	0.23	0.13	0.16	0.13
	max	15.92	15.28	15.92	10.91	12.10	12.10
	mean	4.22	4.21	4.22	2.83	2.72	2.78
	std	2.42	2.69	2.53	1.69	1.90	1.78
	rms	4.87	4.99	4.92	3.30	3.32	3.31

Table 5-2 The approximated accuracy of the Canon BJC8500 for 9x9x9 LUT data

7x7x7 LUT data

		Whole			Tetra12		
		T-lut 343	T-uni 497	T-glo 840	T-lut 343	T-uni 497	T-glo 840
3x04	min	0.16	1.80	0.16	0.71	0.70	0.70
	max	40.67	29.57	40.67	20.74	20.65	20.74
	mean	11.61	9.08	10.35	7.24	7.12	7.18
	std	7.18	3.62	5.36	4.05	2.32	3.14
	rms	13.64	9.78	11.52	8.29	7.49	7.83
3x11	min	1.37	1.74	1.37	0.97	0.97	0.97
	max	24.61	23.00	24.61	19.03	14.53	19.03
	mean	7.80	8.30	8.05	6.41	7.38	6.89
	std	4.03	2.28	3.11	2.69	2.48	2.57
	rms	8.78	8.61	8.68	6.95	7.78	7.45
3x14	min	0.29	1.22	0.29	0.13	0.91	0.13
	max	13.50	18.05	18.05	14.52	14.08	14.52
	mean	6.18	8.99	7.58	5.33	6.20	5.76
	std	2.69	2.86	2.79	2.19	2.31	2.26
	rms	6.74	9.43	8.44	5.76	6.62	6.28
3x20	min	0.16	0.58	0.16	0.20	0.66	0.20
	max	15.93	17.75	17.75	12.20	12.07	12.20
	mean	6.02	8.76	7.39	5.28	5.47	5.37
	std	2.72	3.05	2.91	2.20	2.42	2.33
	rms	6.61	9.27	8.29	5.72	5.98	5.88

Table 5-3 The approximated accuracy of the Canon CLC1120 for 7x7x7 LUT data

9x9x9 LUT data

		Whole			Tetra12		
		T-lut 729	T-uni 501	T-glo 1230	T-lut 729	T-uni 501	T-glo 1230
3x04	min	0.31	1.46	0.31	0.36	2.19	0.36
	max	42.40	24.53	42.40	23.39	17.42	23.39
	mean	11.34	8.10	9.72	7.63	8.32	7.97
	std	7.28	3.72	6.08	4.15	2.15	3.47
	rms	13.47	8.91	11.83	8.68	8.59	8.65
3x11	min	0.86	1.25	0.86	0.11	1.24	0.11
	max	23.62	16.78	23.62	16.72	18.13	18.13
	mean	7.08	6.41	6.75	5.96	8.77	7.36
	std	3.63	2.35	3.17	2.60	2.56	2.58
	rms	7.95	6.83	7.52	6.50	9.13	7.68
3x14	min	0.21	0.65	0.21	0.15	0.33	0.15
	max	15.69	14.10	15.69	15.22	12.38	15.22
	mean	6.69	6.54	6.61	6.49	5.90	6.20
	std	2.63	2.26	2.48	2.17	2.04	2.11
	rms	7.18	6.92	7.08	6.85	6.24	6.60
3x20	min	0.18	0.24	0.18	0.21	0.32	0.21
	max	16.97	10.99	16.97	13.96	10.78	13.96
	mean	5.60	5.69	5.65	5.45	4.91	5.18
	std	2.53	2.05	2.34	1.99	1.97	1.98
	rms	6.14	6.05	6.11	5.80	5.29	5.60

Table 5-4 The approximated accuracy of the Canon CLC1120 for 9x9x9 LUT data

5.2 Effect of the *LUT data size* on Bubble Jet BJC8500

At the beginning of the process, the *LUT data size* are chosen to be 7x7x7 and 9x9x9, relavant to its practical approach. In commercial, the Look-up table size 5x5x5 with *Tone Curve Adjustment* is enough to predict the *Real Model* by interpolation method. In this research, it is not pre-adjusted the *Tone Curve Adjustment*. Therefore, more number of *LUT data* is selected. The huge size of look-up table is definitely better, however it consumes more time and material.

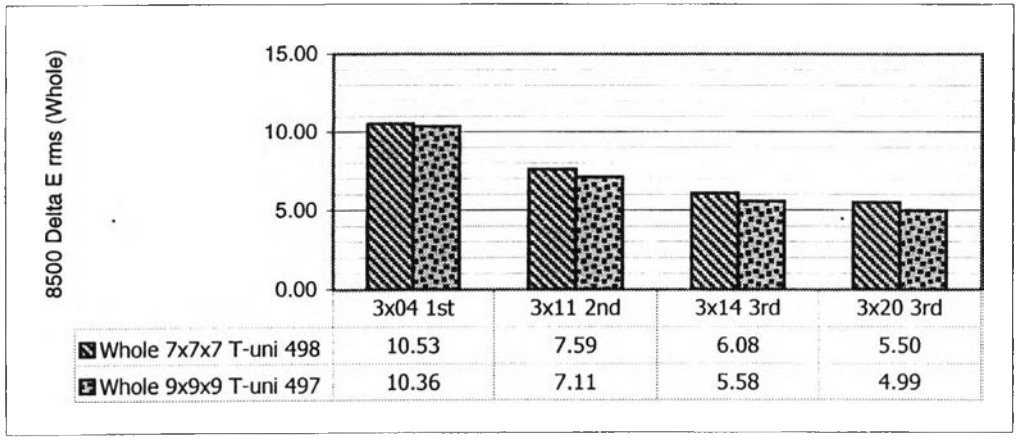
Figure 5-2 shows that the *LUT data size* influences the approximated accuracy as simple way. That is, when *LUT data size* is increased, the ΔE_{rms} will be reduced.

However, it shows that the increase of the *LUT data* size around 200% affects the ΔE_{rms} just a few units. In the same figure, ΔE_{max} shows that the approximated accuracy doesn't relate to the *LUT data size* as the expectation. Nonetheless, this couldn't absolutely conclude because of the incongruous between the *Testing data* and *LUT data*.

5.3 Effect of the *Order of Regression Model* on Bubble Jet BJC8500

The *Regression Model* is chosen as linear model in case of 1st order 4 terms, 2nd order 11 terms, and 3rd order 14 terms as well as 20 terms.

The investigation is not only the result of approximation by degree of order, but also the number of terms in *Regression Model*.



