Characterizing a Filter-based Multispectral Camera using iccMax Profiles

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Introduction

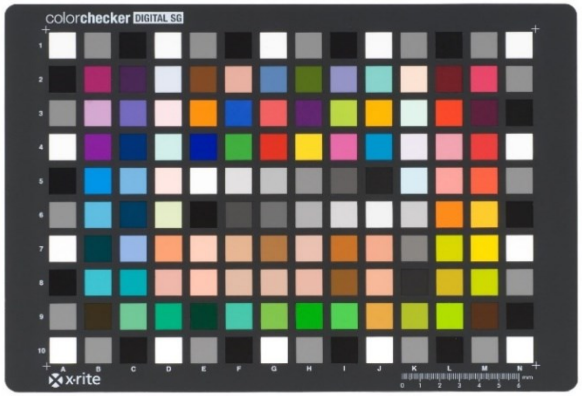
- Multispectral imaging technology is now widespread in all fields such as medical imaging, forensic science, industrial inspection, remote sensing, digital archives and so on.
- As more and more cost effective multispectral imaging devices are available and ICC is currently working on iccMAX for connecting the spectral images with perceptual colors .
- It is the time to study how accurate the new ICC system can be used for spectral imaging.

iccMax

- A new color management system
  1. **Go beyond D50 colorimetry**
  2. Enable new ways of communicating about light, color, and appearance
  3. **Spectral processing** :
     Use spectrally based Profile Connection Spaces (PCSs)
  4. Extended color metrology:
     Supporting for **bi-spectral and multi-angle measurement and processing**

Pixelteq SpectroCam VIS-NIR

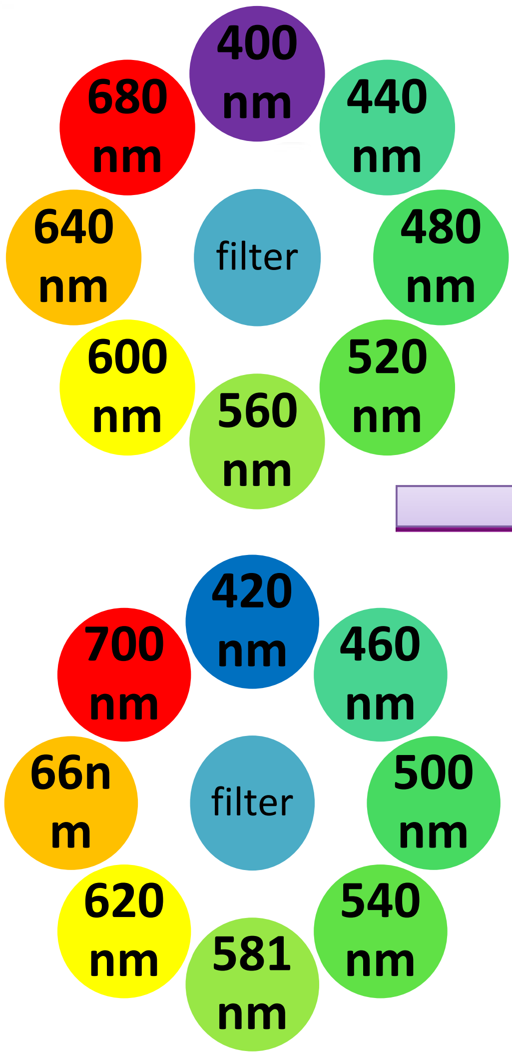
The Macbeth Spectra Light III light booth

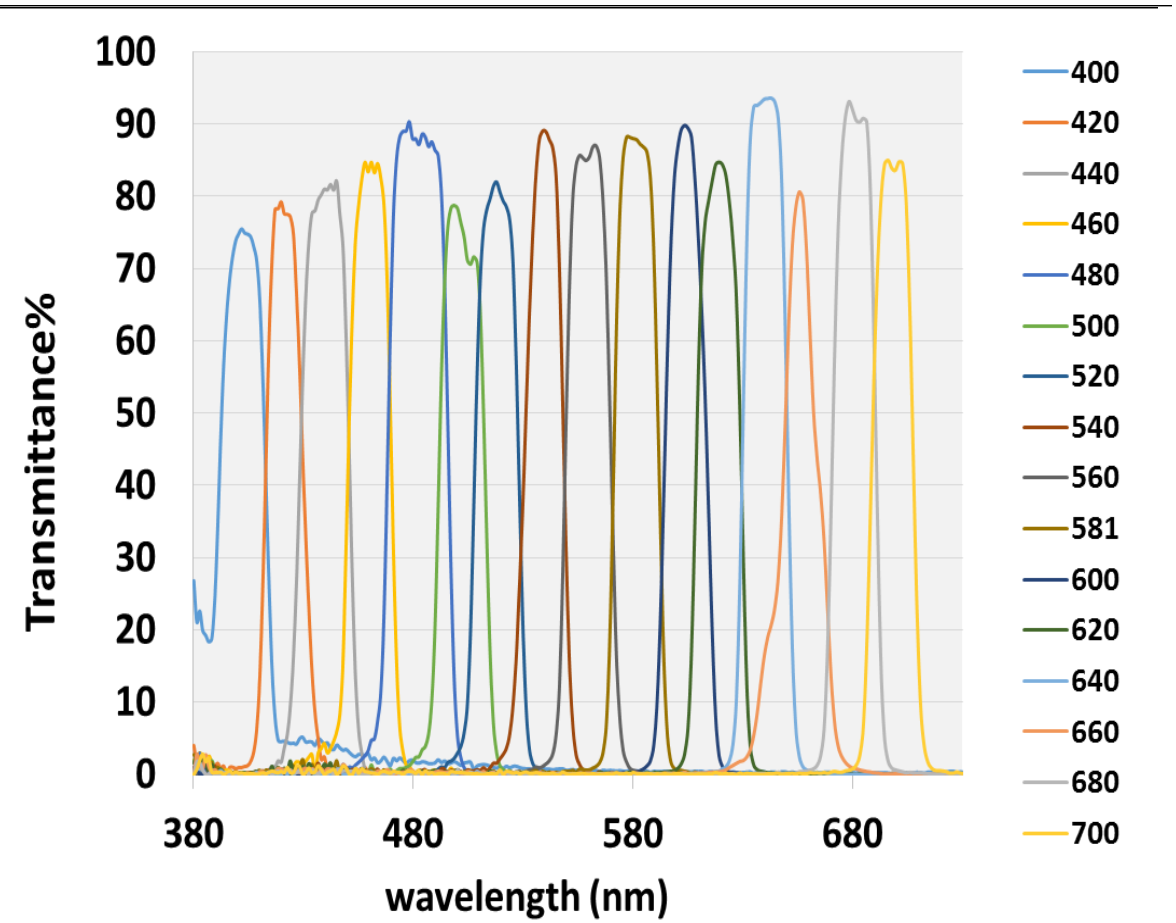


The X-rite Colorchecker SG chart

From left to right: the X-rite Colorchecker SG chart, the Macbeth Spectra Light III light booth, and the Pixelteq SpectroCam VIS-NIR.

