New developments in gamut mapping and inverse output mapping for Indigo 7000 series press for PARAWAC DBS halftoning

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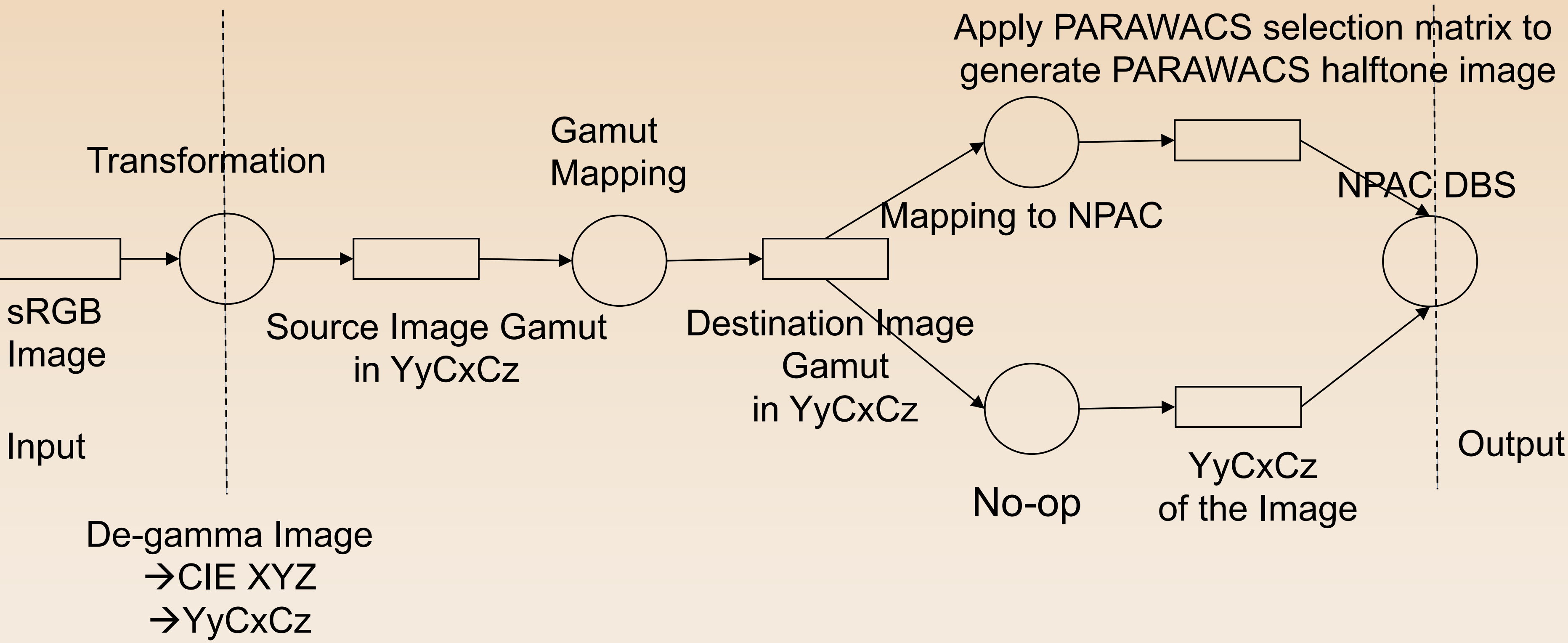
Synopsis

- Overview of color imaging pipeline for NPAC halftoning framework
- Characterization and development of forward and inverse mapping based on Indigo 7000 series prints
- New development of Gamut mapping
- PARAWACS halftone

NPAC stands for Neugebauer Primary Area Coverage

Color Management Block Diagram



Source Image Gamut is all unique YyCxCz pixel values from an image (Remove repeated pixel values).
Destination Image Gamut means all unique pixel values in an image are mapped into Indigo Gamut.
Indigo Gamut is a set of 9*9*9 grid points that describe Indigo gamut.

Synopsis

- Overview of color imaging pipeline for NPAC halftoning framework
- Characterization and development of forward and inverse mapping based on Indigo 7000 series prints
- New development of Gamut mapping
- PARAWACS halftone

Goal

- To develop the color management framework, we want to generate a mapping that given a YyCxCz value, find its NPAC value that when printed will yield the desired YyCxCz value.
- To achieve the goal above, we formed 9*9*9 grid points that can represent Indigo printer gamut. Print these patches on test pages where each patch has a certain NPAC value and use X-Rite DTP 70 to get each patch's XYZ value and transfer into YyCxCz space.
- Store those measured YyCxCz values and NPAC as a inverse mapping.

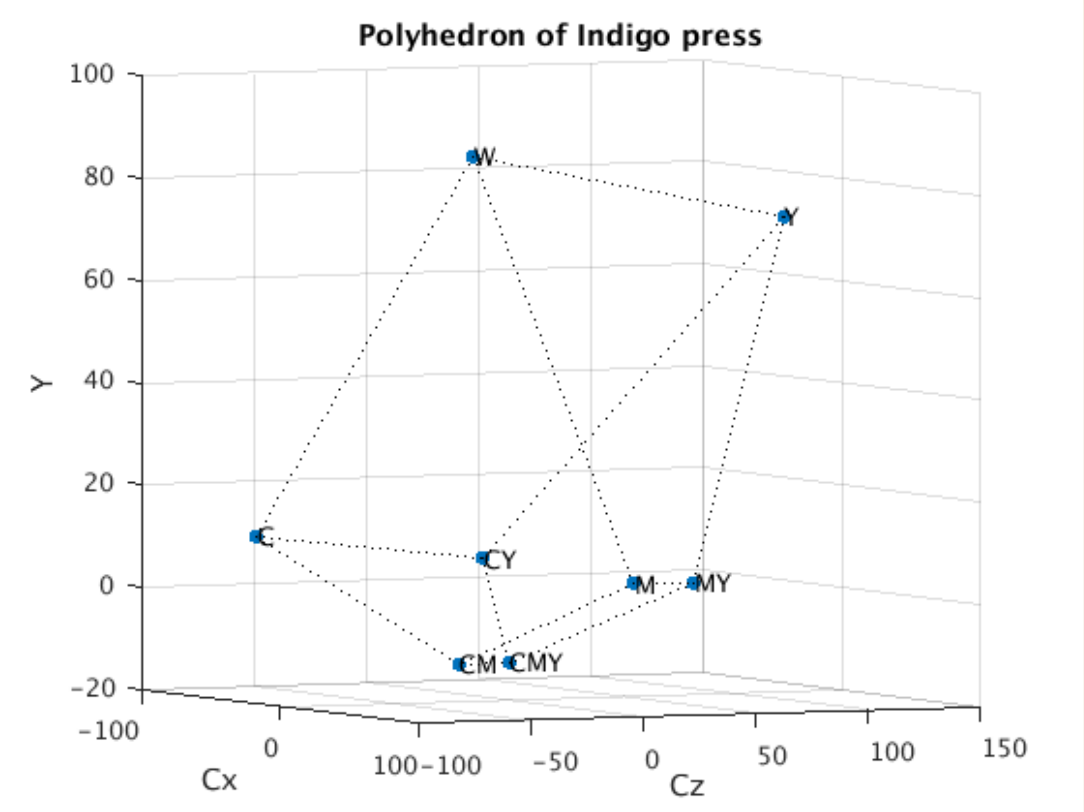
Forward and Inverse Mapping

- Forward and Inverse Mapping are the same set of data. (9*9*9 grid points)
- Forward mapping:
  - » In CMY space, every grid point has a YyCxCz value.
- Inverse mapping:
  - » In YyCxCz space, each grid point has a CMY, and an NPAC value, but we are not using CMY combinations.

Indigo 7000 press

Before Design
Define Indigo press printer gamut

1. We generated solid patches of 8 (W Y C CY M MY CM CMY) NPs (Neugebauer Primaries), printed and measured 8 NPs CIEXYZ values using X-Rite DTP70, and converted them into YyCxCz.
2. To have a better description of Indigo press printer gamut, we need to generate more points that are based on actual target halftoning algorithm.



X-Rite DTP 70

- X-Rite DTP 70 is a X-Y AutoScan Spectrophotometer
- Use X-Rite DTP 70 to get CIEXYZ value for each patch
- Outputs files also includes CIEXYZ, spectral reflection values

Instrument Specifications

General

Measurement Geometry: .... Reflection 45°/0° per ANSI/ISO 5-4 (IT2.17)
Spot Size: .... 3.2 mm diameter
Light Source: .... Gas pressure @ 2850°K
Spectral Sensor:.................... FAST technology, 16-point engine, 31-point reporting
Spectral Range: .... 400 – 700 nm
Illuminant Types: .... A, C, D50, D65, D75, F2, F7, F11 & F12
Standard Observer: .... 2° & 10°
Density Responses: .... Status T, E, I, A, Spectral, HiFi, Hexachrome
Measurement Speed: .... 100 measurements per second
IT8 7/3: 2.5 minutes minimum
ECI: 4.2 minutes minimum
IT8 7/4: 4.5 minutes minimum
Inter-instrument agreement:
(based on DTP70 standard
for 12 BCRA tiles) .... 0.3 ΔE 94 average; 0.5 ΔE 94 maximum
Measurement range: .... 0.00D to 2.50D; 0 to 160% R (reflection)
Repeatability on White: .... 0.2 ΔE max.; ±0.01D max.
Linearity: .... ±0.02D or 2%, 0 to 2.5D
Media Thickness: .... 0.08 mm (0.003 in) to 0.36mm (.014 in)
Physical filter: .... UV in / ex – field switchable
Backer Tray: .... Black / White – field switchable
Data Interface: .... USB 2.0 certified full-speed peripheral device
Calibration: .... Internal calibration reference provided
Warm-up Time: .... None
Physical Dimensions: .... W: 315 mm (12.4 in), D: 193 mm (7.6 in),
H: 150 mm (5.9 in)
Weight: .... 3320 g (7.32 lbs.)

http://www.hezo.com.tw/product_show.php?id=366&series=21

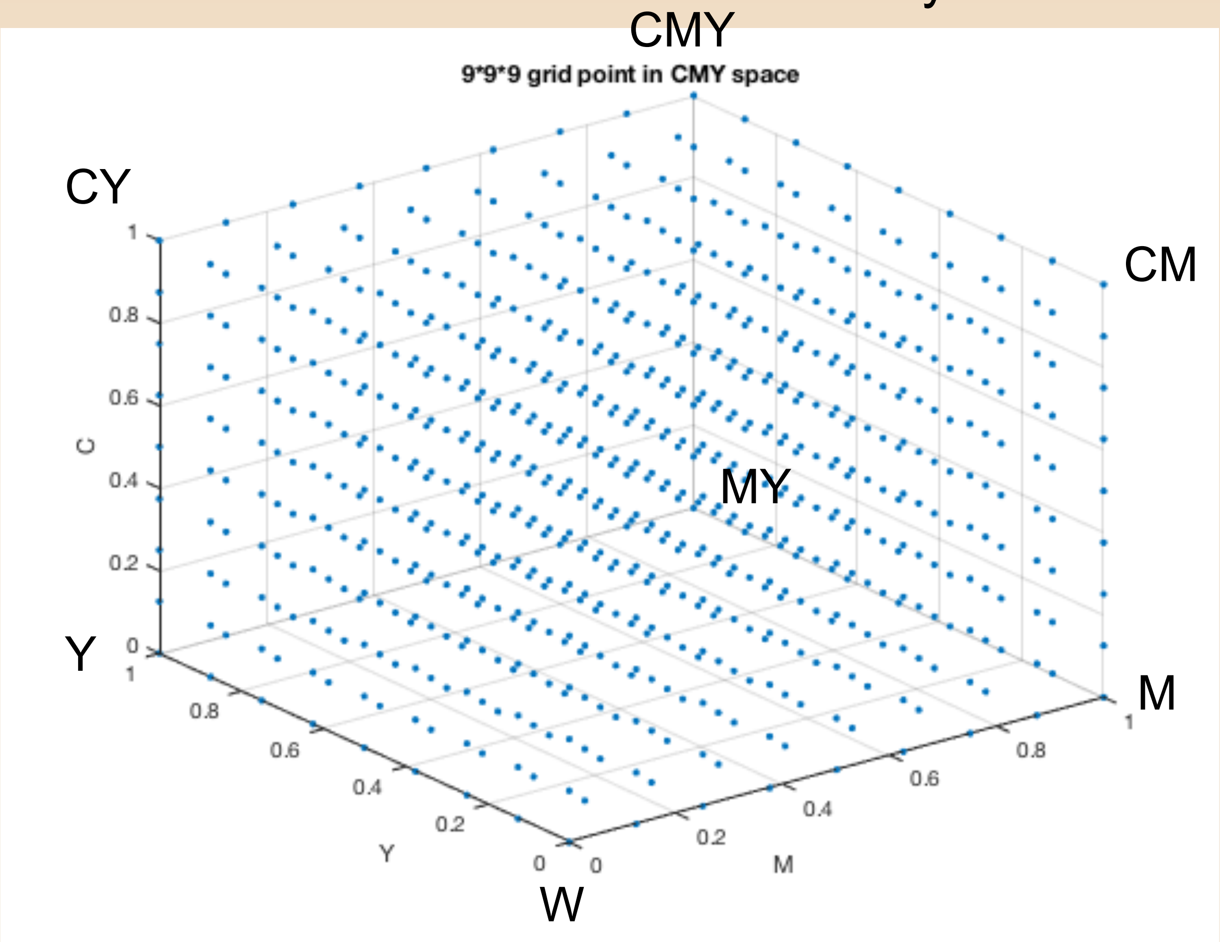
Reference: https://xritephoto.com/documents/manuals/en/DTP70-500_XY_Scan_Spectrophotometer_Operator_Manual_en.pdf