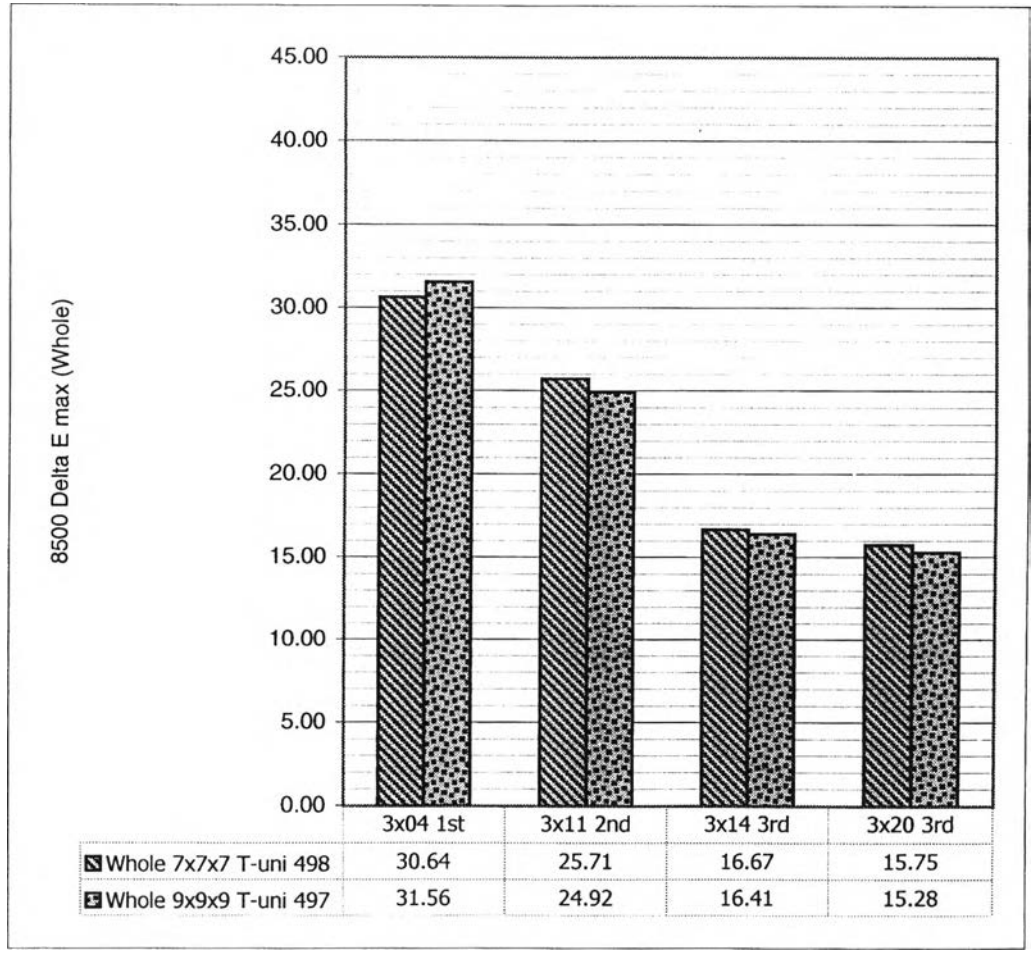
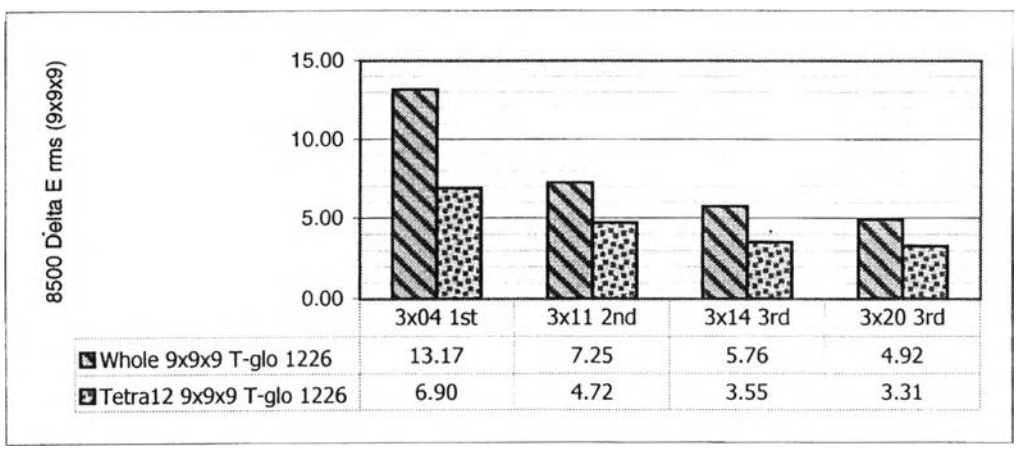


Figure 5-2 Comparison of the the 498 and 497T-uni approximated accuracy of 7x7x7 and 9x9x9 LUT data size