Spectral filter





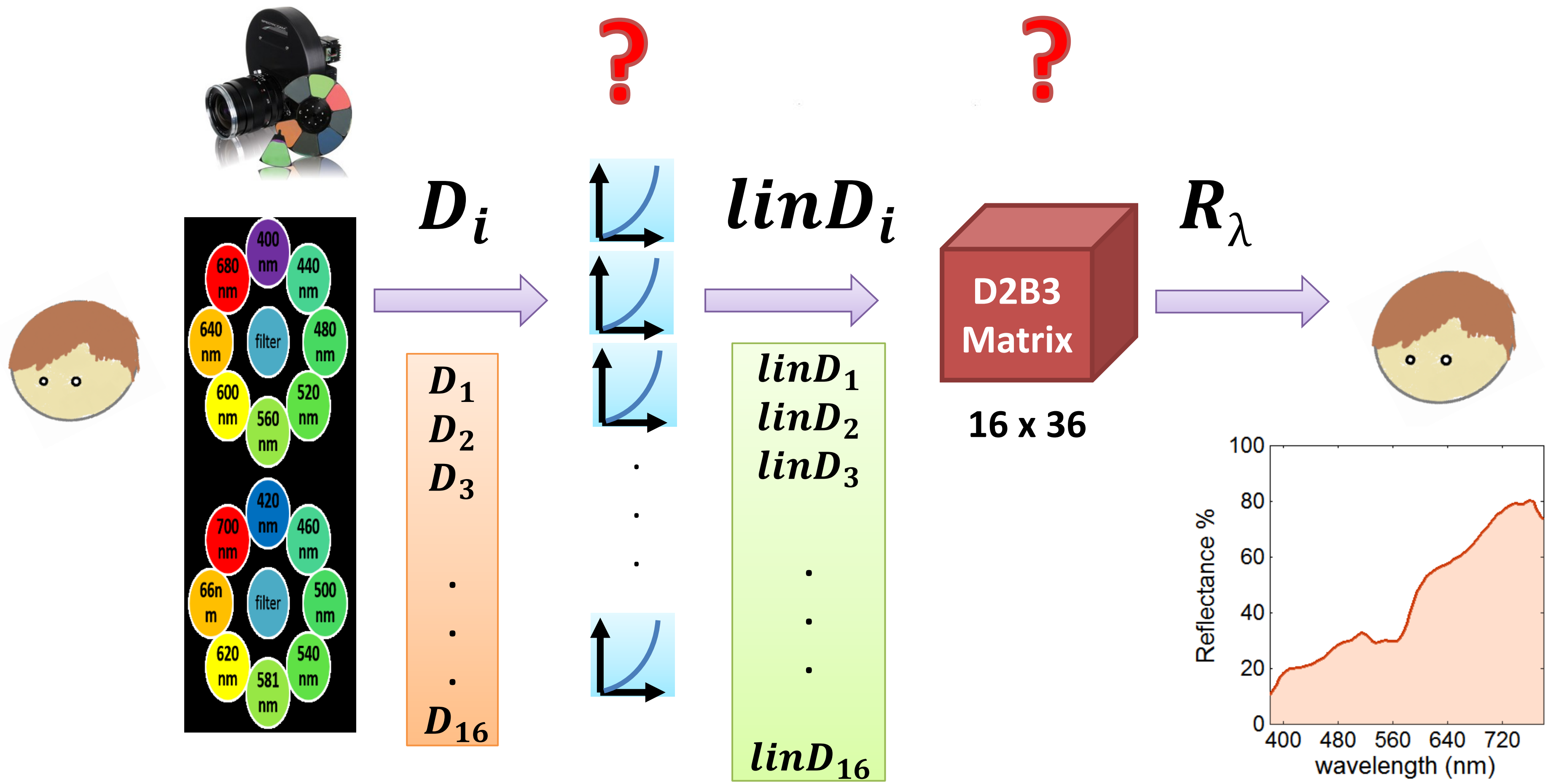
Spectral transmittances

ICC Max D2B3 profile

- D2B3: a forward transform from device space (denoted as **D**) to SpectralPCS (denoted as **B**), '**3**' represents **ICC Absolute Colorimetric** intent.
  - Characterize the color of an imaging device

1. **Tone curves with color mixing matrix**
2. Polynomial regression
3. Color look-up table (CLUT) with interpolation

D2B3 conversion



Tone curve estimation

- To perform tone linearization.
  - ➢ Use **Calculator Elements** to apply gamma, gain and offset to the input signals.

XML expression

```
<MainFunction>
{
in(0,16)
2.2 gamma(16)
mtx(0)
out(0,36)
}
</MainFunction>
```

Use a gamma operator to transform input signals.

- **The main function also can operate input signals of each channel individually.**
- ***It is not suitable*** **for a multispectral camera with complex tone characteristics.**

Tone curve estimation

- To perform tone linearization.
  - **SegmentedCurve** is recommended.

1. SampledSegment : uses a 1D look-up-table
   make the profile bulky
2. **FormulaSegment**: uses predetermined **parameters**

Tone curve estimation

- FormulaSegment : iccMAX provides 4 function types

- D_i: the input camera signal
- $linD_i$: the linearized camera signal
- γ,a,b,c,d: parameters of the tone function

$$linD_i = (a \cdot D_i + b)^{\gamma} + c \quad (1)$$

$$linD_i = a \cdot \log\left(b \cdot D_i^{\gamma} + c\right) + d \quad (2)$$

$$linD_i = a \cdot b^{c \cdot D_i + d} + e \quad (3)$$

$$linD_i = a \cdot \left(b \cdot D_i + c\right)^{\gamma} + d \quad (4)$$

Tone curve estimation

- **Three FormulaSegments** to construct a SegmentedCurve.

XML expression

```
<SegmentedCurve>
    <FormulaSegment Start="-inf" End="0.0" FunctionType="0">1.0 0.0 0.0 0.0
    </FormulaSegment>
    <FormulaSegment Start="0" End="1.0" FunctionType="0"> γ a b c
    </FormulaSegment>
    <FormulaSegment Start="1.0" End="+inf" FunctionType="0">1.0 0.0 0.0 1.0
    </FormulaSegment>
</SegmentedCurve>
```

Tone curve estimation

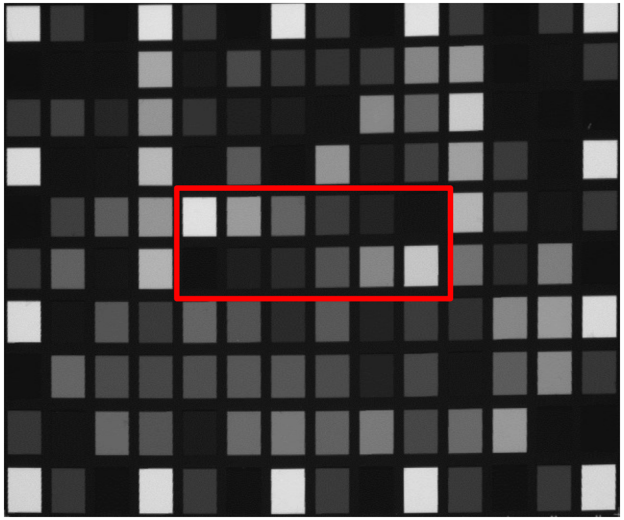
- Estimating the parameters of the Equation 1

$$linD_i = (a \cdot D_i + b)^{\gamma} + c$$

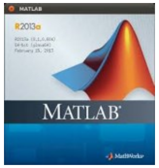
1. Turn on the light booth (illuminant A) and the spectral camera. The f-stop was 5.6. The lighting/measuring geometry is set as 0/45 to eliminate specular reflection.