Design Procedure

- First, uniformly sample along each edge of cube CMY to form 9*9*9 grid points in CMY space.
- Tessellate CMY space into six tetrahedra.
- For each grid point, find one of six tetrahedra that contains it.
- Obtain corresponding YyCxCz tristimulus value via tetrahedral interpolation (2 cases).
  - » Case 1: The point lies inside tetrahedron → Do tetrahedral interpolation
  - » Case 2: The point lies on a 3-D surface or an edge of the tetrahedron → Do area interpolation
- Find each grid point's NPAC value.
  - » Its NPAC value is the interpolation value from previous step
- Generate test patches and test pages.
- Print.
- NPAC stands for Neugebauer Primary area coverage.
- NP order: W , Y , C , CY , M , MY , CM , CMY
- 0 , 1, 2 , 3 , 4 , 5 , 6 , 7

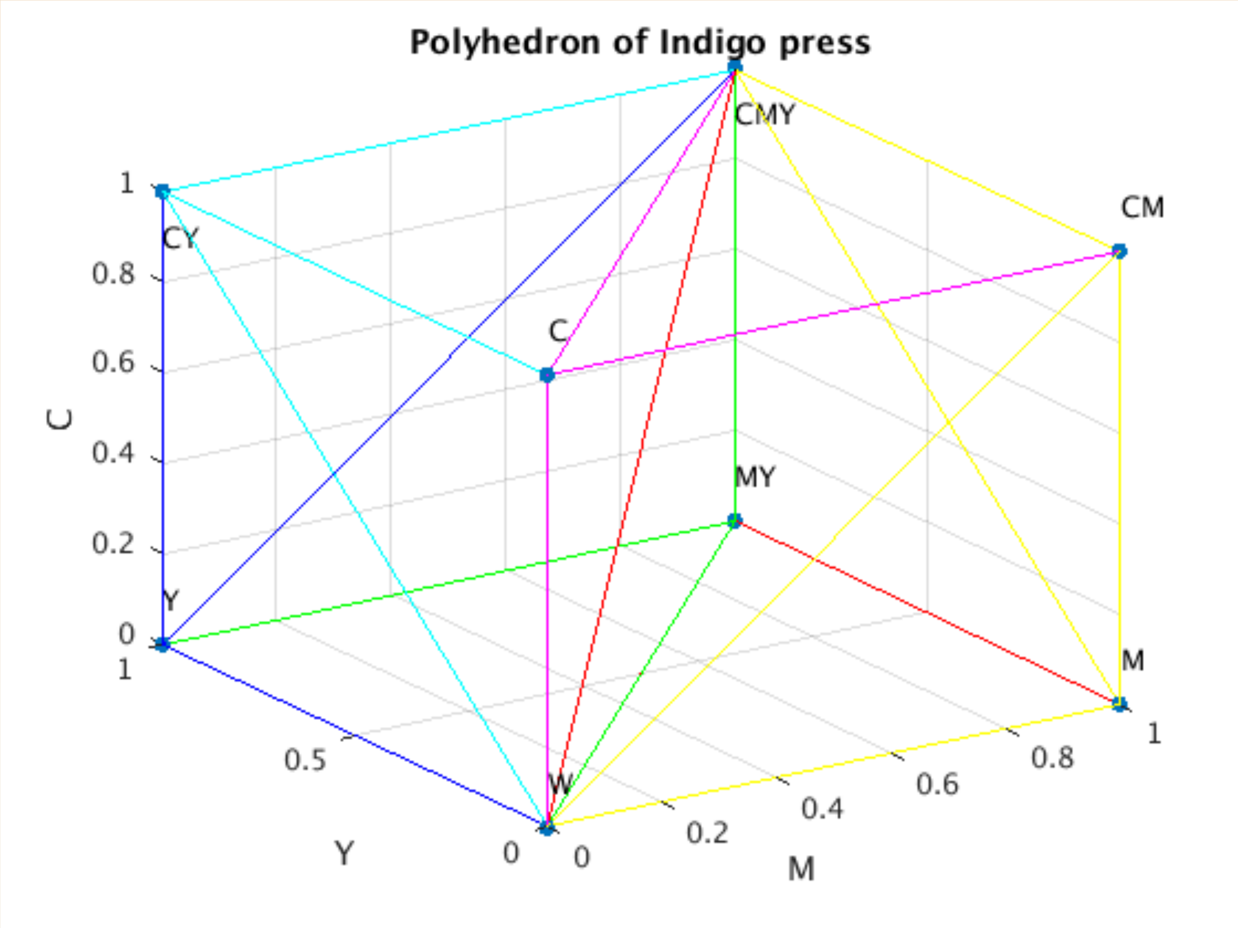
Step 1: Uniformly sample 9*9*9 grid points in CMY space

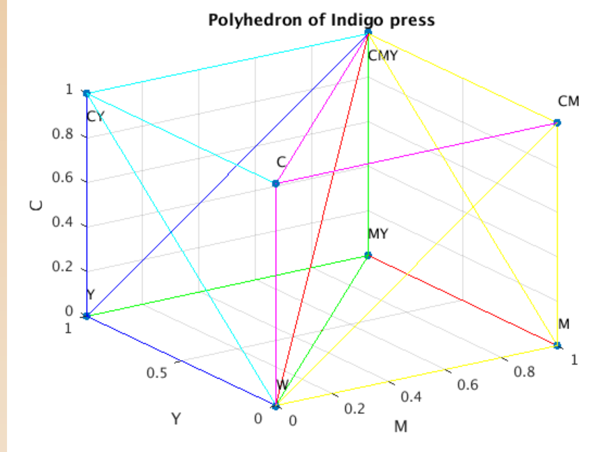
- Step 1: uniformly sample 9*9*9 grid points along each edge of cube CMY space.
- The 8 vertices of this cube are 8 NPs (Neugebauer Primaries) of Indigo press and each vertex has a associate YyCxCz value.



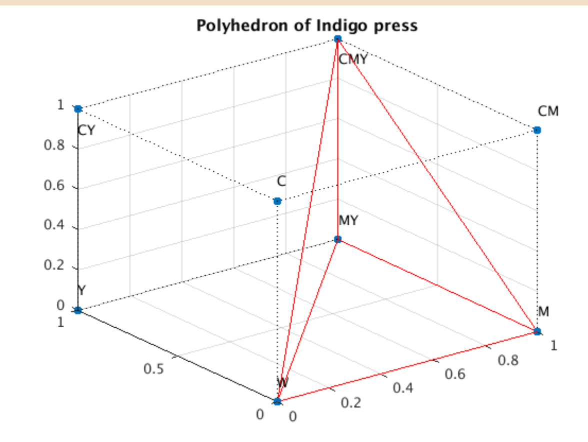
Step 2: Tessellate Indigo press printer gamut

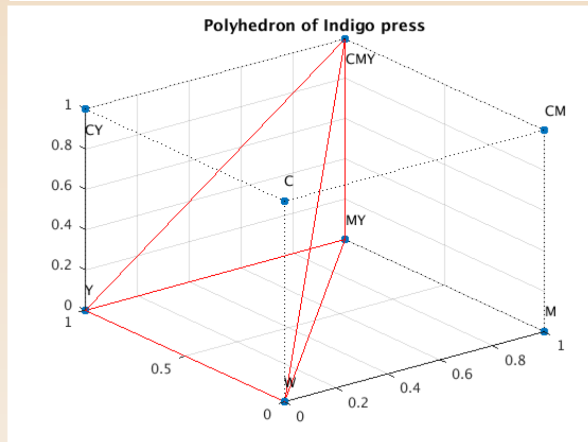
- Step 2: we tessellate Indigo press printer gamut in to 6 big tetrahedra, each tetrahedron is formed by 4 out of 8 NPs.
- We treat W-CMY as our neutral axis and it is included in every tetrahedron.

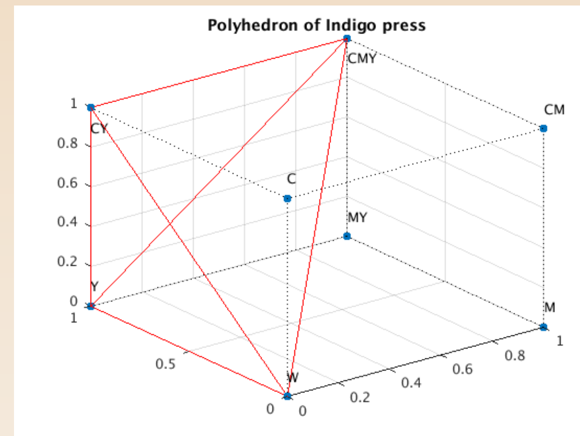


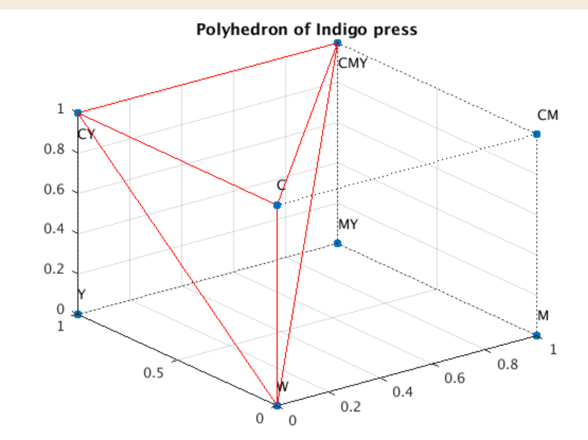


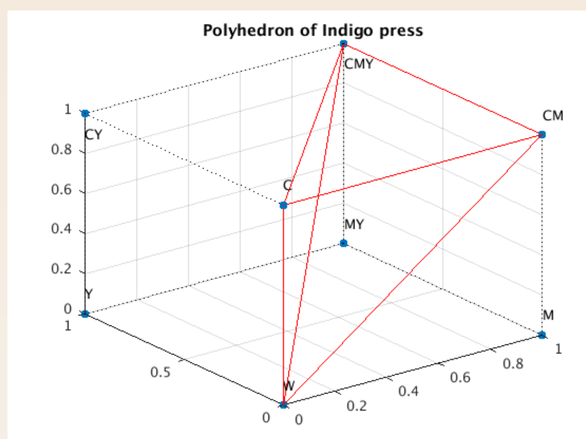
1. W-M-MY-CMY
2. W-Y-MY-CMY
3. W-Y-CY-CMY
4. W-C-CY-CMY
5. W-C-CM-CMY
6. W-M-CM-CMY

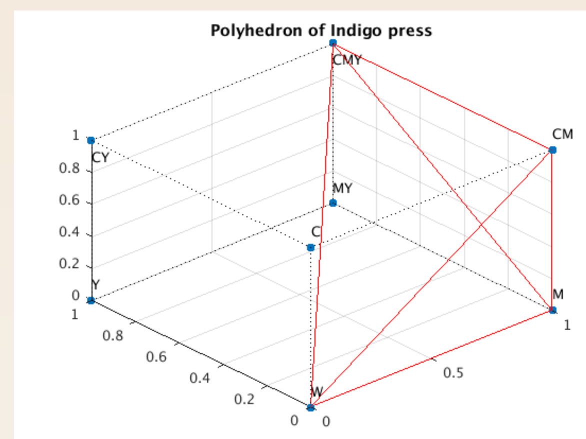






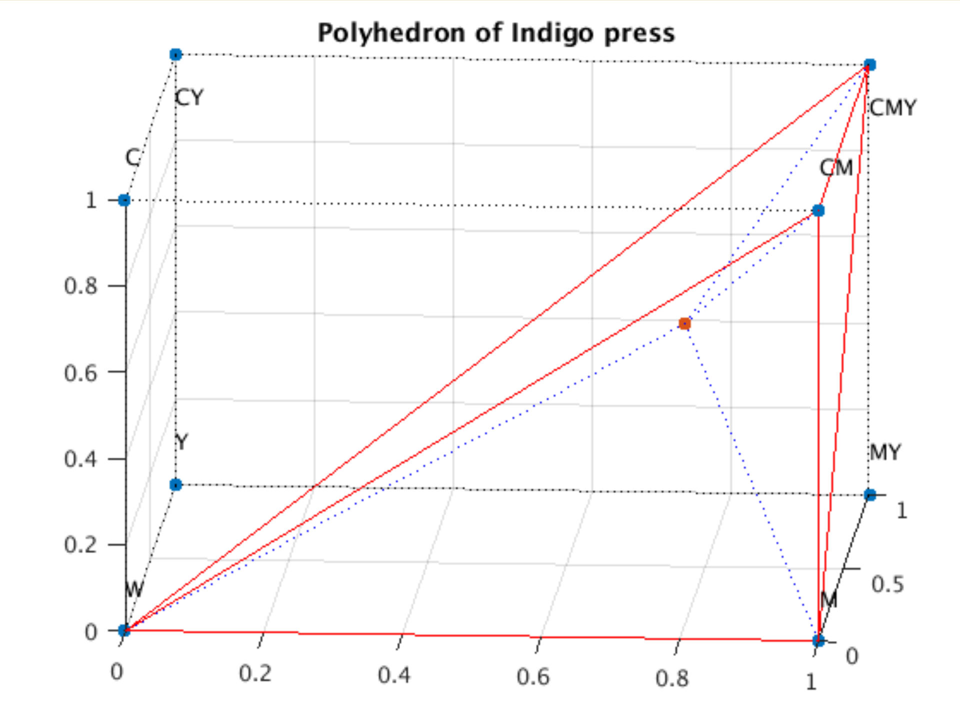






Step 4: Do tetrahedral interpolation to find every grid point's YyCxCz value and NPAC