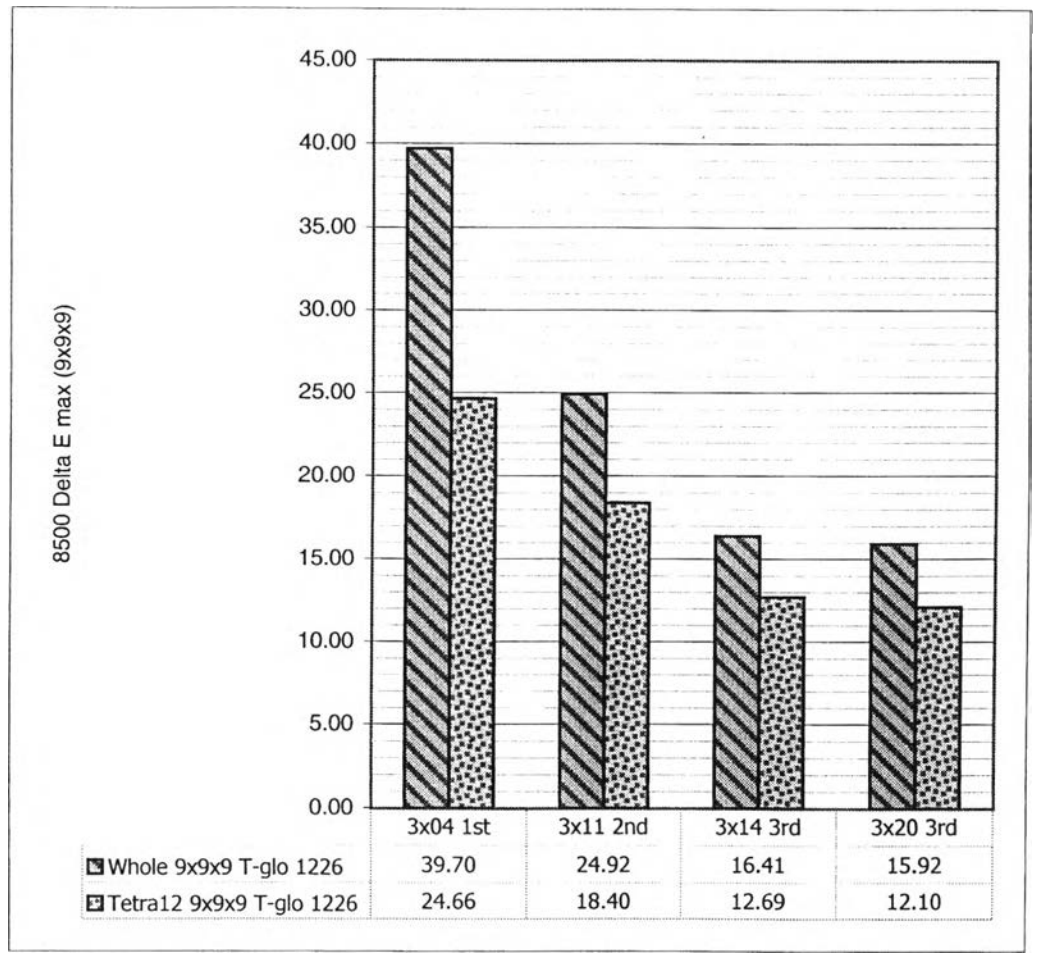
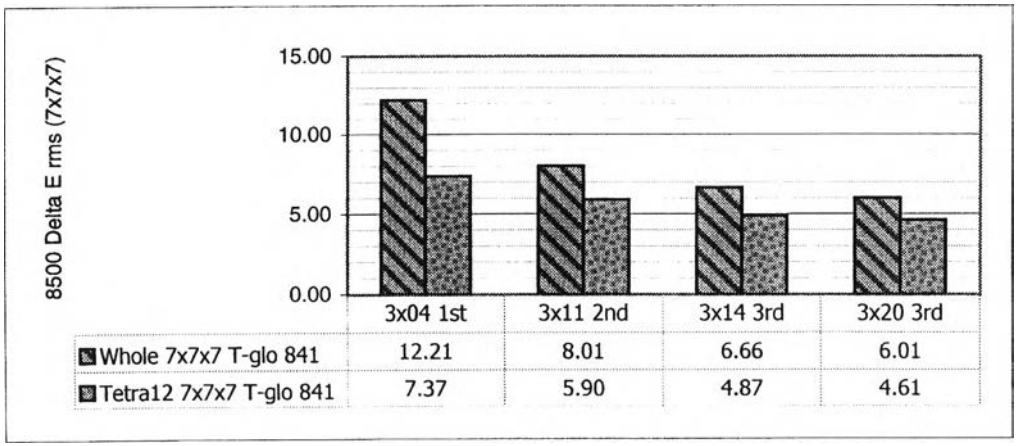


Figure 5-3 Comparison of the the 1226T-glo approximated accuracy of Whole and Tetra12 with 9x9x9 LUT data size



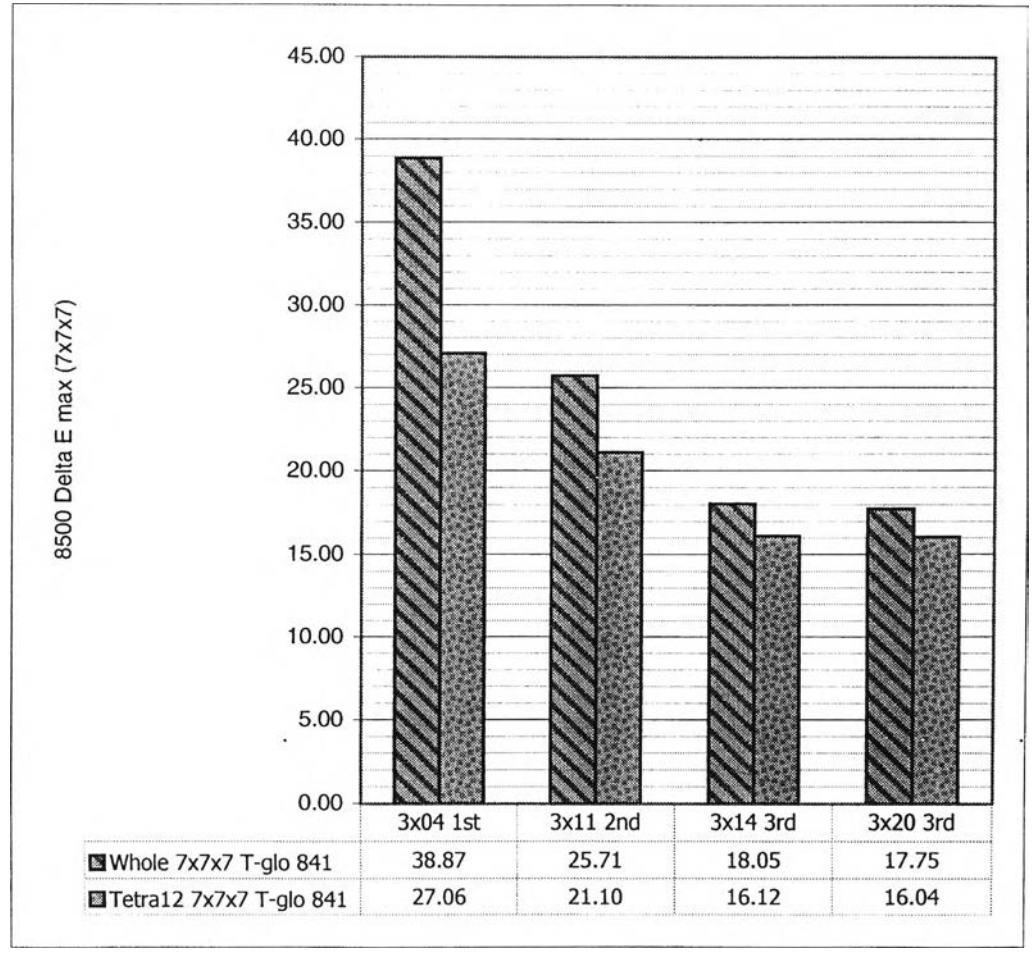


Figure 5-4 Comparison of the the 841T-glo approximated accuracy of Whole and Tetra12 with 7x7x7 LUT data size

The comparisons in the Figure 5-2 through Figure 5-4 show that the *Order of Regression Model* significantly affects the approximated accuracy.

The 1st order has worst approximated accuracy in both of ΔE_{rms} and ΔE_{max}. While the 2nd order has better accuracy and the 3rd order is the best approximated model. The difference of the approximated accuracy between the best and the worst is around 50% for the whole partition as shown in Figure 5-2.

However, It should be noted about the 3rd order that there is no significant difference of ΔE_{rms} and ΔE_{max} between the 14 terms and 20 terms. It is because the extra terms are just the combination of the same input signal.

5.4 Effect of the Partition Method on Bubble Jet BJC8500

Figure 5-3 and Figure 5-4 show that the method of partition significantly affects the approximated accuracy. By Comparison of both partition methods, it is found that the ΔE_{rms} is reduced about 50 % for the 1storder, 38% for the 2nd order, and about the 30% for two of the 3rd order. The ΔE_{max} is also same tendency as ΔE_{rms}.