2. Take and store the spectral photos in 12-bit PNG format.

Tone curve estimation

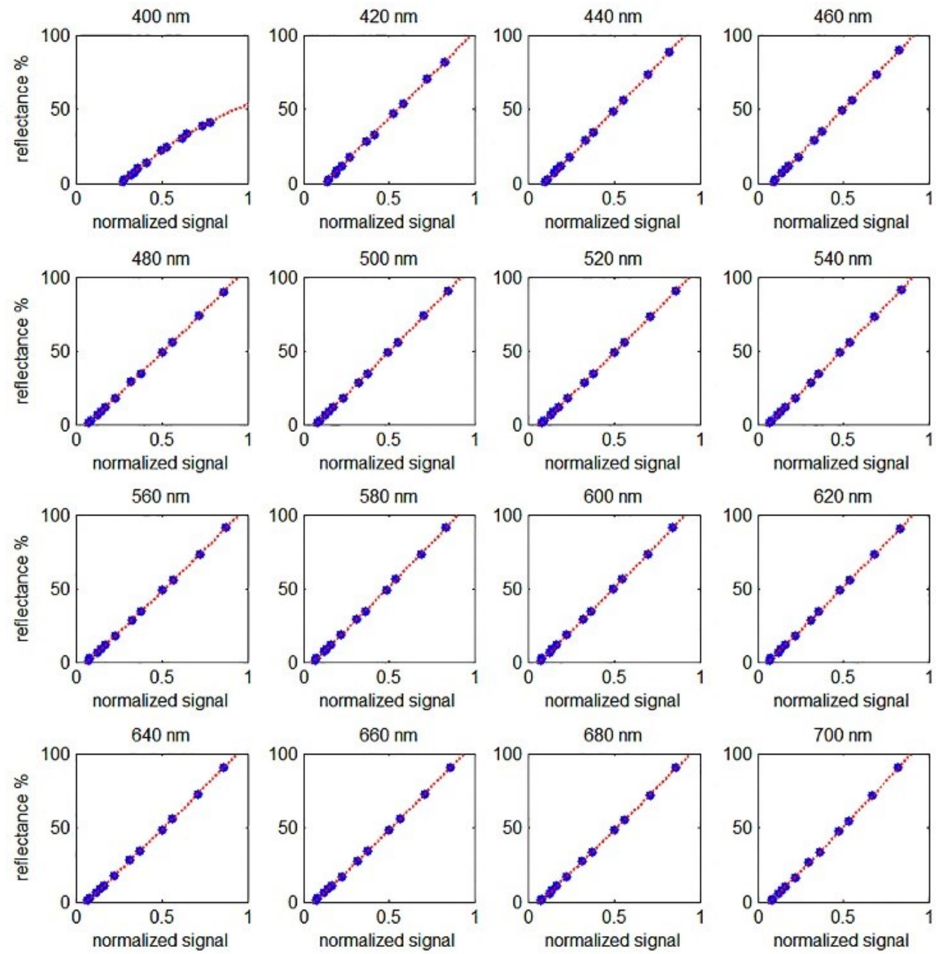


3. Read the 12-level grayscale .
4. Normalize the gray level into [0 1] range and average the center pixel values of each patch. The resulted input signal denotes as D_i.
5. Use pre-measured spectral reflectance of the 12 grayscale patches. Interpolate into the 16 wavebands as target $linD_i$
6. Apply least squared curve fitting using a Matlab function (**lsqcurvefit**).



Tone curve estimation

- The mean values of ***gamma***, ***a*** and ***c***, except the unusually 400nm tone curve, are **1.04**, **1.16** and **-0.07**, respectively.



Least squared curve fitting using Equation 1 with 12 grayscales of the SG chart in 16 channels respectively

- **Blue spots:** the reflectance sample points of the 12 grayscale of the 16 channels.
- **Red lines:** added a constraint (b= 0)

Derive the color mixing matrix

- Convert $linD_i$ to the corresponding spectral reflectances

Pseudo-Inverse of the scaled spectral response functions: Equation(5) is a typical multispectral camera model.

$$linD_i = \sum^{\lambda} E_{\lambda} R_{\lambda} T_{i\lambda} S_{\lambda} \Delta\lambda \qquad (5)$$

- E_{λ}: spectral radiance of the light source
- R_{λ}: spectral reflectance of an object
- $T_{i\lambda}$: the spectral transmittance of the i-th filter
- S_{λ}: the spectral sensitivity of the monochromatic CCD sensor

Derive the color mixing

- If the linear camera signal $linD_i$ matchs the spectral R_λ, both of them can be cancelled out as Equation(6).

$$1 = \left(\overline{E}_\lambda \cdot \overline{S}_\lambda\right)\sum^{\lambda} T_{i\lambda}\Delta\lambda \qquad (6)$$

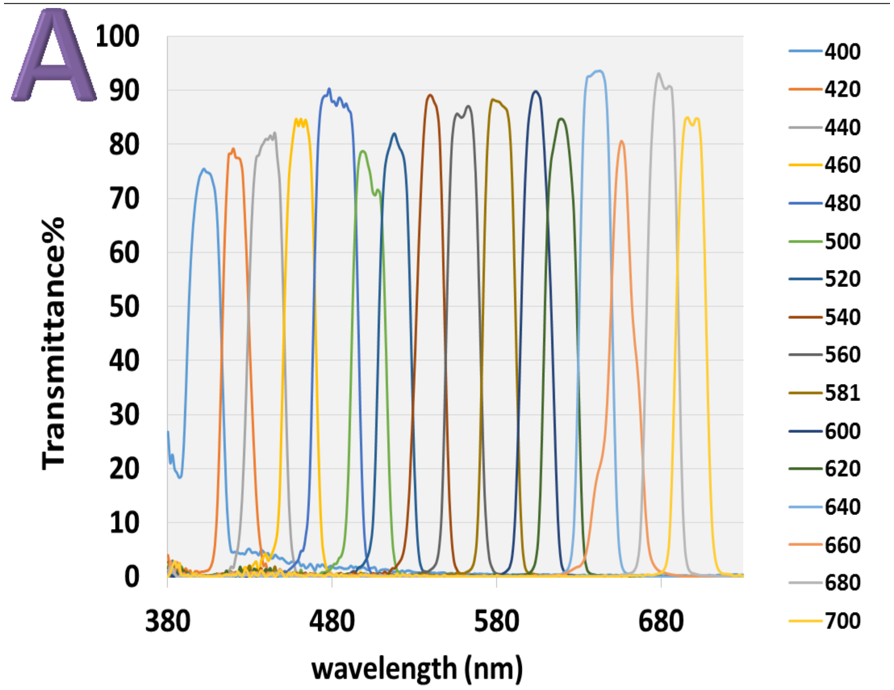
$$c_i = \left(\overline{E}_\lambda \cdot \overline{S}_\lambda\right) = 1/\sum^{\lambda} T_{i\lambda}\Delta\lambda \qquad (7)$$