- Step 4: do tetrahedral interpolation
- Tetrahedral interpolation is divided into two cases
  - » 1. points inside big tetrahedron
  - » 2. points lies on a 3-D triangular surface or an edge of a big tetrahedron
- Find grid points' YyCxCz value and NPAC based on tetrahedral interpolation results

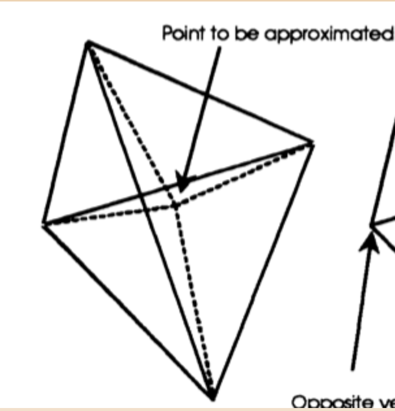


Case 1:Tetrahedral interpolation

- Tetrahedral interpolation is defined by

$$\vec{p} = \overrightarrow{p_0} + \sum_{i=1}^{3} u_i(\overrightarrow{p_i} - \overrightarrow{p_0})$$

$$v = v_0 + \sum_{i=1}^{3} u_i(v_i - v_0) \qquad v_i = f(\overrightarrow{p_i})$$



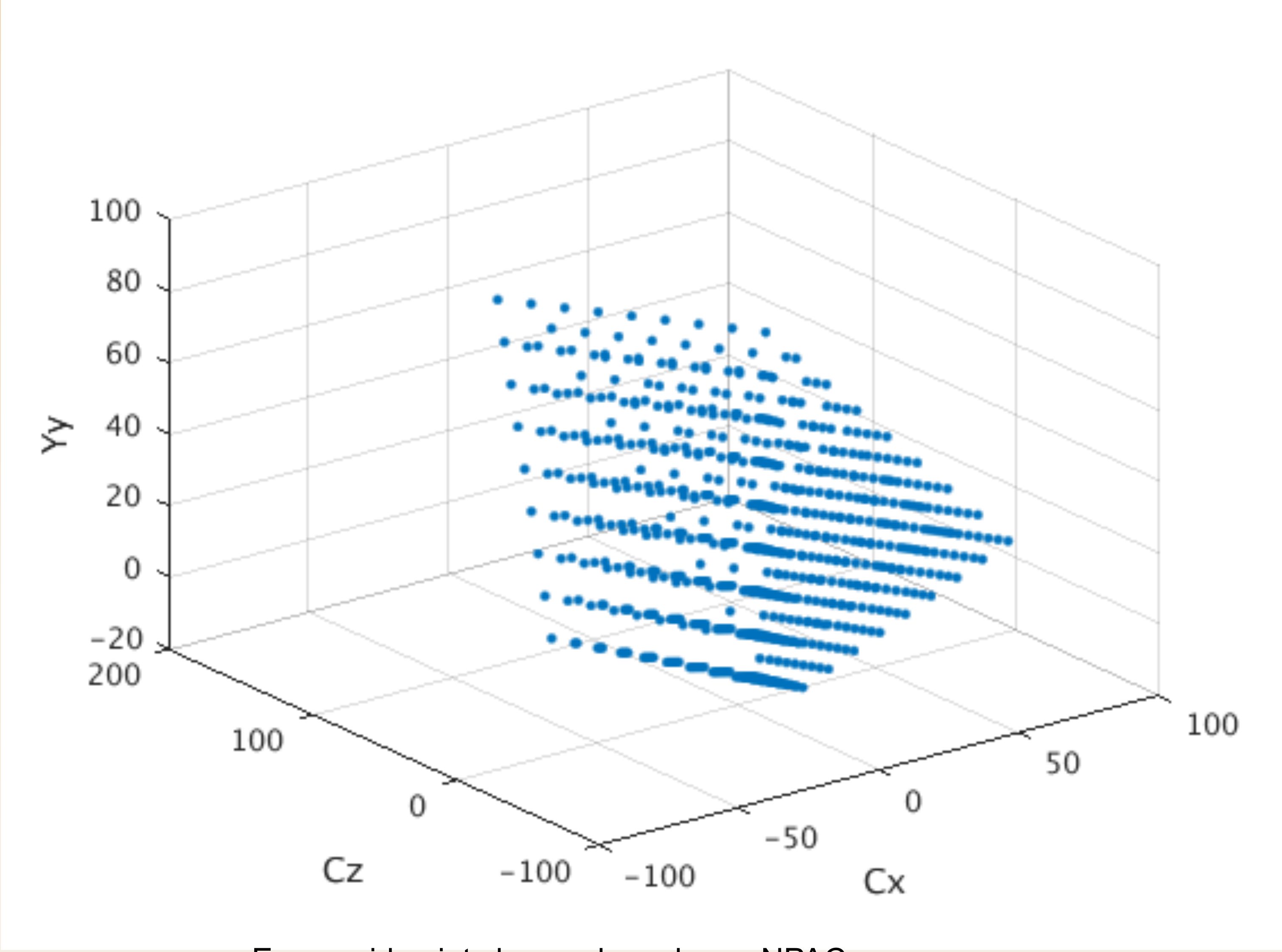
- The value at point $\vec{p}$ is the value at the point $\overrightarrow{p_0}$ plus the values at each of the points $\overrightarrow{p_i}$, scaled by the corresponding factors u_i
- The values of the u_i are usually stated in a ratio-of volumes form:

$$u_i = \frac{V_i}{V}$$

- where V is the volume of the tetrahedron defined by the four points at which the function value is known, and V_i is the volume of the tetrahedron defined by the remaining points if $\vec{p}$ is substituted for the point $\overrightarrow{p_i}$.

Reference: J. M. Kasson, W. Plouffe, and S. I. Nin, ”A tetrahedral interpolation technique for color space conversion” SPIE Vol.1909 (4 August 1993)

9*9*9 grid points in YyCxCz space



Every grid point shown above has a NPAC,
Ideally, when printed it should give us desired YyCxCz value.

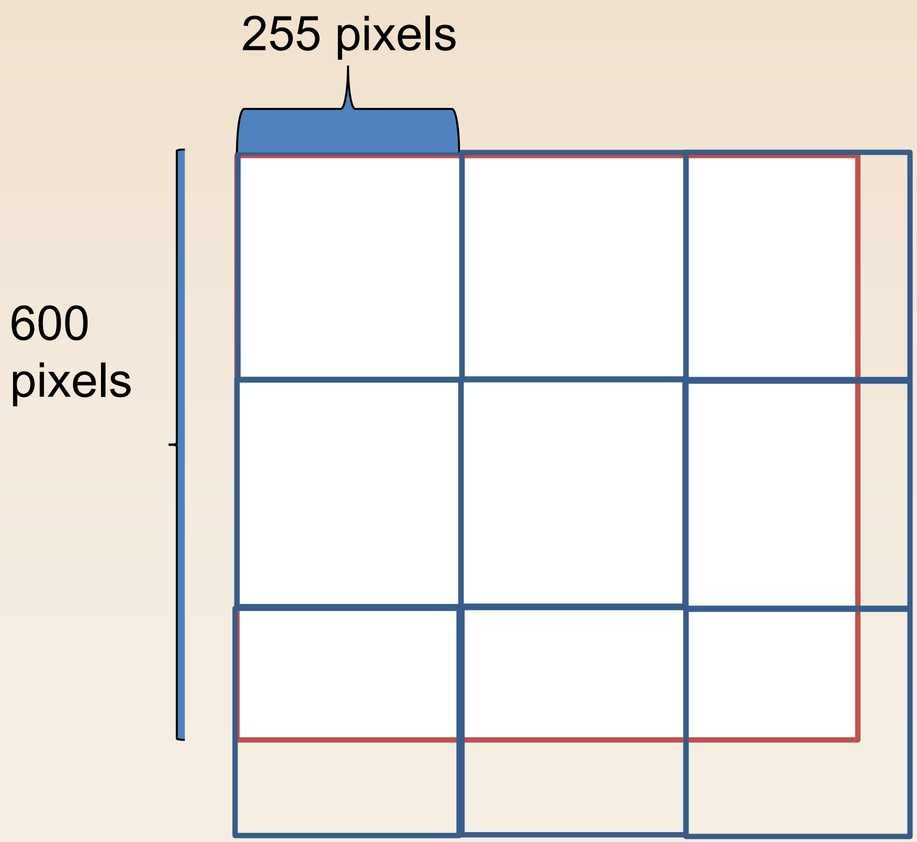
Forward Mapping (Ideal case)

- 9*9*9 grid point plotted last slide, showed as a table.

Index	C	M	Y	Yy	Cx	Cz	W	Y	C	CY	M	MY	CM	CMY	Index of Tetrahedra
1	0	0	0	116	0	0	1	0	0	0	0	0	0	0	1
2	0	0	0.125	113.919513	-2.2407833	19.1115054	0.875	0.125	0	0	0	0	0	1.11E-16	2
3	0	0	0.25	111.839025	-4.4815665	38.2230107	0.75	0.25	0	0	0	0	0	1.11E-16	2
4	0	0	0.375	109.758538	-6.7223498	57.3345161	0.625	0.375	0	0	0	0	0	5.55E-17	2
5	0	0	0.5	107.678051	-8.963133	76.4460215	0.5	0.5	0	0	0	0	0	0	2
6	0	0	0.625	105.597563	-11.203916	95.5575268	0.375	0.625	0	0	0	0	0	0	2
7	0	0	0.75	103.517076	-13.4447	114.669032	0.25	0.75	0	0	0	0	0	1.11E-16	2
8	0	0	0.875	101.436588	-15.685483	133.780538	0.125	0.875	0	0	0	0	0	1.11E-16	2
9	0	0	1	99.3561011	-17.926266	152.892043	0	1	0	0	0	0	0	0	2
10	0	0.125	0	104.4202	13.207089	0.44389019	0.875	0	0	0	0.125	0	0	1.11E-16	1
11	0	0.125	0.125	104.402876	11.7254421	4.33157983	0.875	0	0	0	0	0.125	0	1.11E-16	1
12	0	0.125	0.25	102.322389	9.48465882	23.4430852	0.75	0.125	0	0	0	0.125	0	0	2
13	0	0.125	0.375	100.241902	7.24387556	42.5545906	0.625	0.25	0	0	0	0.125	0	0	2
14	0	0.125	0.5	98.1614143	5.0030923	61.6660959	0.5	0.375	0	0	0	0.125	0	0	2
15	0	0.125	0.625	96.0809269	2.76230905	80.7776013	0.375	0.5	0	0	0	0.125	0	0	2
16	0	0.125	0.75	94.0004396	0.52152579	99.8891067	0.25	0.625	0	0	0	0.125	0	0	2
17	0	0.125	0.875	91.9199522	-1.7192575	119.000612	0.125	0.75	0	0	0	0.125	0	0	2
18	0	0.125	1	89.8394648	-3.9600407	138.112117	0	0.875	0	0	0	0.125	0	0	2
19	0	0.25	0	92.8404004	26.414178	0.88778039	0.75	0	0	0	0.25	0	0	1.11E-16	1
20	0	0.25	0.125	92.8230766	24.9325311	4.77547002	0.75	0	0	0	0.125	0.125	0	0	1
21	0	0.25	0.25	92.8057528	23.4508842	8.66315965	0.75	0	0	0	0	0.25	0	1.11E-16	1
22	0	0.25	0.375	90.7252654	21.2101009	27.774665	0.625	0.125	0	0	0	0.25	0	0	2
23	0	0.25	0.5	88.6447781	18.9693176	46.8861704	0.5	0.25	0	0	0	0.25	0	0	2
24	0	0.25	0.625	86.5642907	16.7285344	65.9976758	0.375	0.375	0	0	0	0.25	0	0	2
25	0	0.25	0.75	84.4838033	14.4877511	85.1091811	0.25	0.5	0	0	0	0.25	0	0	2
26	0	0.25	0.875	82.403316	12.2469679	104.220686	0.125	0.625	0	0	0	0.25	0	0	2
27	0	0.25	1	80.3228286	10.0061846	123.332192	0	0.75	0	0	0	0.25	0	0	2
28	0	0.375	0	81.2606005	39.621267	1.33167058	0.625	0	0	0	0.375	0	0	5.55E-17	1
29	0	0.375	0.125	81.2432768	38.1396201	5.21936021	0.625	0	0	0	0.25	0.125	0	0	1
30	0	0.375	0.25	81.225953	36.6579731	9.10704985	0.625	0	0	0	0.125	0.25	0	0	1
31	0	0.375	0.375	81.2086292	35.1763262	12.9947395	0.625	0	0	0	0	0.375	0	5.55E-17	1
32	0	0.375	0.5	79.1281418	32.935543	32.1062448	0.5	0.125	0	0	0	0.375	0	0	2
33	0	0.375	0.625	77.0476545	30.6947597	51.2177502	0.375	0.25	0	0	0	0.375	0	0	2
34	0	0.375	0.75	74.9671671	28.4539765	70.3292556	0.25	0.375	0	0	0	0.375	0	0	2
35	0	0.375	0.875	72.8866797	26.2131932	89.440761	0.125	0.5	0	0	0	0.375	0	0	2
36	0	0.375	1	70.8061924	23.9724099	108.552266	0	0.625	0	0	0	0.375	0	0	2
37	0	0.5	0	69.6808007	52.828356	1.77556077	0.5	0	0	0	0.5	0	0	0	1
38	0	0.5	0.125	69.6634769	51.3467091	5.66325041	0.5	0	0	0	0.375	0.125	0	0	1
39	0	0.5	0.25	69.6461532	49.8650621	9.55094004	0.5	0	0	0	0.25	0.25	0	0	1
40	0	0.5	0.375	69.6288294	48.3834152	13.4386297	0.5	0	0	0	0.125	0.375	0	0	1
41	0	0.5	0.5	69.6115056	46.9017683	17.3263193	0.5	0	0	0	0	0.5	0	0	1
42	0	0.5	0.625	67.5310182	44.660985	36.4378247	0.375	0.125	0	0	0	0.5	0	0	2
43	0	0.5	0.75	65.4505309	42.4202018	55.54933	0.25	0.25	0	0	0	0.5	0	0	2
44	0	0.5	0.875	63.3700435	40.1794185	74.6608354	0.125	0.375	0	0	0	0.5	0	0	2