It should be noted that the best approximated accuracy is $\Delta E_{rms} = 3.31$ and $\Delta E_{max} = 12.10$, which is resulted from combination of *9x9x9 LUT data size* and *Tetrahedral partition.*

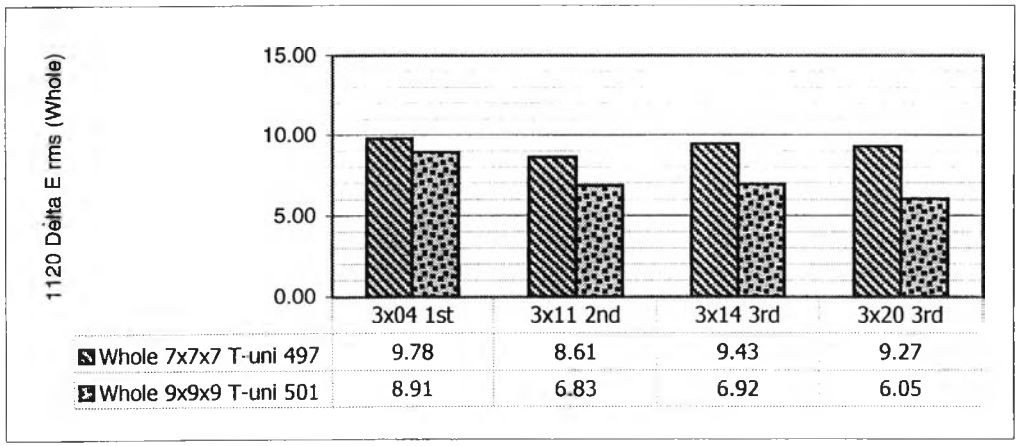
5.5 Effect of the *LUT data size* on Color Laser Copier CLC1120

A figure 5-5 shows that the *LUT data size* also influences the approximated accuracy as simple way. That is, when *LUT data size* is increased, the ΔE_{rms} is decreased. This is, in this case, also true for ΔE_{max}.

5.6 Effect of the *Order of Regression Model* on Color Laser Copier CLC1120

The comparisons in the Figure 5-5 through Figure 5-7 show that the *Order of Regression Model* is still a significantly affective of the approximated accuracy. For *9x9x9 LUT data size*, The 1st order has worst approximated accuracy in both of ΔE_{rms} and ΔE_{max}. While the 2nd order has better accuracy and the 3rd order is the best approximated model. The difference of the approximated accuracy between the best and the worst is about 30% for whole partition as shown in Figure 5-5.

There is some interested result for *7x7x7 LUT data size* that its behaviour is not simple as printer model of Bubble Jet BJC8500. The approximated accuracy does not gradually decrease as the *Degree of Regression Model* increases. It is because of its highly non-linear characteristic model, as clearly shown in Figure 5-8. The *7x7x7 LUT data size* is supposed to be too less to represent the major characteristic of the *Real Model* to produce the high accurate approximated coefficients. However the unexpected effect does not result in *9x9x9 LUT data size* model which supposed that *LUT data size* is large enough to represent its major characteristic.



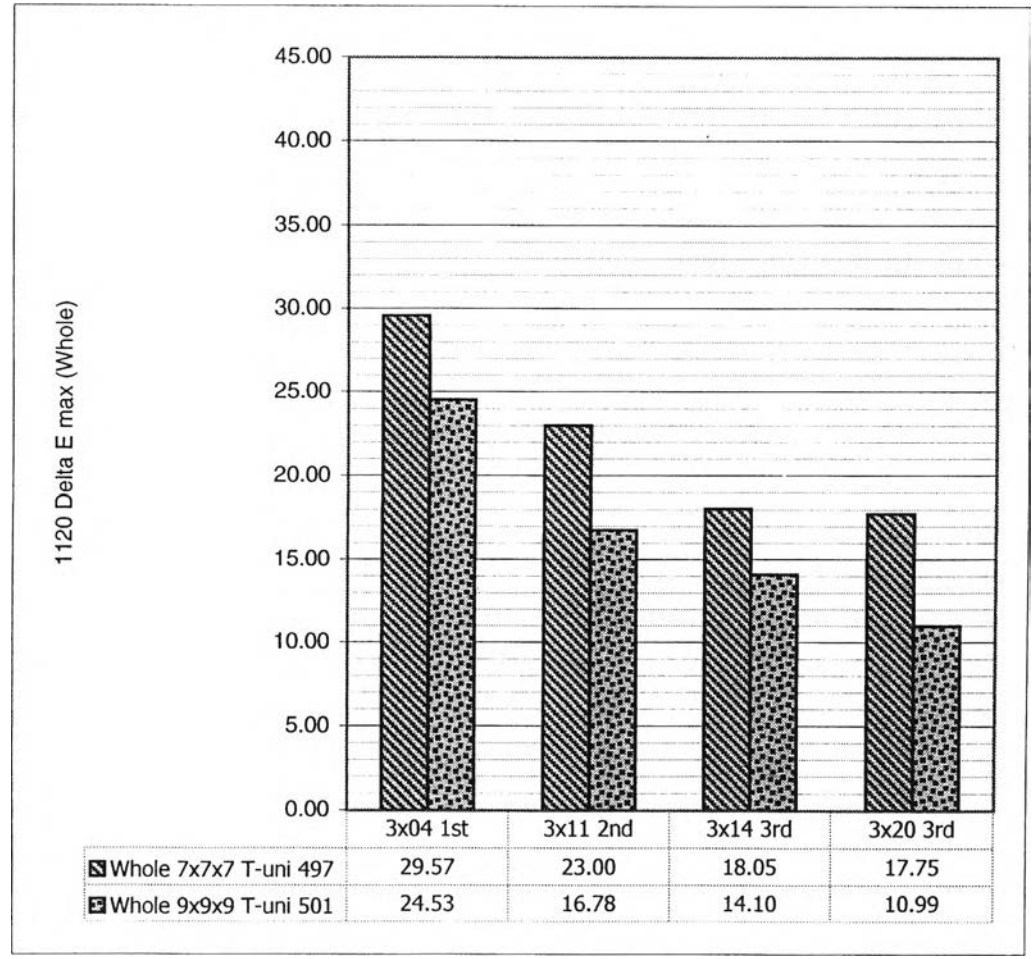
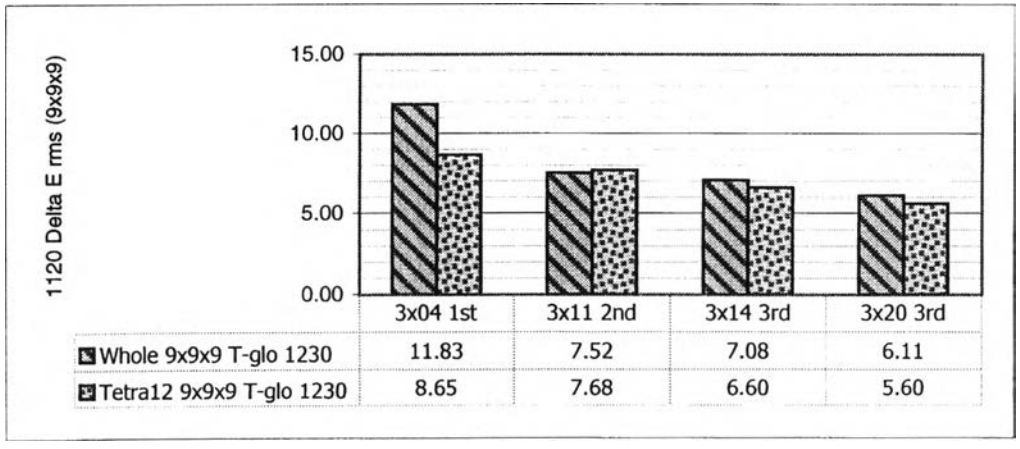