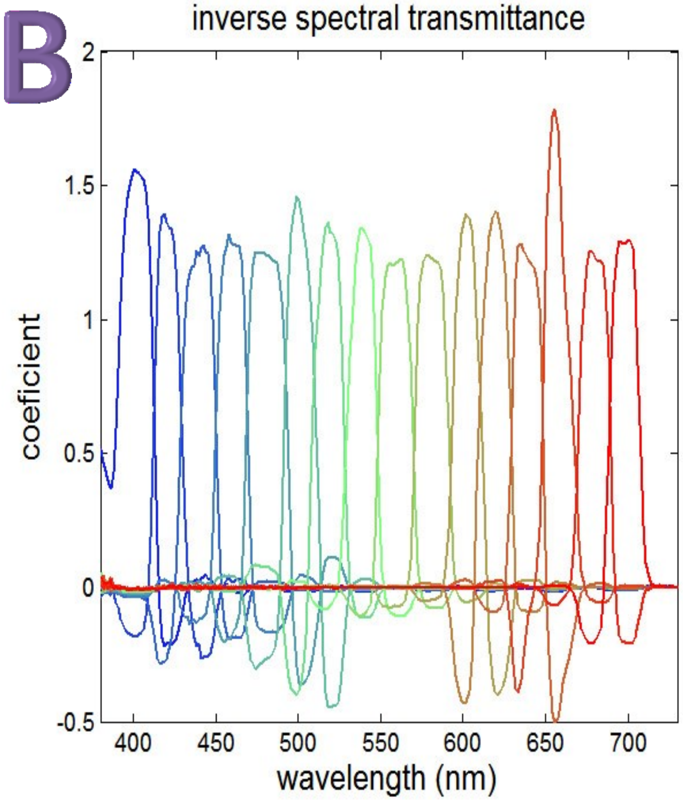
- **Using the spectral transmittance $T_{i\lambda}$ and the scaling factor C_i can convert a spectral reflectance to the linear camera signal.**

Derive the color mixing

- **Pseudo – inverse** of the spectral transmittance matrix.

Spectral transmittances of 16 VIS filters.



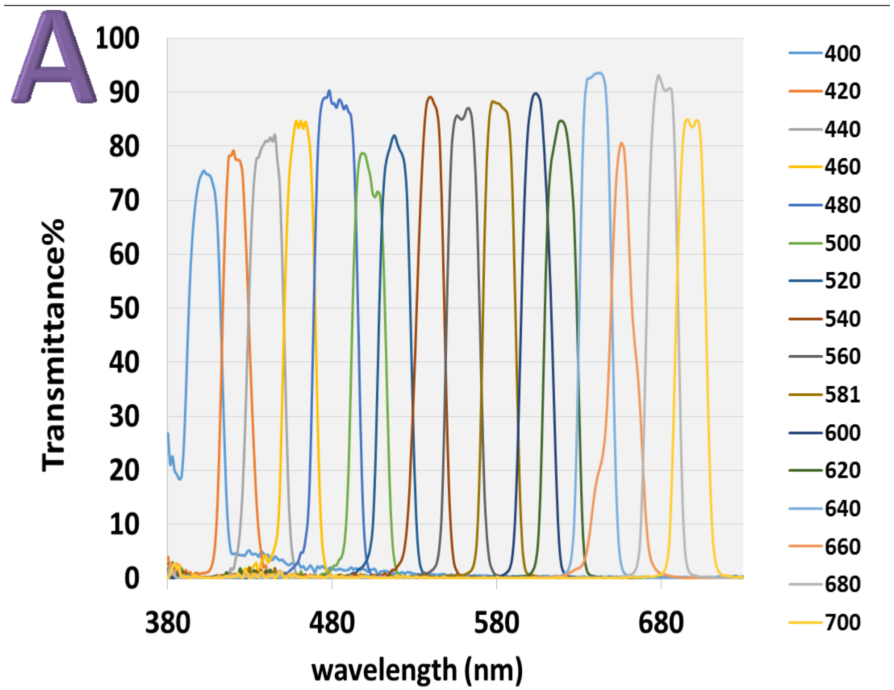


Derive the color mixing

- ***Nyquist–Shannon sampling theorem***: **a low-pass spatial filter** must be applied before the down-sampling

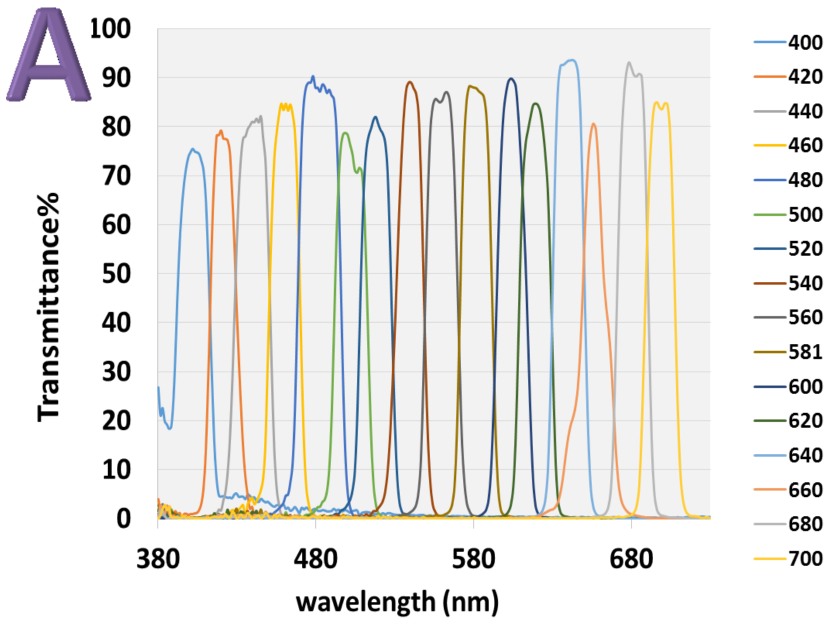
- To test the effect of low-pass filtering, 4 cases were tested.

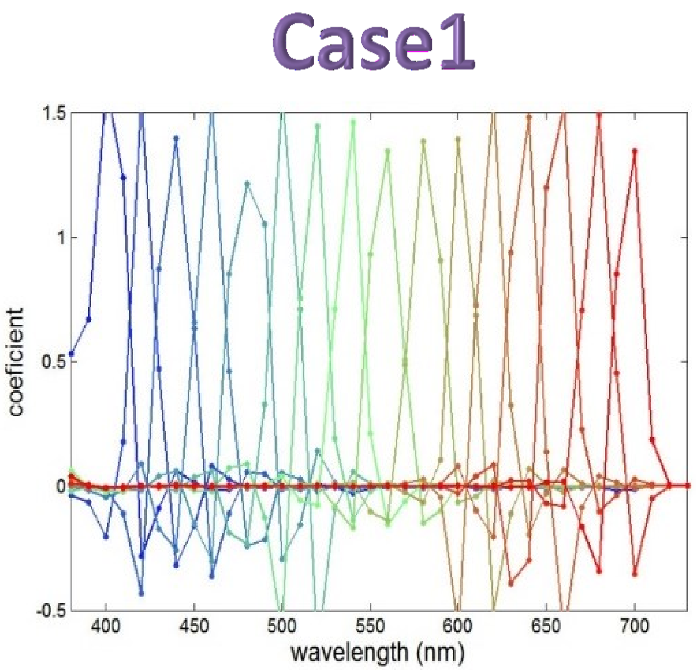
Spectral transmittances of 16 VIS filters.