Generate sample color patches given YyCxCz value and NPAC

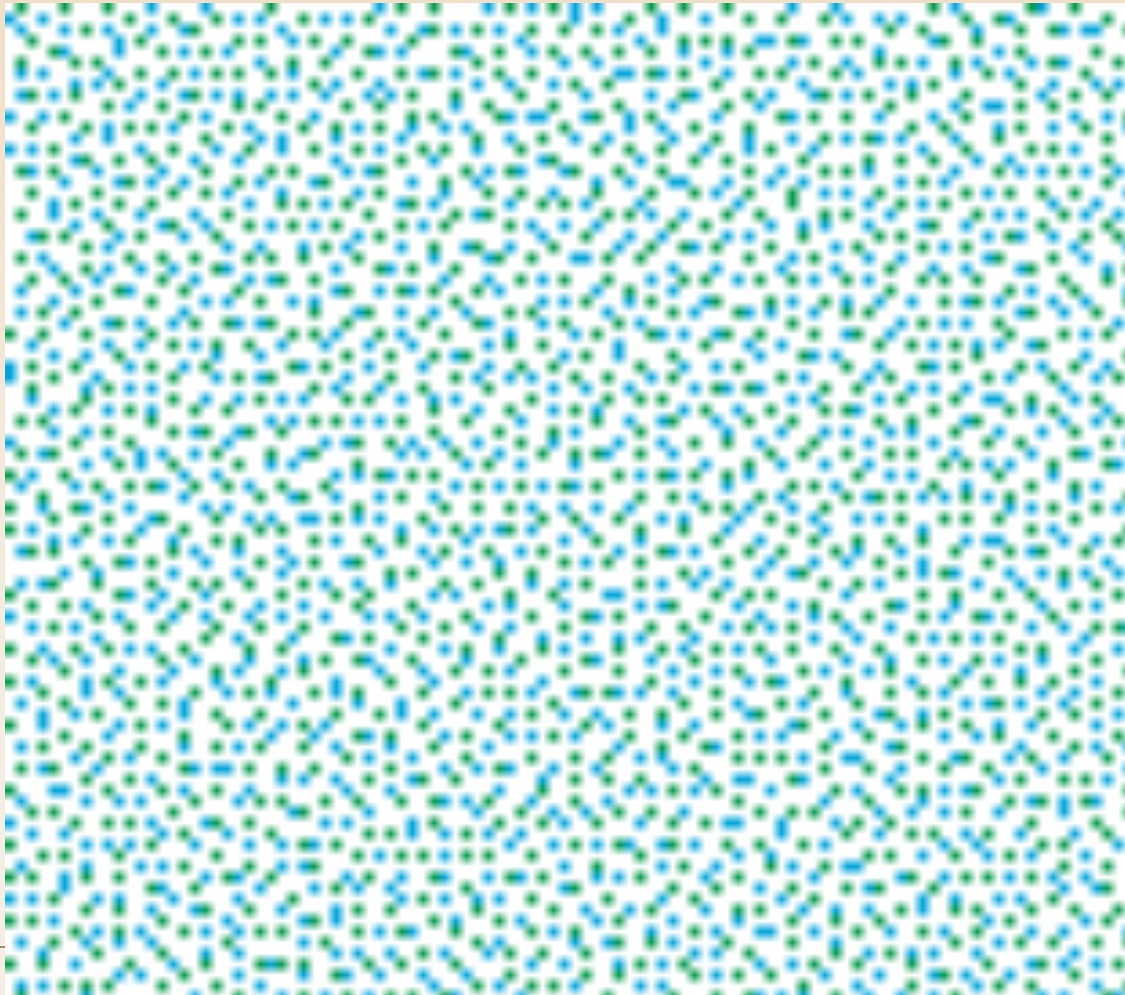
- Use PARAWACS selection matrix to tile over the patch and no overlap
- PARAWACS selection matrix is a matrix with random number from 0-254
- PARAWACS selection matrix size: 255x255
- Patch size: 600x600



For example: 0-254 numbers and
W, C, CY, CMY=(0.75, 0.125, 0.125, 0),
Accumulated NPAC: (0.75, 0.875, 1, 1)
Multiply by 254 and get
(190, 222, 254, 254)
0-190 assigned to White
191-222 assigned to Cyan
223- 254 assigned to CY (Green)
No number assigned to Black

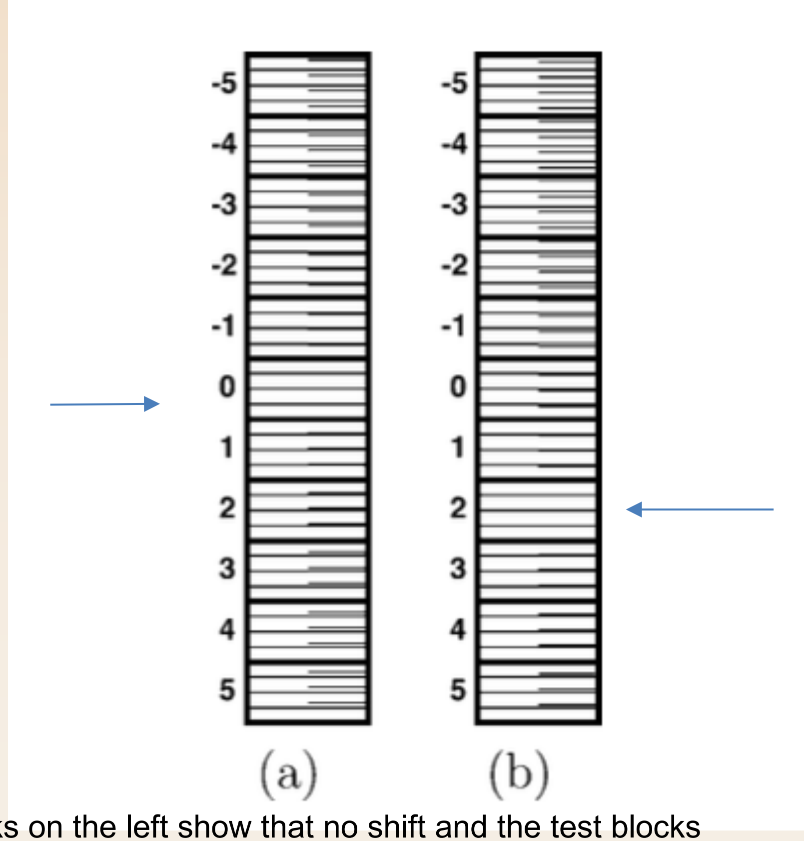
A midtone patch

- A midtone patch example
- NPAC: W-C-CY(Green)-CMY=[0.75, 0.125, 0.125, 0]



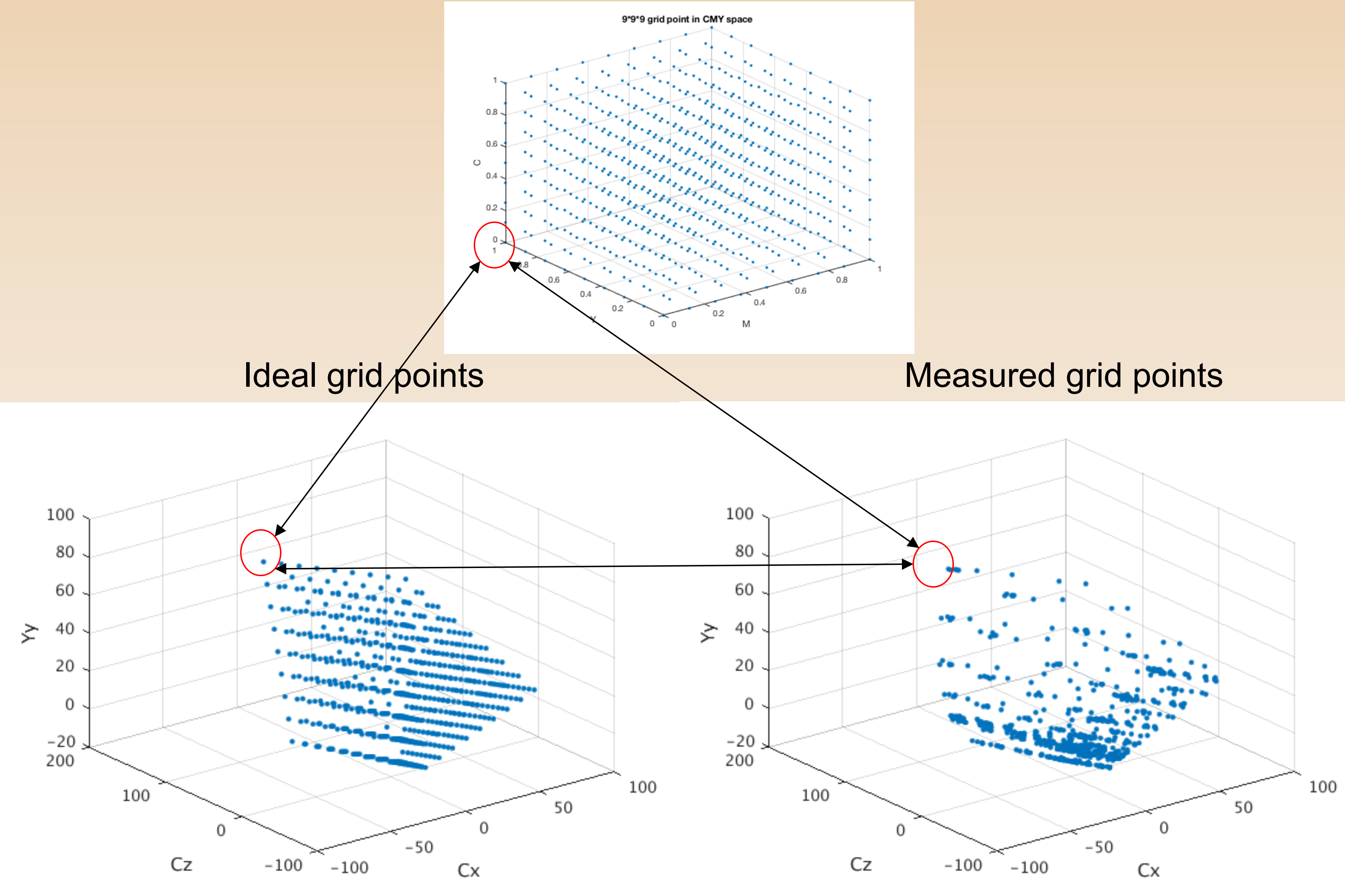
Generate test pages

- Black blocks are registration marks.
- We add Test block for Color Plane Registration(CPR) to find how much each color plane is displaced relative to the magenta color plane.
- One big patch is 600*600, made up by 9 200*200 small patches. We only use center one's XYZ value as this patch's XYZ. Each patch location is randomized and repeated 5 times. There are 44 test pages in total.



The test blocks on the left show that no shift and the test blocks on the right show that there is a 2 pixels shift.

Ideal and Measured grid points



Current inverse mapping (Measured)

- In CMY space, every grid point has a YyCxCz value. (Forward Mapping)
- In YyCxCz space, each grid point has a CMY, and an NPAC value, but we are not using CMY combinations.
- We use this mapping to generate PARAWACS Halftone.