Figure 5-5 Comparison of the the 497 and 501T-uni approximated accuracy of 7x7x7 and 9x9x9 LUT data size



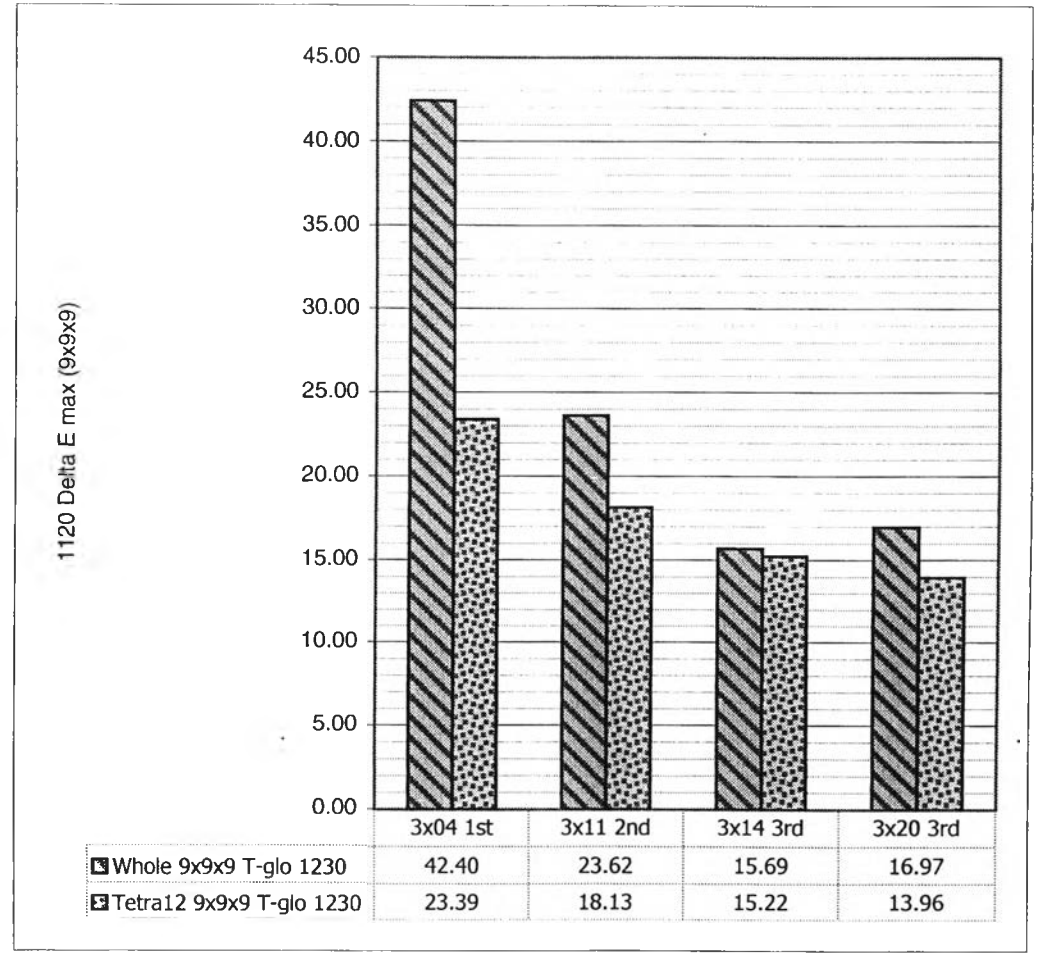
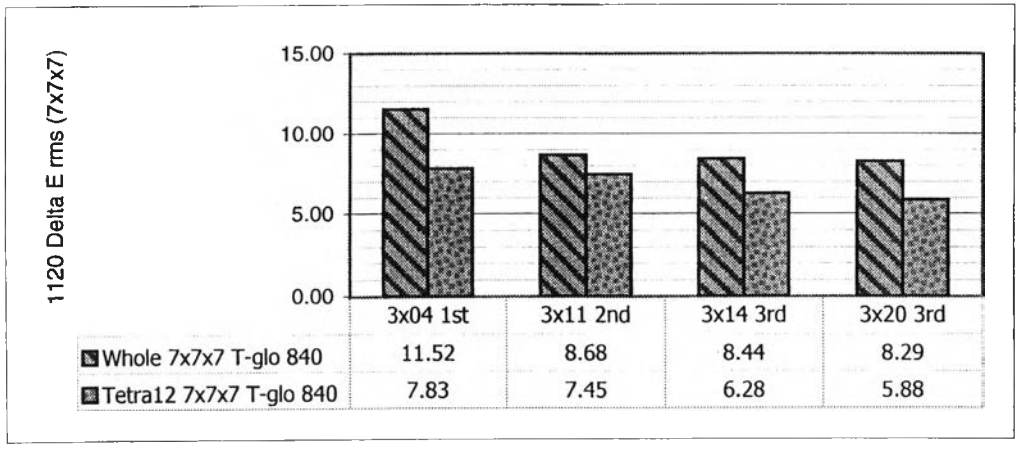


Figure 5-6 Comparison of the the 1230T-glo approximated accuracy of Whole and Tetra12 with 9x9x9 LUT data size