Derive the color mixing

Spectral transmittances of 16 VIS filters.





Case 1:

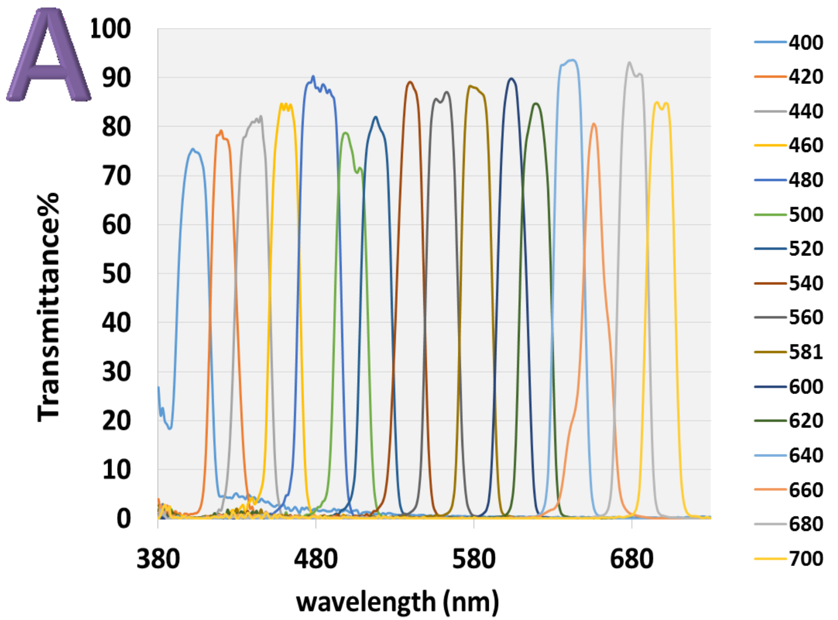
Step 1- direct down-sample to 36 bands.

Step 2- scale each of the curves to 1.

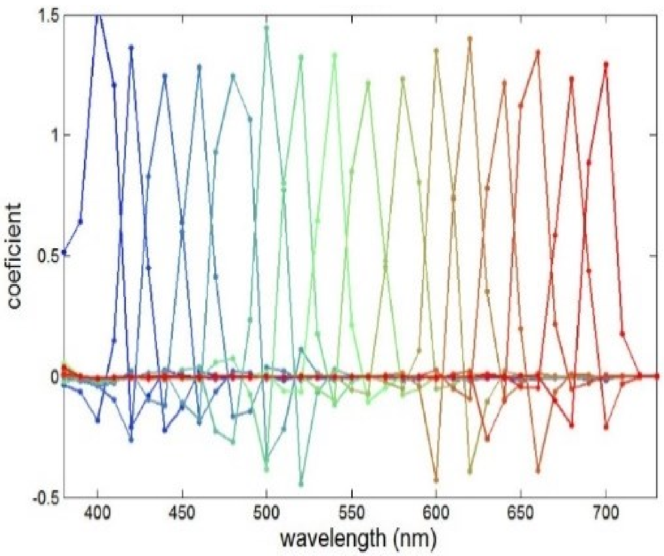
Step 3- pseudo-inverse.

Derive the color mixing

Spectral transmittances of 16 VIS filters.



Case2



Case 2:

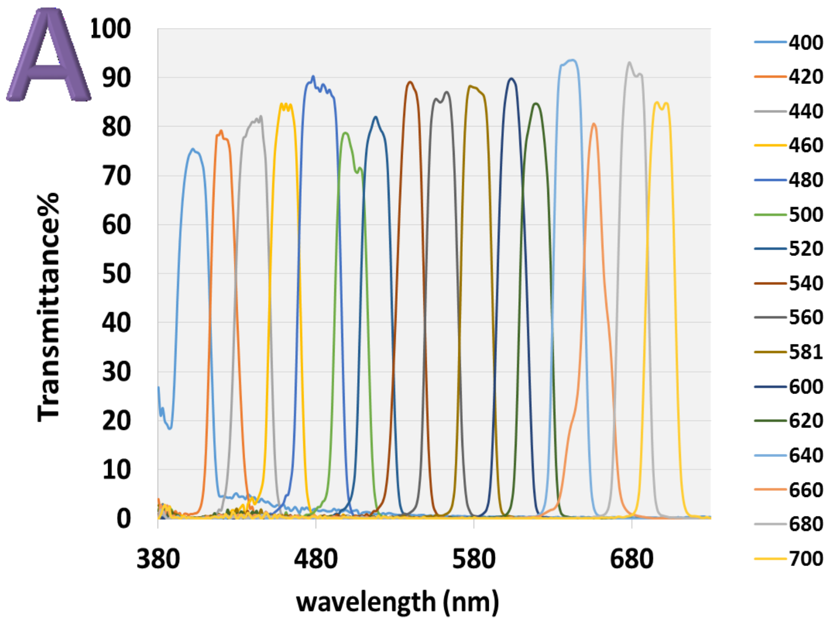
Step 1- scale each of the curves to 1.

Step 2- pseudo-inverse of the matrix.

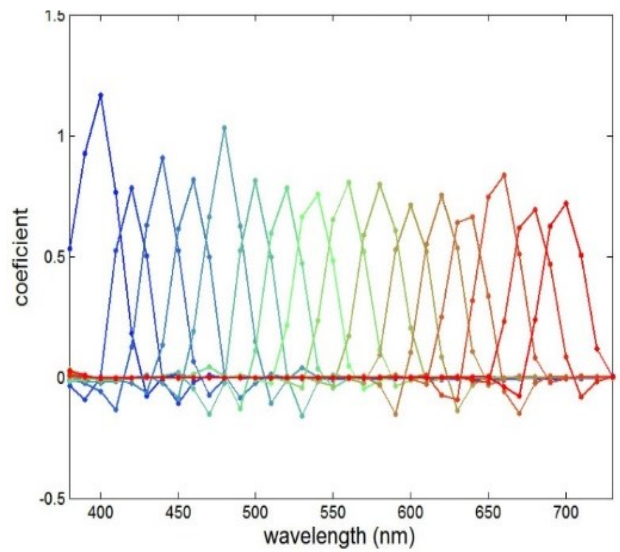
Step 3- down-sample to 36 bands.

Derive the color mixing matrix

Spectral transmittances of 16 VIS filters.



Case3



Case 3:

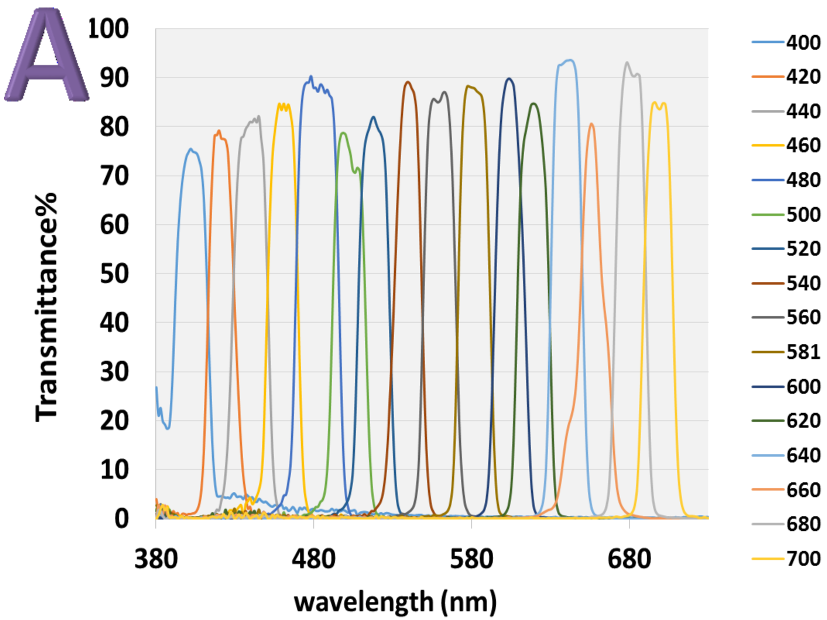
Step 1- scale each of the curves to 1.