65*65*65 grid points table

Interpolated based on measured data (Yy, Cx, Cz)

From ideal 65*65*65 grid points (W, Y, C, CY, M, MY, CM, CMY)

Index	Yy	Cx	Cz	W	Y	C	CY	M	MY	CM	CMY	Index of Tetrah
1	116	0	0	1	0	0	0	0	0	0	0	1
2	115.578346	-1.0857135	5.15721398	0.96875	0.03125	0	0	0	0	0	1.11E-16	2
3	115.156692	-2.1714269	10.314428	0.9375	0.0625	0	0	0	0	0	0	2
4	114.735038	-3.2571404	15.4716419	0.90625	0.09375	0	0	0	0	0	1.25E-16	2
5	114.313383	-4.3428538	20.6288559	0.875	0.125	0	0	0	0	0	1.11E-16	2
6	113.460923	-6.0239357	30.5121487	0.84375	0.15625	0	0	0	0	0	0	2
7	112.608462	-7.7050176	40.3954414	0.8125	0.1875	0	0	0	0	0	1.39E-16	2
8	111.756002	-9.3860995	50.2787342	0.78125	0.21875	0	0	0	0	0	2.78E-17	2
9	110.903541	-11.067181	60.162027	0.75	0.25	0	0	0	0	0	1.11E-16	2
10	109.915759	-12.426791	69.6597096	0.71875	0.28125	0	0	0	0	0	0	2
11	108.927977	-13.786401	79.1573923	0.6875	0.3125	0	0	0	0	0	1.11E-16	2
12	107.940195	-15.146011	88.655075	0.65625	0.34375	0	0	0	0	0	1.67E-16	2
13	106.952413	-16.505621	98.1527576	0.625	0.375	0	0	0	0	0	5.55E-17	2
14	106.18886	-17.490681	105.139621	0.59375	0.40625	0	0	0	0	0	5.55E-17	2
15	105.425306	-18.475741	112.126485	0.5625	0.4375	0	0	0	0	0	5.55E-17	2
16	104.661752	-19.460801	119.113349	0.53125	0.46875	0	0	0	0	0	1.11E-16	2
17	103.898199	-20.445861	126.100213	0.5	0.5	0	0	0	0	0	0	2
18	103.883817	-20.657316	127.010595	0.46875	0.53125	0	0	0	0	0	1.11E-16	2
19	103.869435	-20.868771	127.920978	0.4375	0.5625	0	0	0	0	0	0	2

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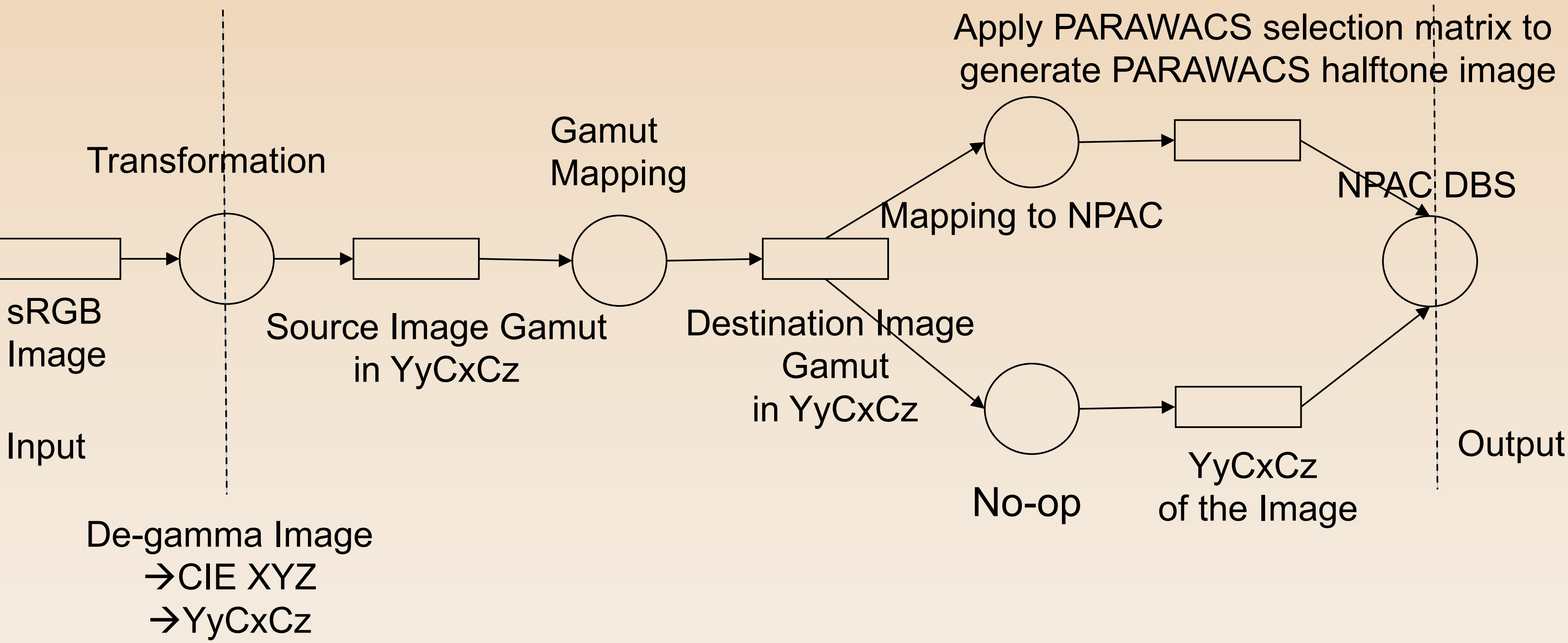
Color Management Block Diagram

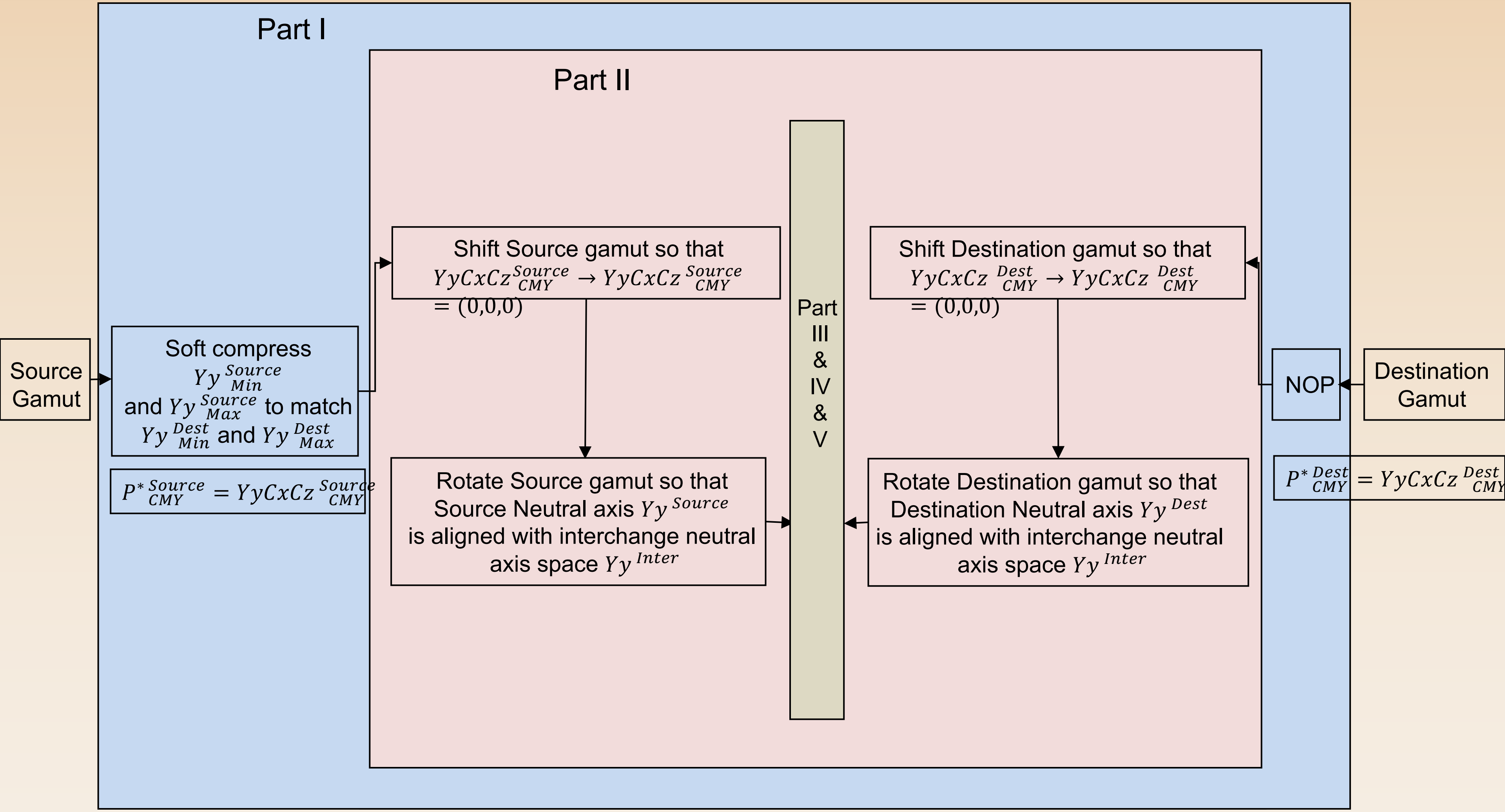


Source Image Gamut is all unique YyCxCz pixel values from an image (Remove repeated pixel values).
Destination Image Gamut means all unique pixel values in an image are mapped into Indigo Gamut.
Indigo Gamut is a set of 9*9*9 grid points that describe Indigo gamut.

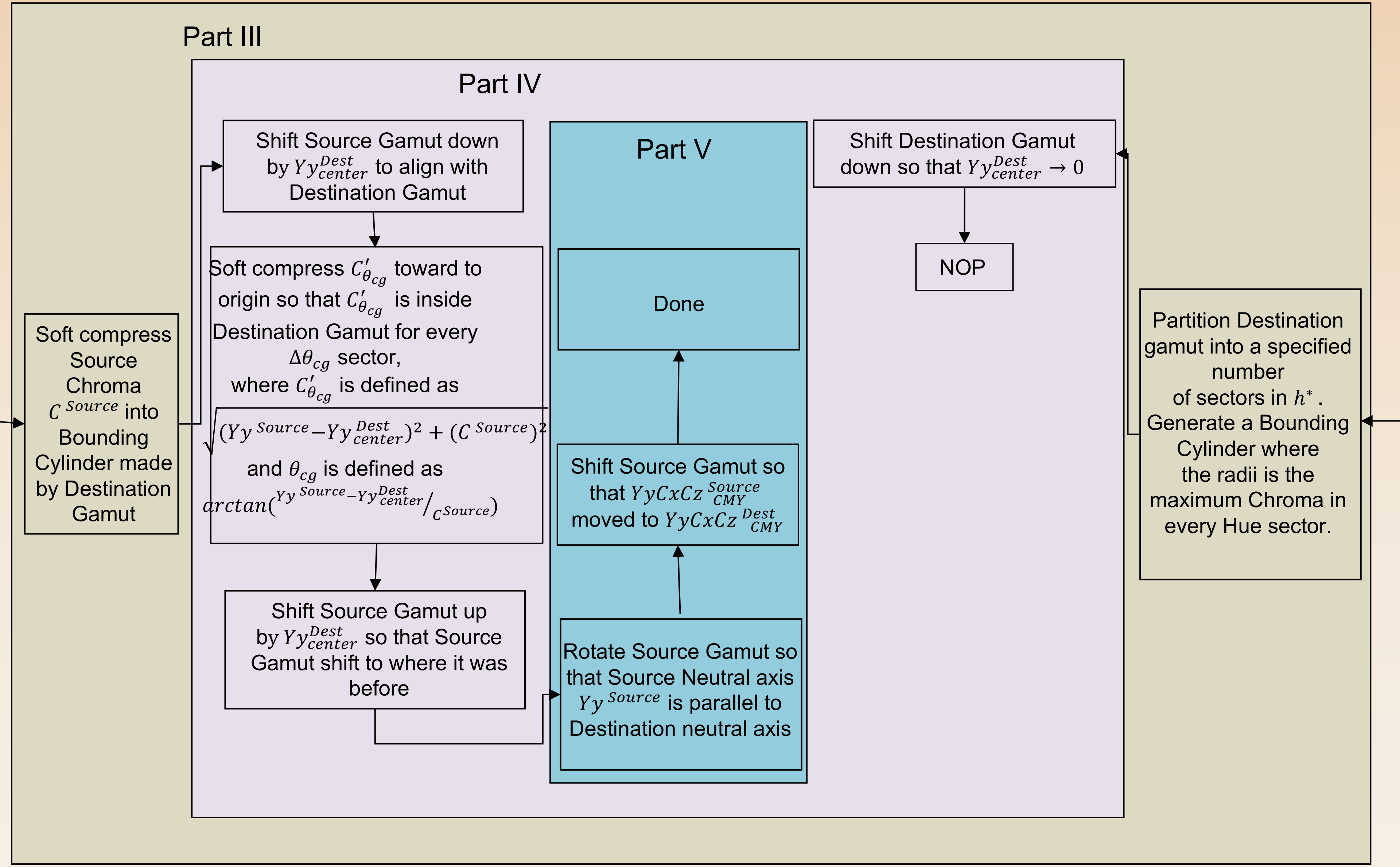
Gamut mapping
Goal

- Due to color gamut mismatch between display and print, gamut mapping is needed to display and print with a satisfactory level of visual quality.
- The case we focus on is that some input colors are not realizable at the output printing system.
- We did gamut mapping in YyCxCz space
- Our method was based on two papers:
  - » R. S. Gentile, E. Walowit, and J. P. Allebach, “A Comparison of Techniques for Color Gamut Mismatch Compensation”, Journal of Imaging Technology Volume 16, Number 5, October 1990
  - » M. Wolski, J. P. Allebach and C. A. Bouman, “Gamut Mapping Squeezing the Most out of Your Color System”, IS&T and SID’s 2nd Color Imaging Conference: Color Science, System and Application (1994)-89