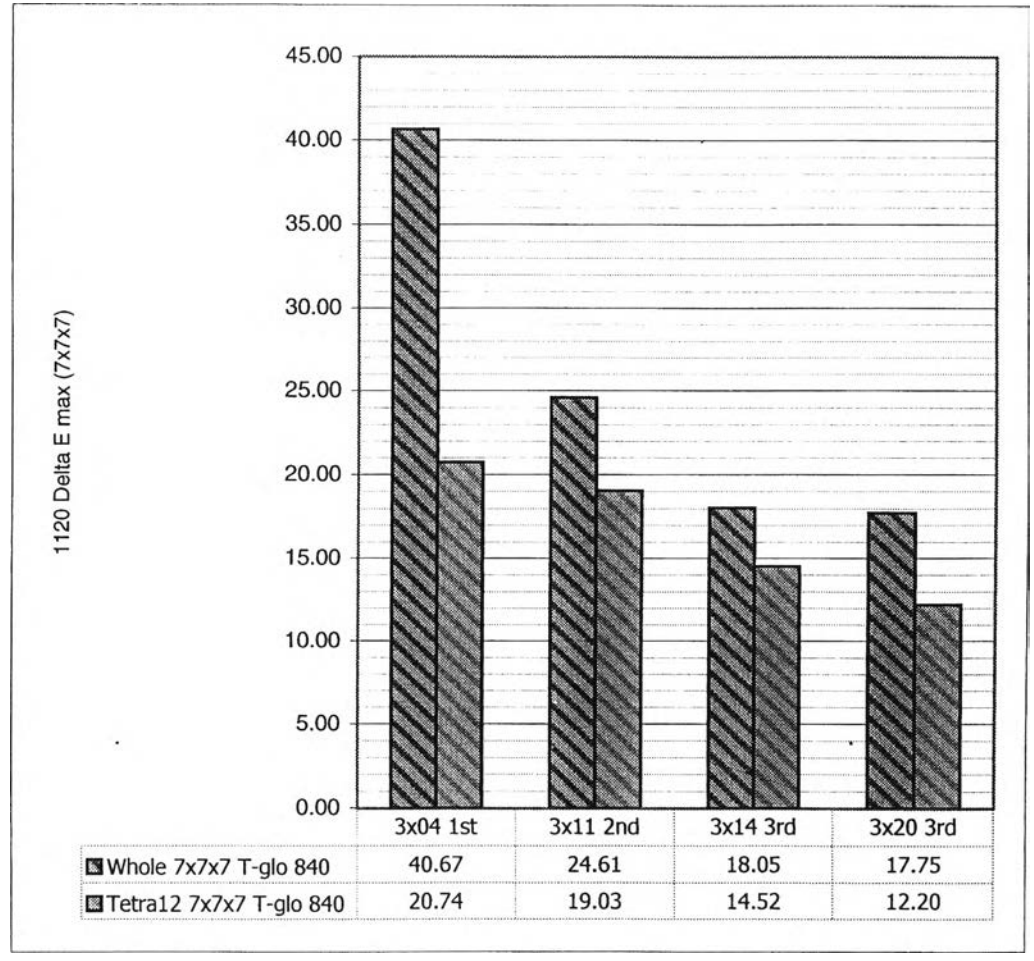
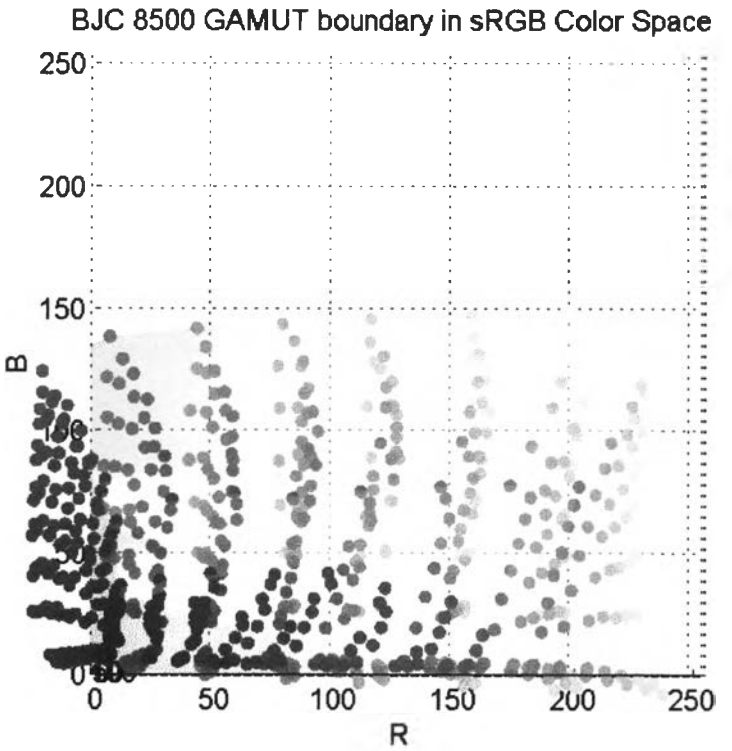
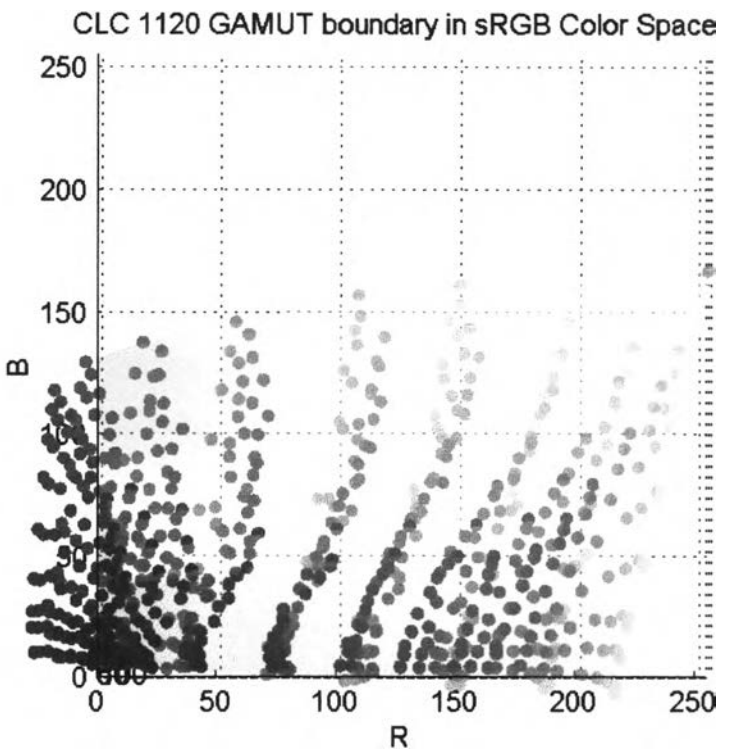


Figure 5-7 Comparison of the the 840T-glo approximated accuracy of Whole and Tetra12 with 7x7x7 LUT data size



(a) BJC8500



(b) CLC1120

Figure 5-8 The characteristic of the printer model (a)BJC8500 and (b)CLC1120

5.7 Effect of Partition Method on Color Laser Copier CLC1120

Figure 5-6 and Figure 5-7 show that the method of partition significantly affects the approximated accuracy. The approximated accuracy gradually reduces as the *Degree of Regression Model* increase. It is supposed to be the compensation of the tetrahedral method.

It should be noted that the best approximated accuracy are $\Delta E_{rms} = 5.60$ and $\Delta E_{max} = 13.96$, which is resulted from the combination of 9x9x9 *LUT data size* and *Tetrahedral partition.*

5.8 Effect of Overlapping partition

Figure 5-9 and Figure 5-10 are graphically show the *Printer gamut boundary* of each printer which divided as tetrahedral partition. In *sRGB* color space the neutral axis of partitions is *Gray Axis*. The Figures show that the *Printer gamut boundary* is not asymmetric shape and position in *sRGB* color space. Thus, each partition does not contain equally amount of *LUT data*. Therefore each *Coefficient Partition* does not evenly accurate approximate for each corresponding *Target Partition* of the *Real Model*.