Step 2- pseudo-inverse of the matrix.

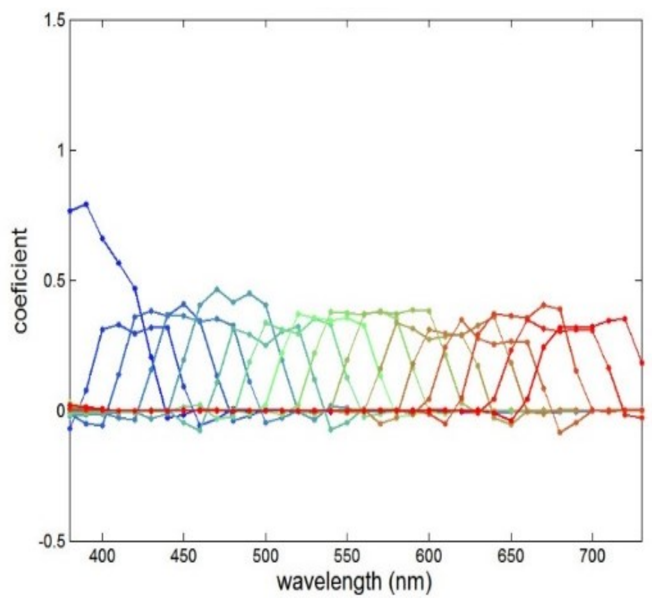
Step 3- **apply a low-pass filter with 20nm width**. down-sample to 36 bands.

Derive the color mixing matrix

Spectral transmittances of 16 VIS filters.



Case4



Case 4:

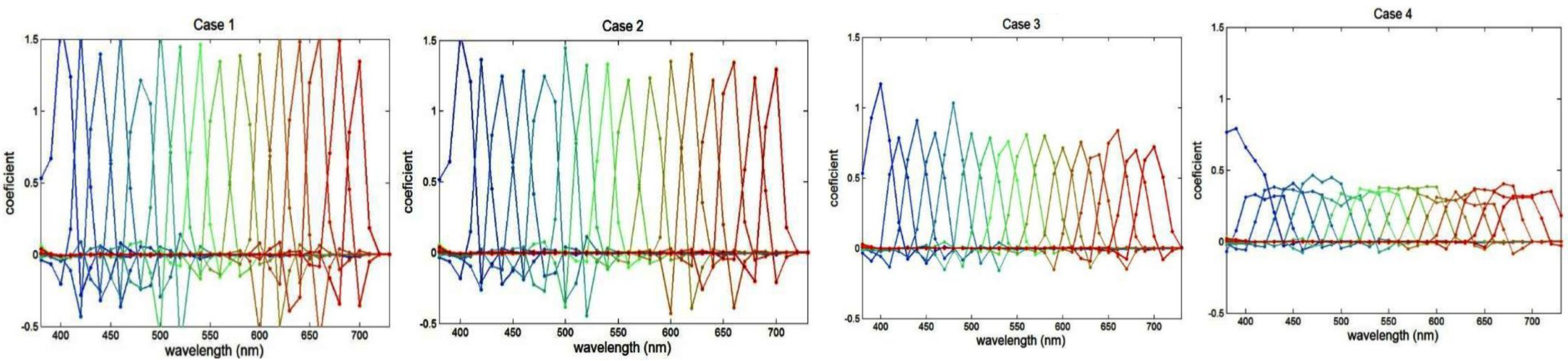
Step 1- scale each of the curves to 1.

Step 2- pseudo-inverse of the matrix.

Step 3- **apply a low-pass filter with 40nm width**. down-sample to 36 bands.

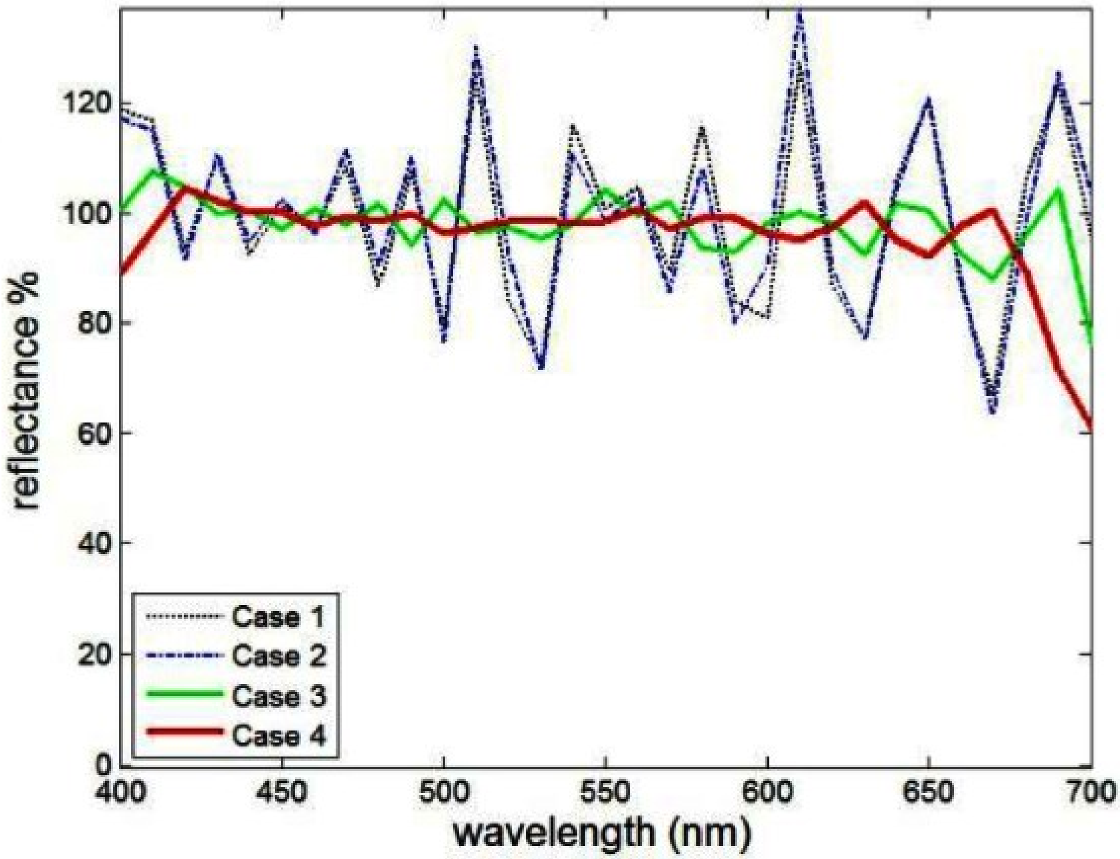
Derive the color mixing matrix

- **Case 3** and **Case 4** which **processed by low-pass spatial filters** have more spectral overlay between each channel and have less negative parts.