Flowchart of Gamut Mapping I



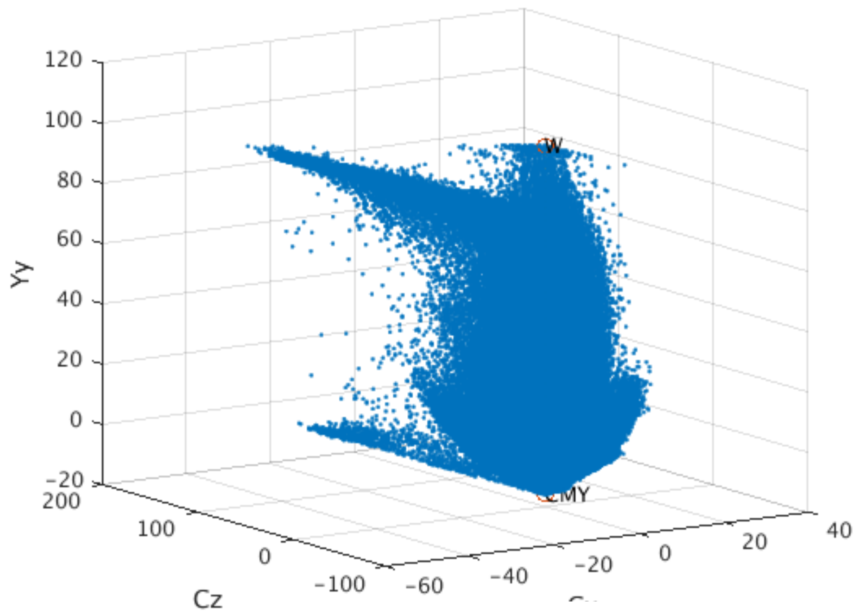
Flowchart of Gamut Mapping II



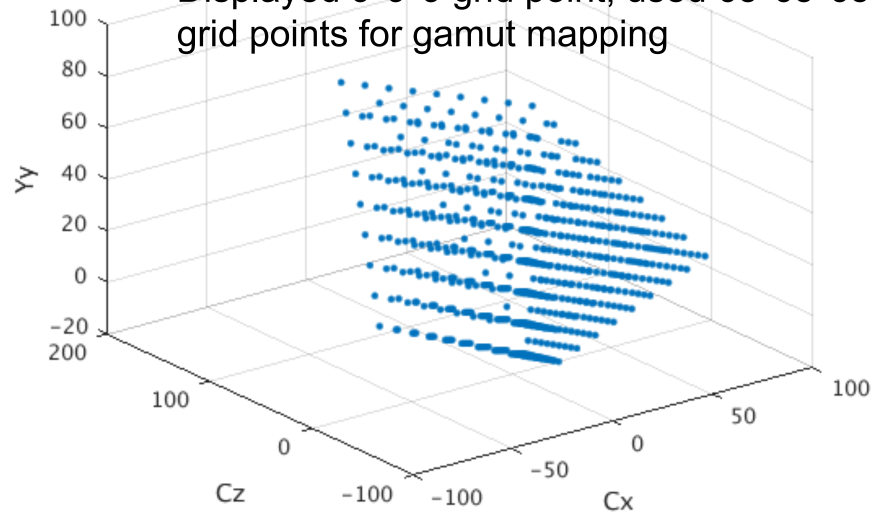
Every hue angle=5°

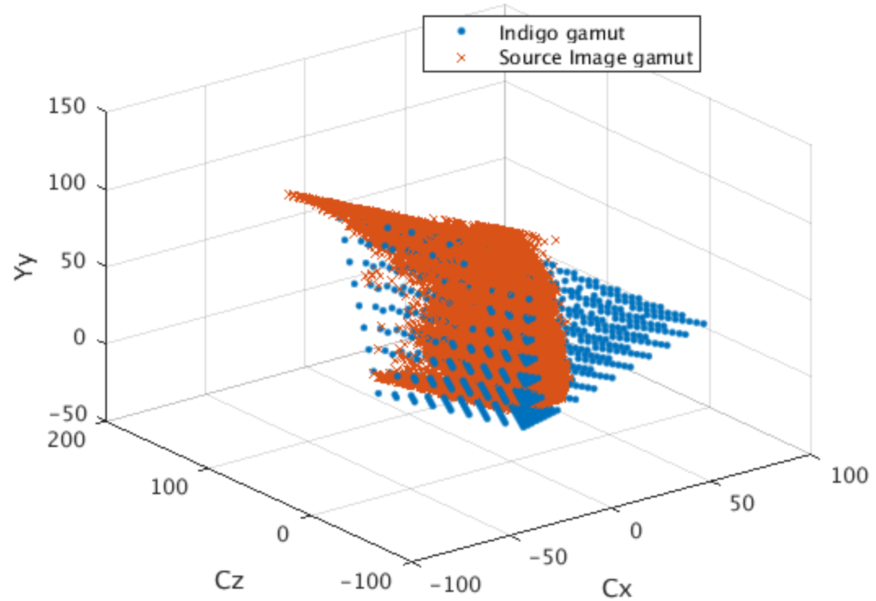
Input Image (source)

Source Image Gamut and Ideal Destination Gamut

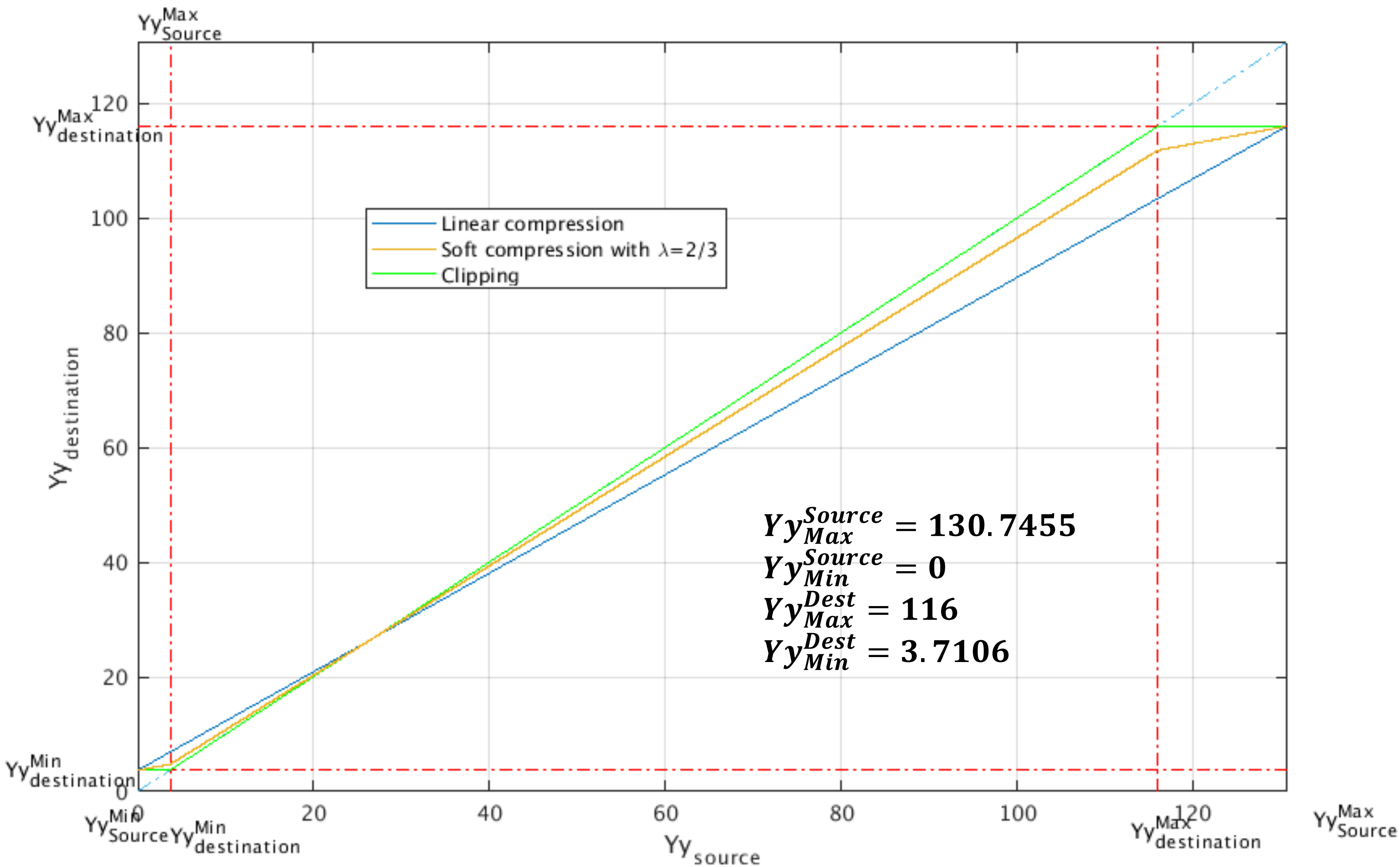


All data was theoretical value,
but 8 NPs are measured data
Displayed 9*9*9 grid point, used 65*65*65 grid points for gamut mapping



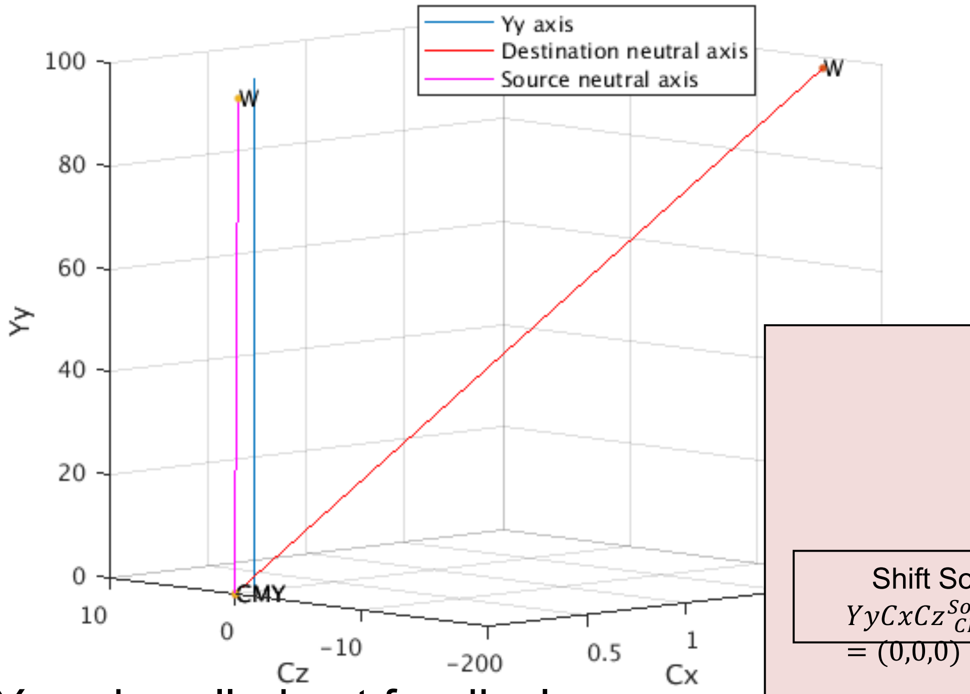


Gamut mapping procedure (Part I) (Soft compression of lightness)



$$Yy^{Source}_{Max} = 130.7455$$
$$Yy^{Source}_{Min} = 0$$
$$Yy^{Dest}_{Max} = 116$$
$$Yy^{Dest}_{Min} = 3.7106$$

After shift to origin



Yy axis pulled out for display

Part II

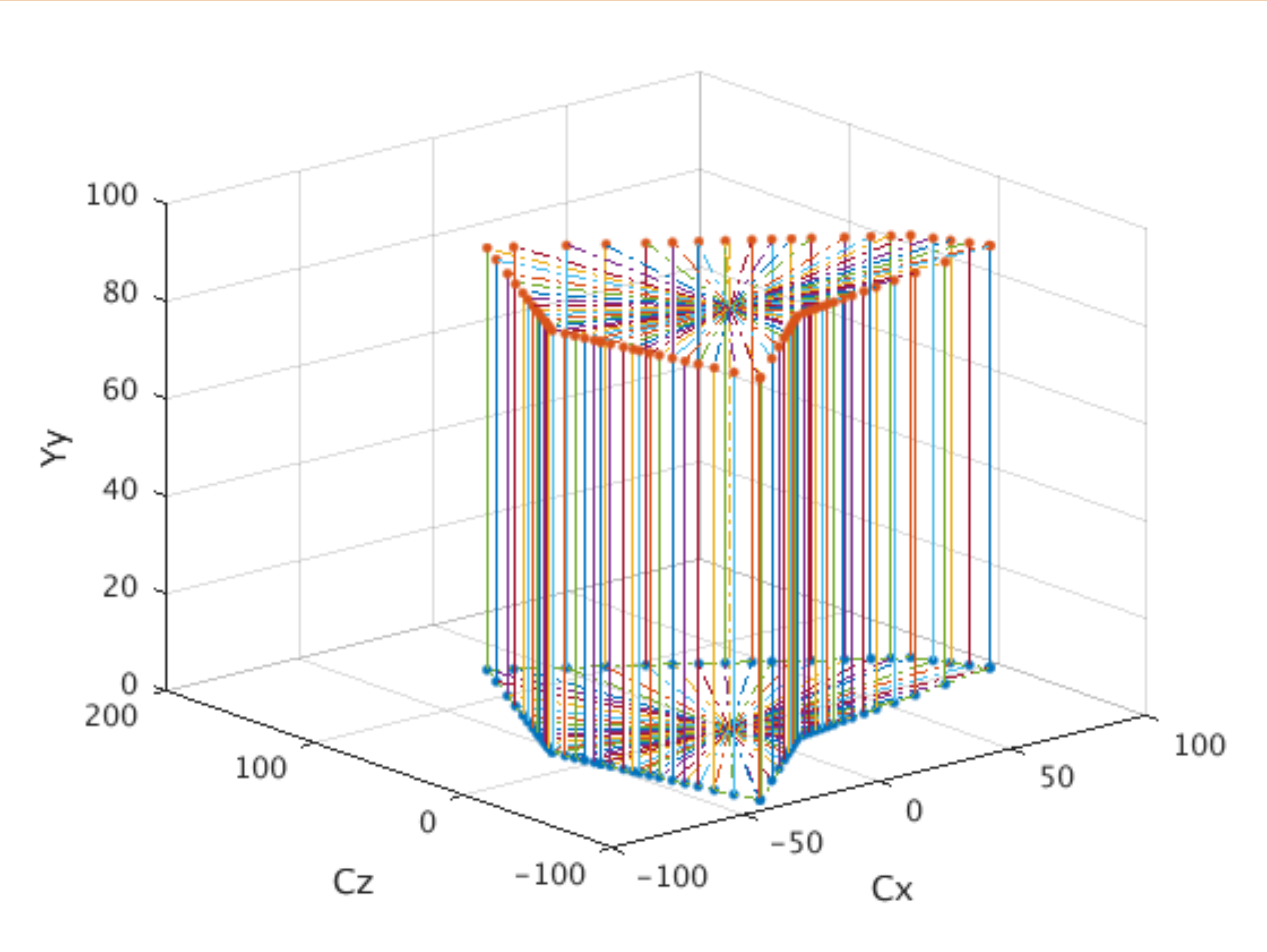
Shift Source gamut so that $YyCxCz^{Source}_{CMY} \rightarrow YyCxCz^{Source}_{CMY} = (0,0,0)$