The approximated accuracy, evaluated by ΔE_{rms} and ΔE_{max}, is only represented as its overall performance but in particular. It does not indicate that how particularly accuracy values distribute themselves in its boundary.

Nonetheless, the accuracy values are found that it's gradually changed in its boundary but among each partition. This is because the approximated model is obtained from *Linear Regression Model* assumption. Figure 5-11 (a) shows the sample of gray step, which approximated without partition method. The reproduction is gradually changes in its boundary. This is also called as *'Continuity'*.

While Figure 5-11 (b) shows the sample of gray step, which approximated with partition method. The partition method is the *sRGB* color space which divided by the plane of $R+G+B=383$. Hence the wall of each boundary is at middle of *Gray Axis*. The reproduction is not gradually change across this boundary. And this is also called a *'Discontinuity'*.

Basically, the tetrahedral method groups the same color characteristic together along the *Gray Axis*. The change of characteristic among each partition is hue. Thus,

the approximated accuracy of each partition is also gradually changed along the *Gray Axis* but in hue direction.

To remedy this undesirable effect, It is necessary to extend the *Coefficient Partition* to overlap each other. This is a balance between the approximated accuracy and the gradualness.

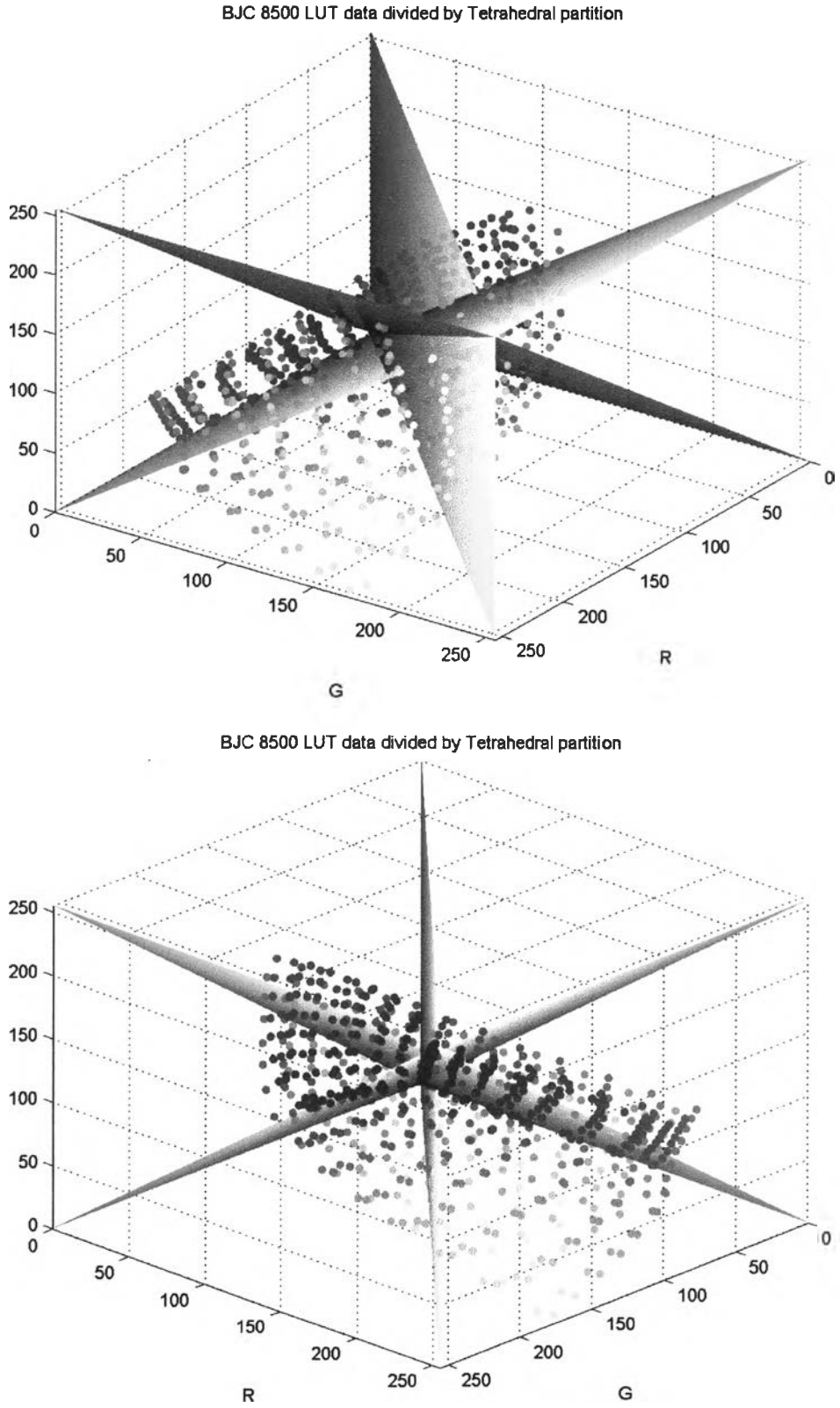


Figure 5-9 The *Printer Gamut boundary* of printer model BJC8500 with Tetrahedral partition