Four different inverse matrices

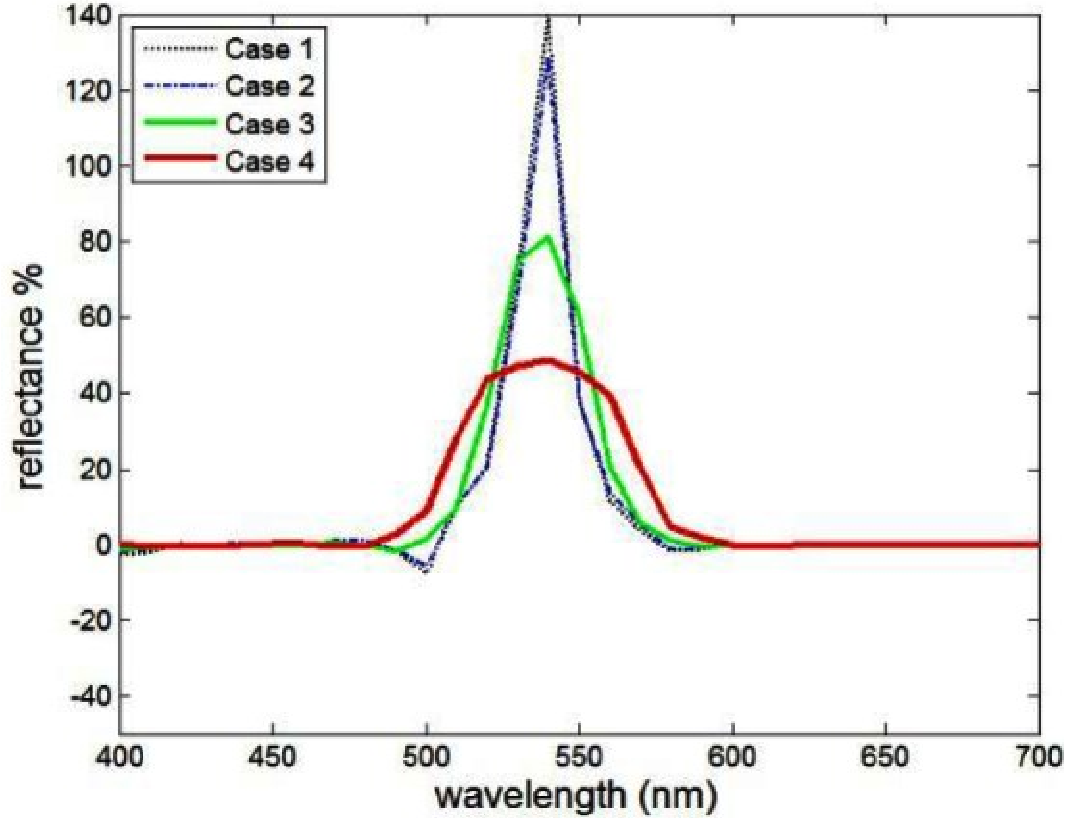
Derive the color mixing matrix



Spectral reconstruction of all 1 signals using four different color-mixing matrices.

- We send 1 (maximum signal) to all 16 channel as a test. The results show that **Case 3** and **Case 4** which applied low-pass spatial filters are **smoother** in its spectral reconstruction.

Derive the color mixing matrix



Spectral reconstruction of all 0 signals except one channel (at 540nm) using four different color-mixing matrices.

- We also reset all channels to be 0 except give 1 to the channel at 540nm.
- The results show that Case 1 and Case 2 recovered the spectral reflectance sharply. But the curve for Case 4 is too smooth.

Results

- Camera-to-SpectralPCS
  - ICC provides tools, named **RefIccMAX**, for users to generate and apply binary iccMAX profiles by way of text XML data.
  - generated a set of iccMAX profile based on MultiProcessElements using two SubElements: **CurveSetElement** and **MatrixElement**.

XML expression

```
<MultiProcessElements InputChannels="16" OutputChannels="36">
    <CalculatorElement InputChannels="16" OutputChannels="36">
    <SubElements>
          <!--Element 0 -->
            <CurveSetElement InputChannels="16" OutputChannels="16"> <!-- curv[0] -->
          <!--Element 1 -->
            <MatrixElement InputChannels="16" OutputChannels="36">  <!-- mtx[1] -->
        </SubElements>
        <MainFunction> {
        in(0,16)
        curv(0)
        mtx(1)
        out(0,36) }
        </MainFunction>
    </CalculatorElement>
</MultiProcessElements>
```

MultiProcessElements using two CurveSetElement and MatrixElement sub-elements.

Results

- Camera-to-SpectralPCS
  - the root mean squared errors (RMSE) of the spectral estimation and color differences of the 140 patches of the SG chart under 5 illuminants including D50, A, CWF, TL84 and white LED.

Table 1: Camera-to-SpectralPCS errors (unit: CIEDE2000)

	Case 1		Case 2	
	mean	max	mean	max
RMSE	0.061	0.160	0.063	0.165
D50	2.45	12.55	2.84	12.29
A	2.21	10.09	2.53	9.99
CWF	2.39	11.46	2.62	11.14
TL84	3.70	12.91	4.63	12.36
W LED	2.61	13.26	3.11	12.82
avg.	2.67	12.05	3.15	11.72

Table 2: Camera-to-SpectralPCS errors (unit: CIEDE2000)

	Case 3		Case 4	
	mean	max	mean	max
RMSE	**0.029**	**0.087**	0.042	0.114
D50	2.34	12.56	2.62	13.30
A	2.08	10.19	2.33	10.96
CWF	2.26	11.37	2.37	12.29
TL84	2.06	11.64	2.59	11.80
W LED	2.42	13.02	2.59	13.64
avg	**2.23**	11.76	2.50	12.40

Results

- Camera-via-PCC-to-sRGB
  - Late-binding processing elements
  - Applied D50, A, D65, and D93 **PCC profile** (**P**rofile **C**onnection **C**ondition) with 2 degree observers in either absolute colorimetry (denoted as Abs) or applied a CIECAT02 chromatic adaptation transform (denoted as CAT) to minimize color shift.
  - Regarded a virtual sRGB display as the destination.
  - The profile sequence is from camera via illuminants to RGB.

Results

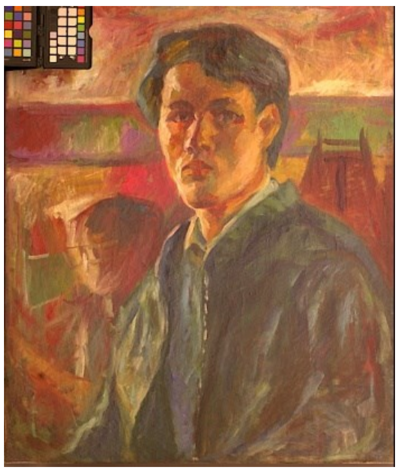
- Camera-via-PCC-to-sRGB
  - ➢ After the illuminant transform, the Lab values convert to sRGB using a B2A transform with sRGB profile. The change of illuminant would bring some colors outside the sRGB gamut.
  - ➢ **The native D50 is the best.** Illuminant A-Abs and D93-Abs are worse than all the others, as they shift color towards yellow and blue, respectively. The outside-gamut errors significantly reduced by applying the chromatic adaptation transform.