Shift Destination gamut so that $YyCxCz^{Dest}_{CMY} \rightarrow YyCxCz^{Dest}_{CMY} = (0,0,0)$

Rotate Source gamut so that Source Neutral axis Yy^{Source} is aligned with interchange neutral axis space Yy^{Inter}

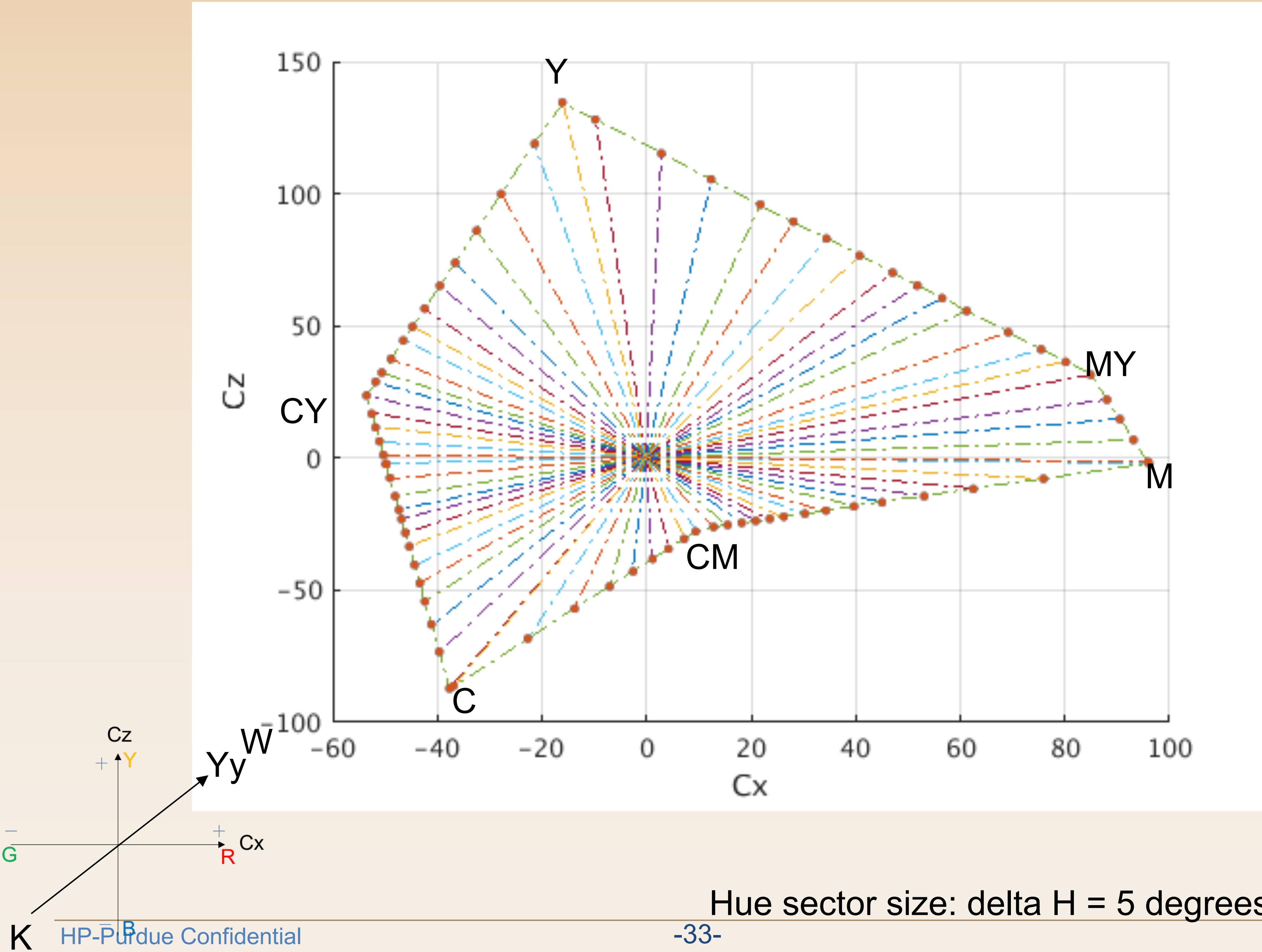
Rotate Destination gamut so that Destination Neutral axis Yy^{Dest} is aligned with interchange neutral axis space Yy^{Inter}

Destination Gamut Bounding Cylinder (perspective view)



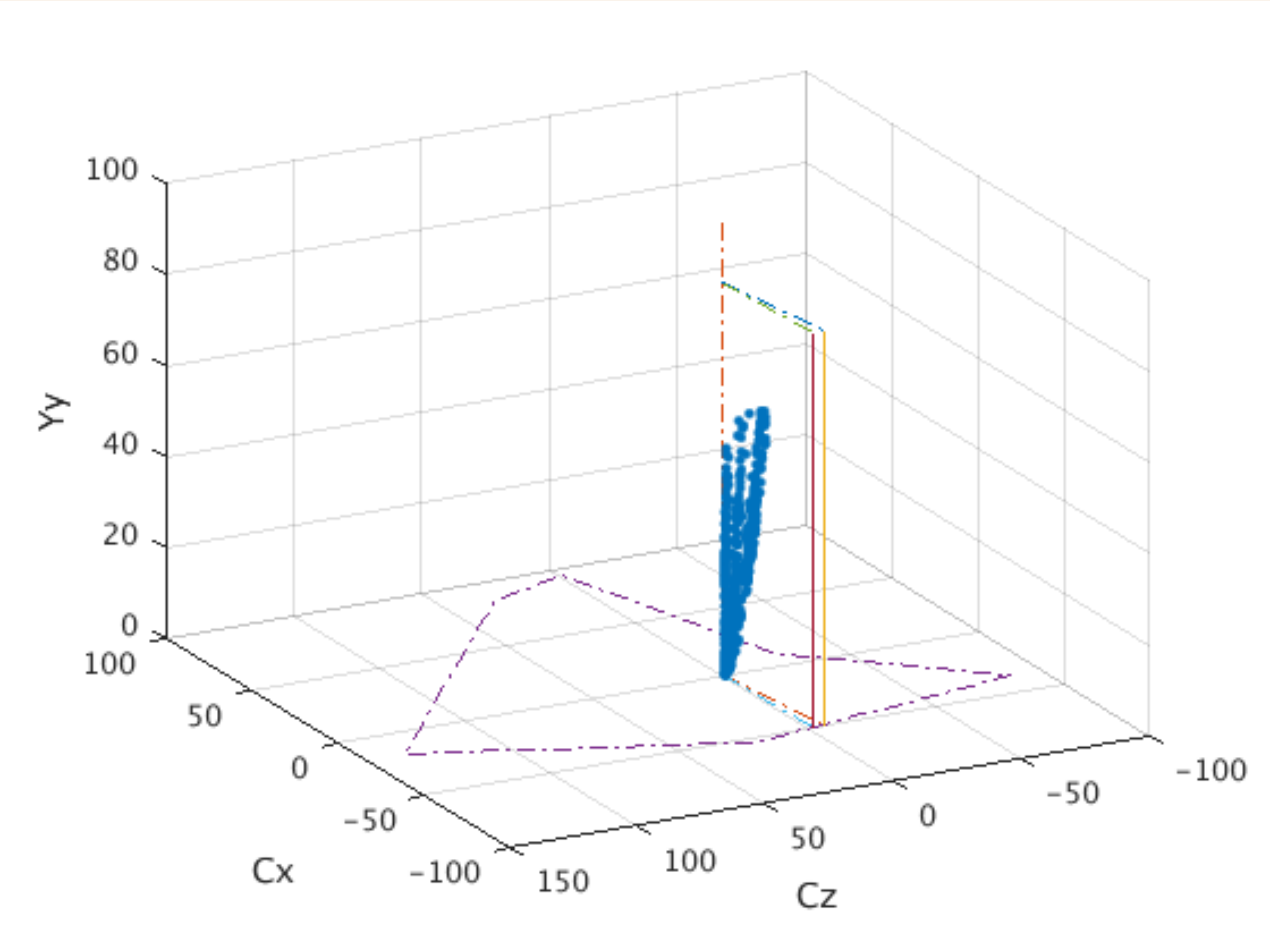
Hue sector size: delta H = 5 degrees

Destination Gamut Bounding Cylinder (Top view)