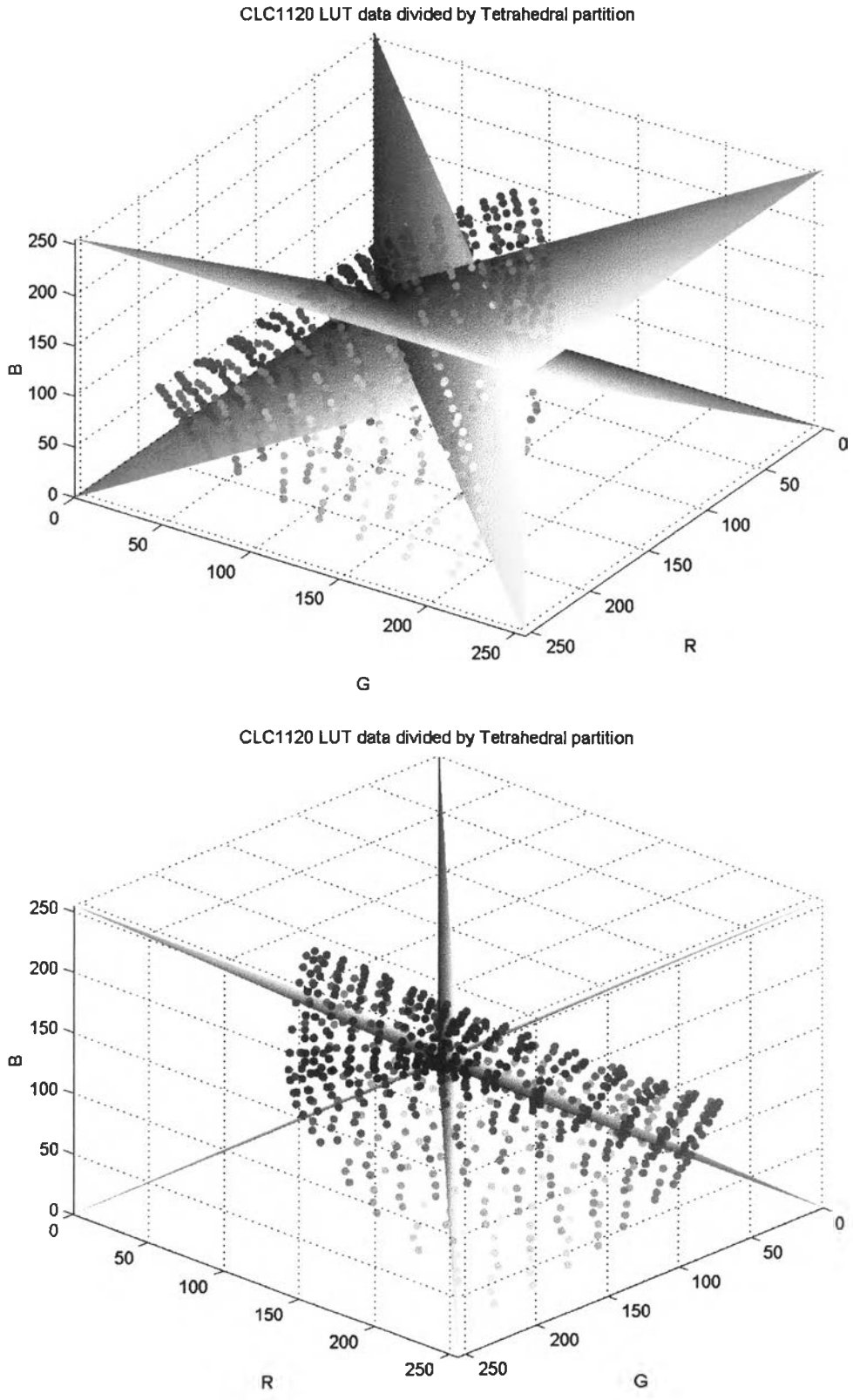
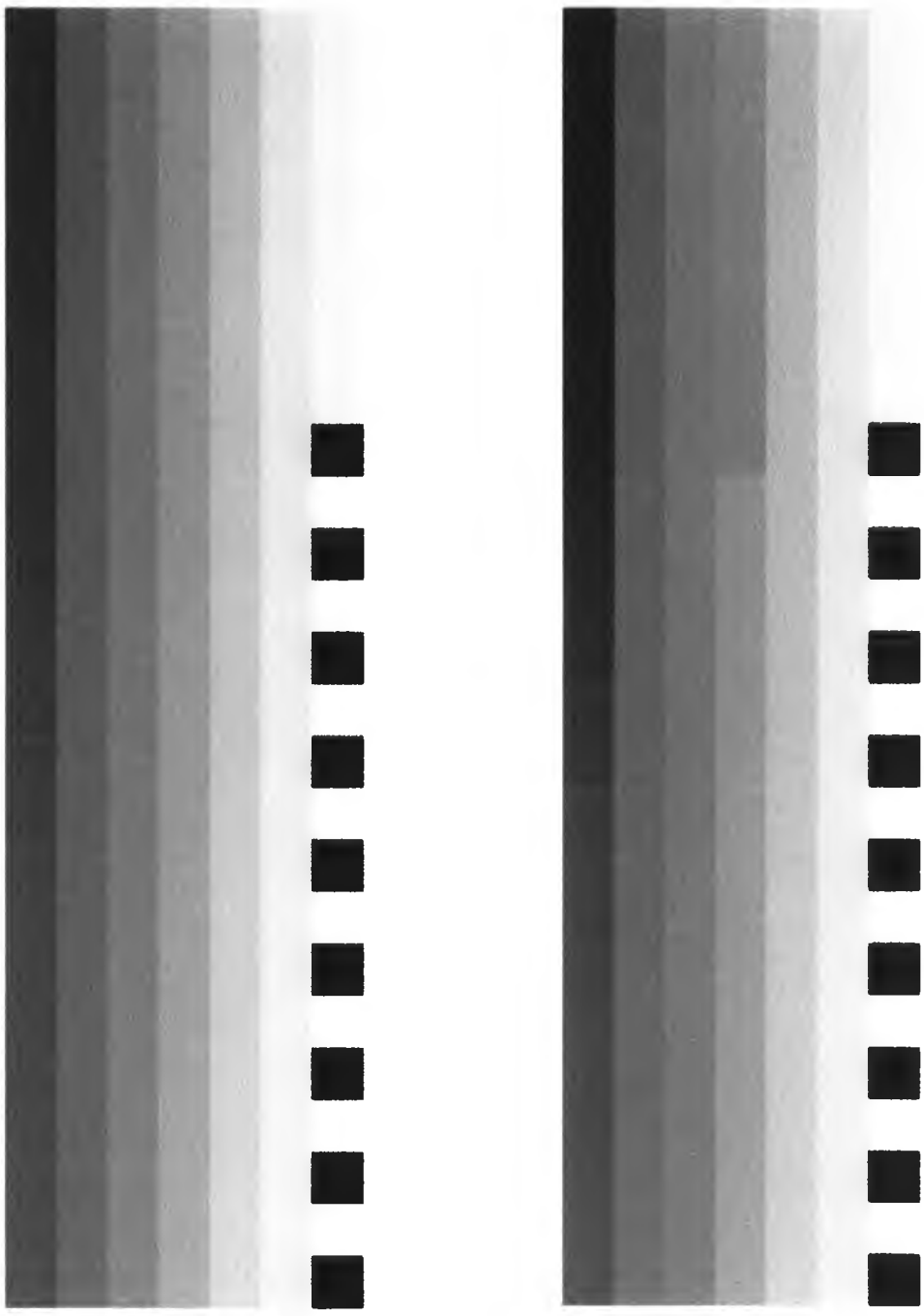


Figure 5-10 The *Printer Gamut boundary* of printer model CLC1120 with Tetrahedral partition



(a) (b)

Figure 5-11 (a) The gray step that is approximated from the whole partition

(b) The gray step that is approximated from the whole partition method divided by plane of $R+G+B=383$

For tetrahedral partition method, each *Coefficient Partition* has 25 unit extend boundary. This value is obtained from trial and error to approximate the *Real Model*. If this value is too less, the boundary of *Coefficient Partition* will close to *Target Partition*. Then the approximated of some color has the color error up to $\Delta E \approx 80$ that is not accepted in practical use. This is because of the outer range of *LUT data boundary* as discuss in section 3.4