Table 3: Camera-via-PCC-to-sRGB errors (unit: CIEDE2000).

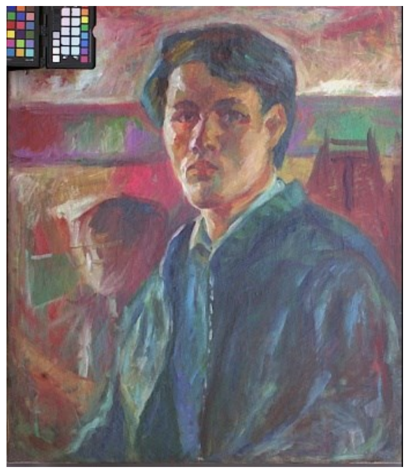
		mean	std	95%	max	outside gamut %
D50		0.42	1.21	3.35	5.79	18.0
A	Abs	2.00	3.67	11.18	12.37	45.7
	CAT	0.46	1.14	3.53	4.95	20.0
D65	Abs	1.17	2.31	6.67	8.06	21.4
	CAT	0.45	1.34	3.63	6.65	18.6
D93	Abs	2.47	4.62	14.27	16.13	36.4
	CAT	0.49	1.46	3.84	7.39	17.9

Results

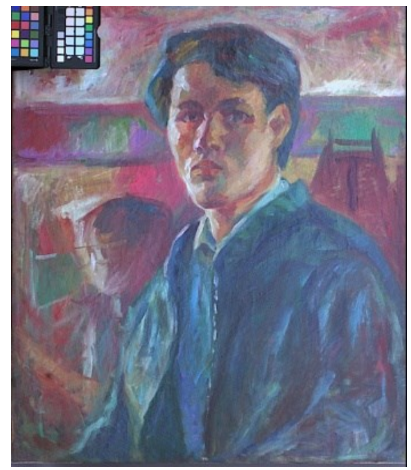
- Camera-via-PCC-to-sRGB simulation (absolute transform)



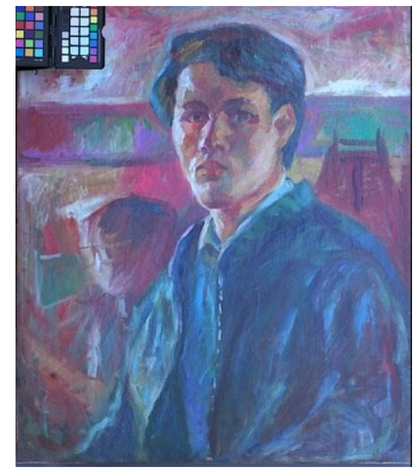
illuminant A



D50

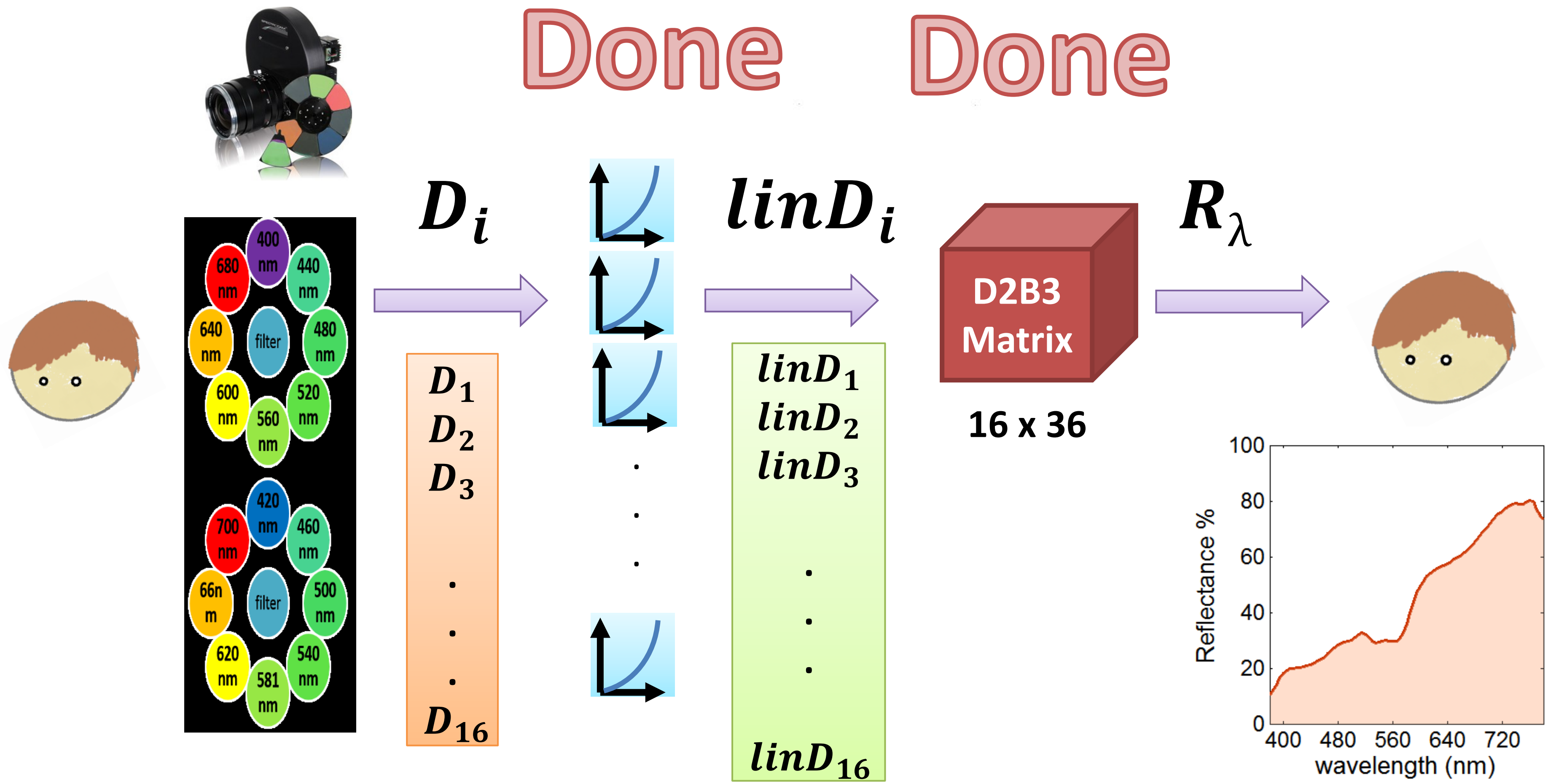


D65



D93

Conclusions



Conclusions

- The spectral and color accuracy of both camera-to-spectralPCS and camera-via-PCC-to-sRGB conversions were estimated and the resulted errors are acceptable.
- The iccMAX is much powerful than the ICC v4 as the former provides freedom to store, and to process a variety of image and viewing condition data.
- As iccMAX is complex and provides too much freedom, how to educate the users will be a great challenge in the future.

Acknowledgement:
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Thank You!

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