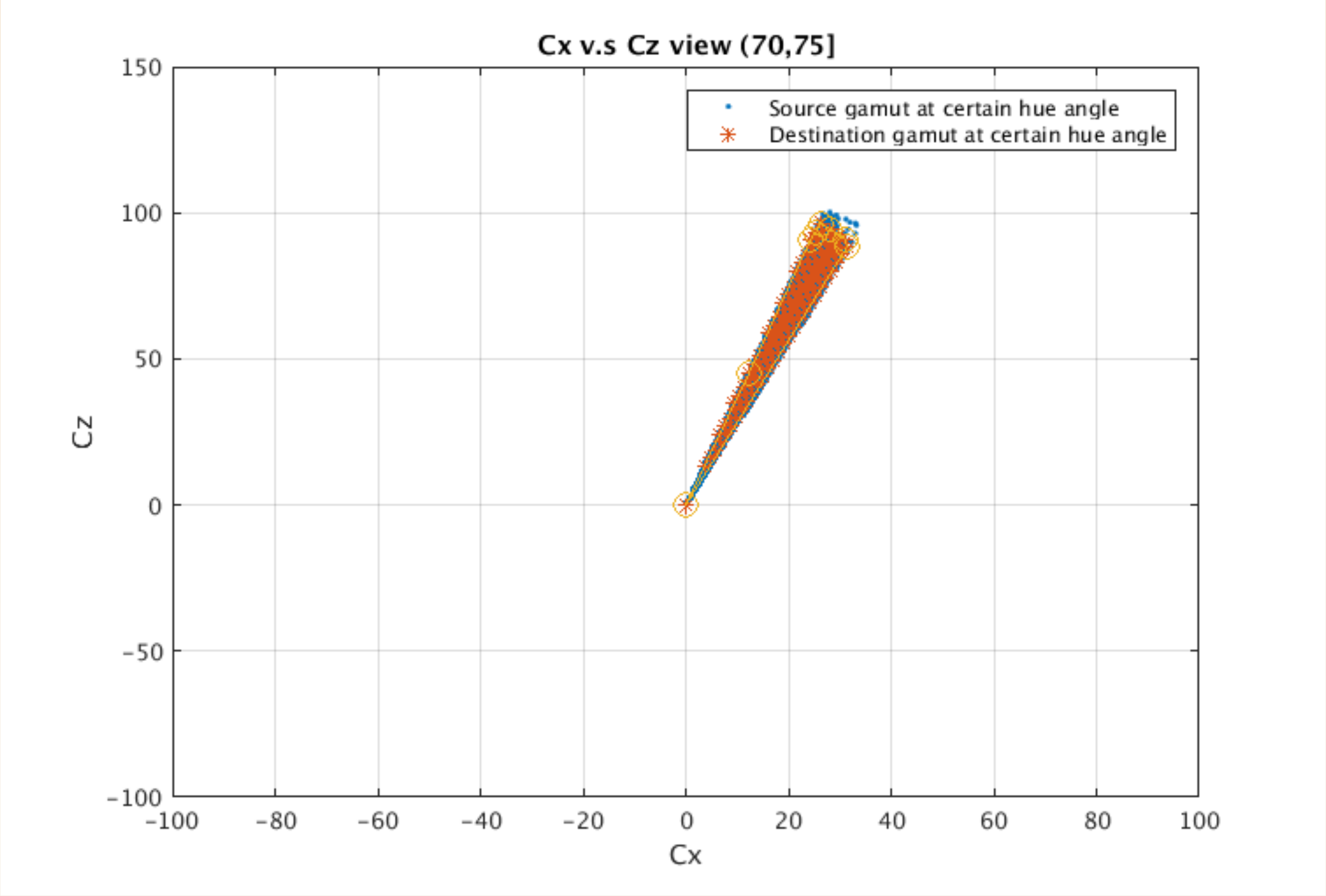


Hue sector size: delta H = 5 degrees

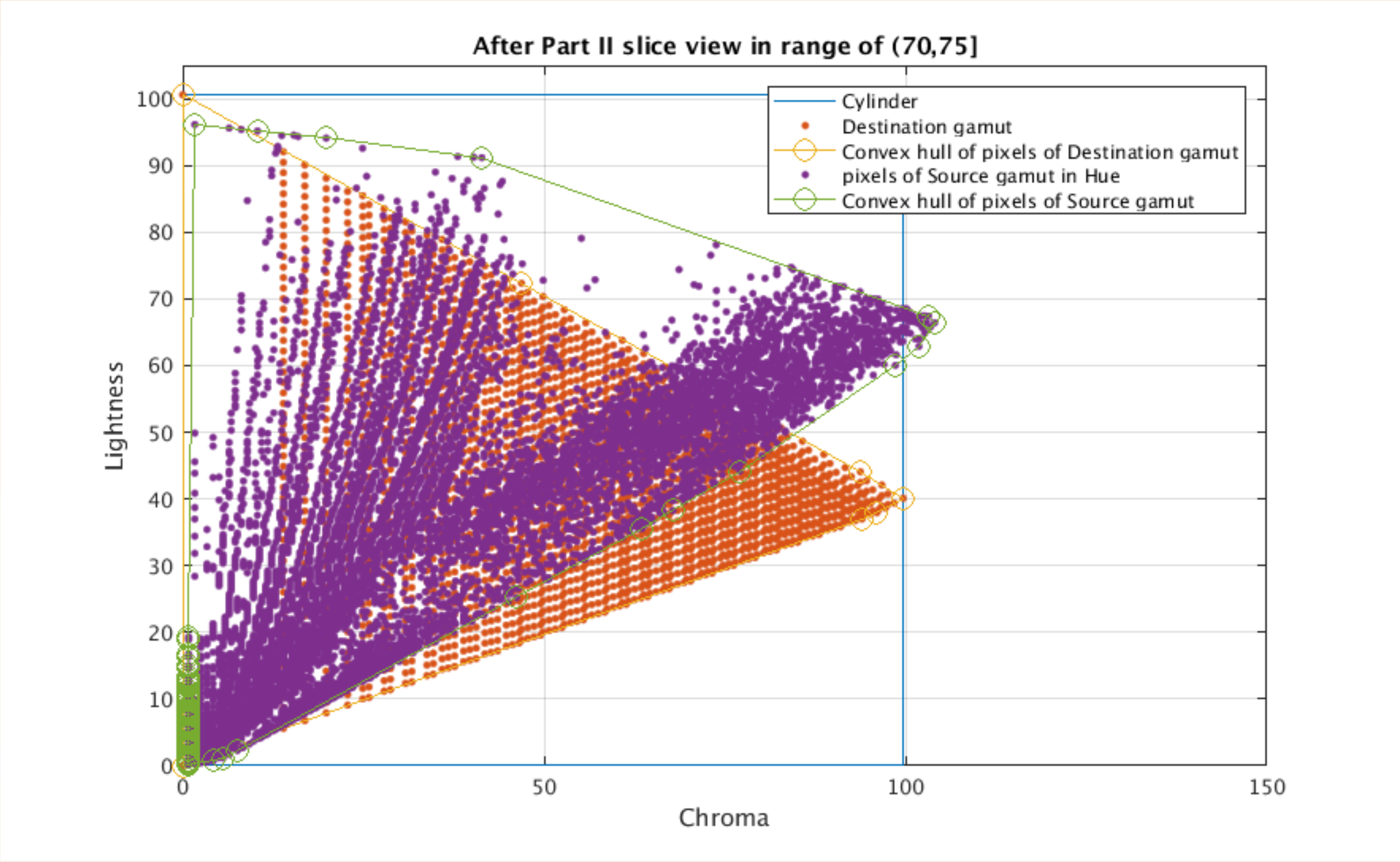
A hue sector



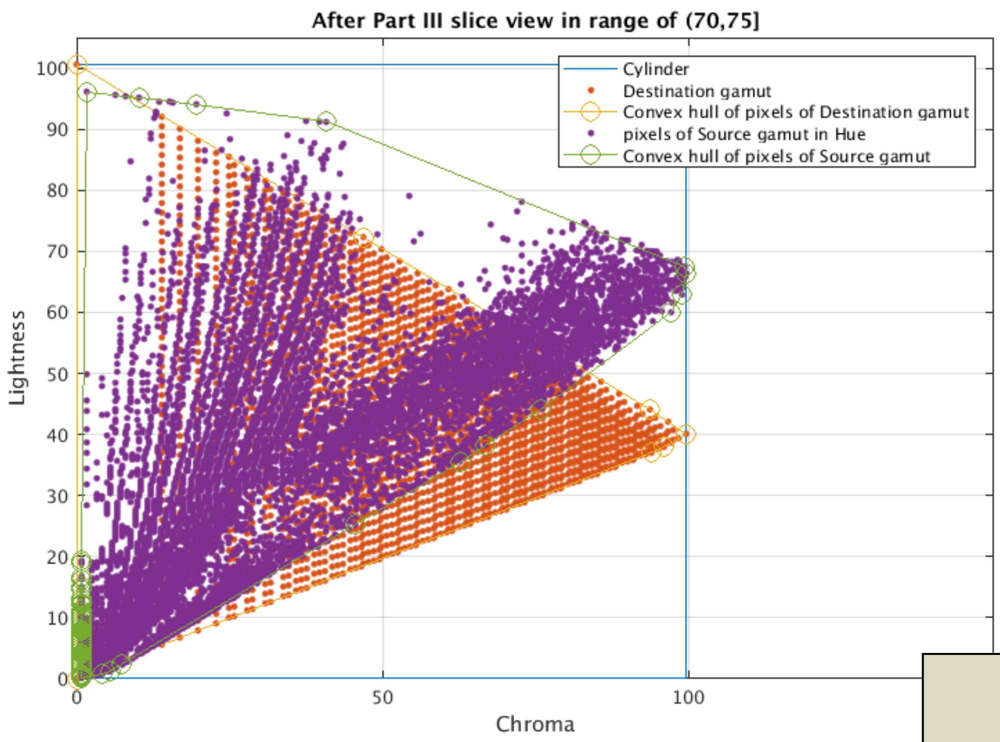
Cx vs Cz view where Hue=(70,75] in degree



Hue sector view where Hue=(70,75] in degree



After Part III compress with $\lambda = {}^{2}/_{3}$

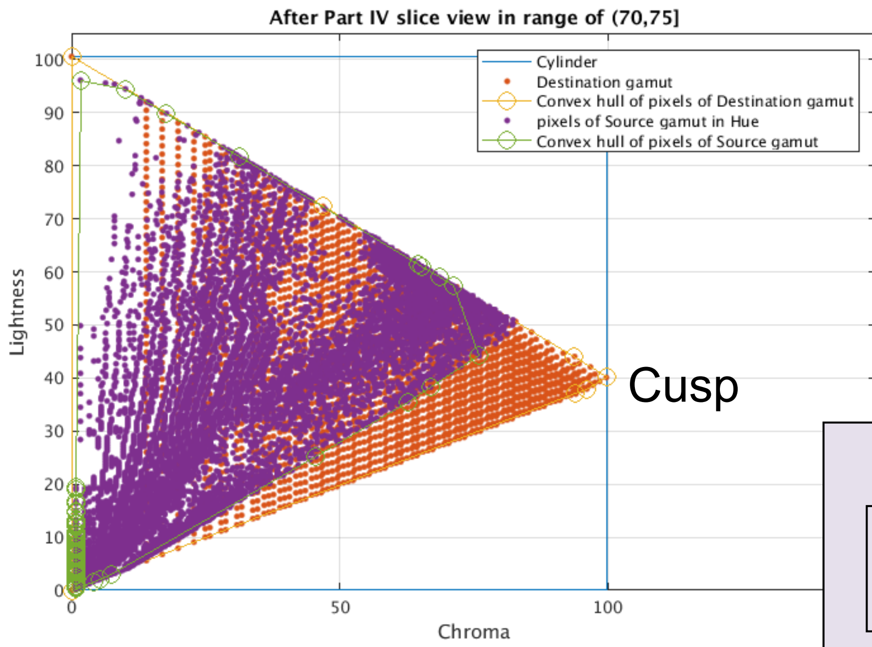


Part III

Soft compress Source Chroma C^{Source} into Bounding Cylinder made by Destination Gamut

Partition Destination gamut into a specified number of sectors in h^*. Generate a Bounding Cylinder where the radii is the maximum Chroma in every Hue sector.

After Part IV compress with $\lambda = {}^{2}/_{3}$



Part IV

Shift Source Gamut down by Yy^{Dest}_{center} to align with Destination Gamut

↓

Soft compress $C'_{\theta_{cg}}$ toward to origin so that $C'_{\theta_{cg}}$ is inside Destination Gamut for every $\Delta\theta_{cg}$ sector, where $C'_{\theta_{cg}}$ is defined as

$$\sqrt{(Yy^{Source} - Yy^{Dest}_{center})^2 + (C^{Source})^2}$$

and θ_{cg} is defined as

$$arctan\left({}^{Yy^{Source} - Yy^{Dest}_{center}}/_{C^{Source}}\right)$$

↓

Shift Source Gamut up by Yy^{Dest}_{center} so that Source Gamut shift to where it was before

Shift Destination Gamut down so that $Yy^{Dest}_{center} \rightarrow 0$

↓

NOP

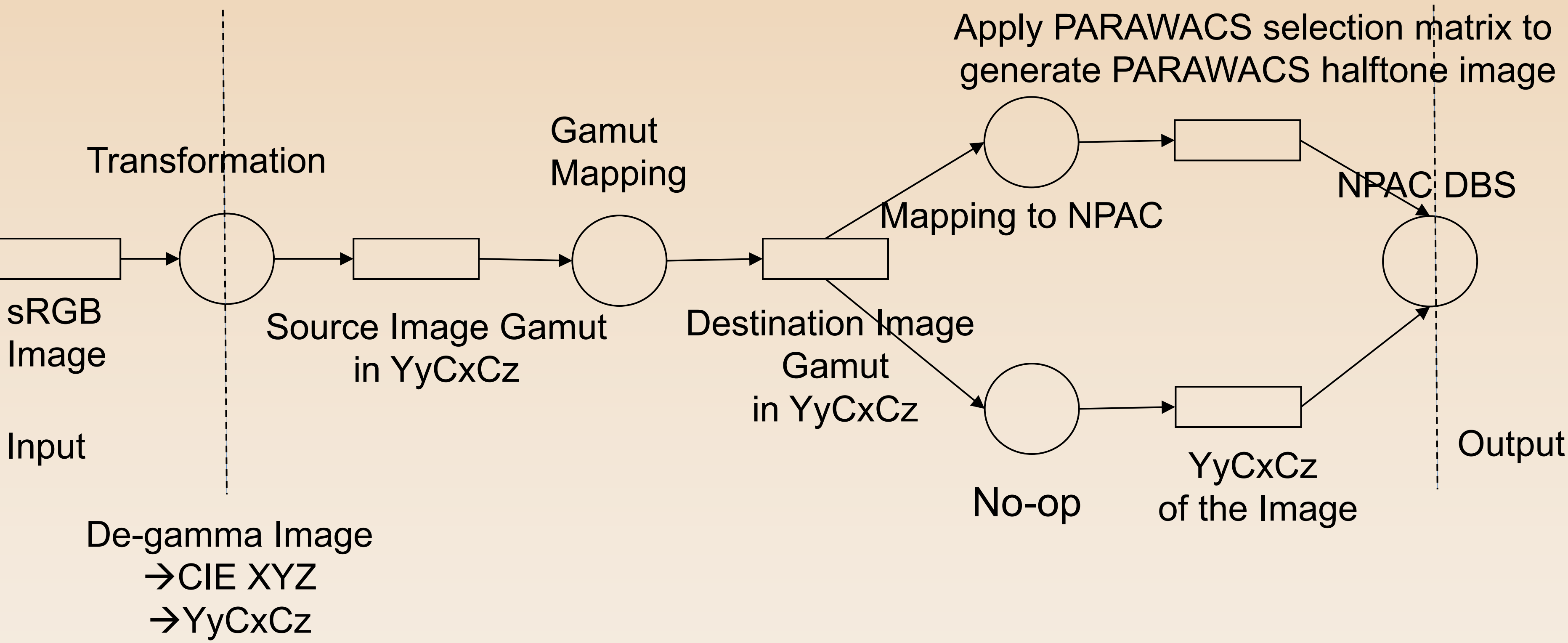
Compared with Original Image

Original Image →

Synopsis

- Overview of color imaging pipeline for NPAC halftoning framework
- Characterization and development of inverse mapping based on Indigo 7000 series prints
- New development of Gamut mapping
- PARAWACS halftone

Color Management Block Diagram



Source Image Gamut is all unique YyCxCz pixel values from an image (Remove repeated pixel values).
Destination Image Gamut means all unique pixel values in an image are mapped into Indigo Gamut.
Indigo Gamut is a set of 9*9*9 grid points that describe Indigo gamut.

Procedure to generate PARAWACS halftone based on continuous-tone image

- Procedure:
  - Halftone image applied PARAWACS selection matrix (or called PARAWACS Halftone)
    - After gamut mapping, for every image pixel in (YyCxCz), find one of six tetrahedra contains it.
    - By finding its four nearest neighbors (from inverse mapping 65*65*65 grid points) in that tetrahedron found in previous step, using tetrahedral interpolation to find it's NPAC and multiply NPAC by 254. Calculate accumulated NPAC. Repeat for every pixel.
    - Tile PARAWACS selection matrix over the image. For a pixel in the image, find corresponding value in the PARAWACS selection matrix. It is a number between 0-254. Comparing this number with its NPAC, find the number falls in which one of four NP ranges. Then the corresponding NP number 0-7 will be the halftone image applied PARAWACS selection matrix in a pixel.
    - [W Y C CY M MY CM CMY] → [0 1 2 3 4 5 6 7]
    - An example
      - A pixel's NPAC is (W,M,MY,CMY)=(10%,20%,50%,20%) , the rest of four NPs are 0s.
      - Or represented as (25, 51, 127, 51) or accumulated NPAC (25, 76, 203, 254)
      - If the corresponding PARAWACS selection matrix pixel is 60. And 60 falls in between 25 and 76.
      - In the halftone applied PARAWACS selection matrix, the number correspond should be M.

Continuous-tone Image after Gamut mapping

PARAWACS Halftone

Continuous-tone

Parawacs Halftone

Continuous-tone

Parawacs Halftone

Continuous-tone

Parawacs Halftone

THANK YOU!