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Spectral reconstruction of surfaces based on digital images

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Introduction, motivation

Spectral data with **moderate precision** can be important in many situations:

- dye investigation
- quality assurance
- recognition of faked documents

Spectrophotometry is not suitable in many situations:

- cost
- availability
- time and organisation problems

Digital cameras:

- can be found everywhere
- collects colour information with high spatial resolution

Can we get some spectral information from digital photos?

It can be useful if there is no way to apply spectrophotometry.

Basic considerations

Note: our calculations can be applied to emission spectra of light sources and reflectivity functions. We will refer them as “spectra”.

Spectrum → RGB is a well defined operation,
but has **no inverse**.

For a given (R, G, B) triplet
we have infinite number of spectra (metamers).

Problem: **Which is the real spectrum?**

Constraints:

- a real **spectrum is non-negative** (for all wavelengths)
- **qualitative properties of the object** can reduce the number of suitable spectra

Example: most of the materials have smooth spectrum.

The first partial results are shown in this talk.

First idea: method of base functions

$F(\lambda; p_1, p_2, \ldots, p_k)$: parametric set of spectra.
(λ: wavelength; $p_1, p_2, \ldots, p_k$: parameters)

Let $\underline{c}$ be the vector of colour components (e.g. R,G,B triplet),
$\underline{CMF}$ is the vector of colour matching functions.

It is easy to calculate $\underline{c}$ for every parameter set:

$$\underline{c}\,(p_1, p_2, \ldots, p_k) = \int F(\lambda; p_1, p_2, \ldots, p_k)\, \underline{CMF}(\lambda)\, d\lambda$$

Digital image $\rightarrow \underline{c}_0 \rightarrow$ find $(p_1, p_2, \ldots, p_k)$ so that

$$\underline{c}_0 = \underline{c}\,(p_1, p_2, \ldots, p_k)$$

With this parameters $F(\lambda; p_1, p_2, \ldots, p_k)$ is a metamer for $\underline{c}_0$ from our set of functions.

An example set of base functions

A plausible choice is a set of gaussians.

$$F_{gauss}(\lambda; A, \lambda_0, \sigma) = A \exp\left(-(\lambda-\lambda_0)^2 / (2\sigma^2) \right)$$

($A>0$, $350\text{ nm}<\lambda_0<750\text{ nm}$, $\sigma>0$)

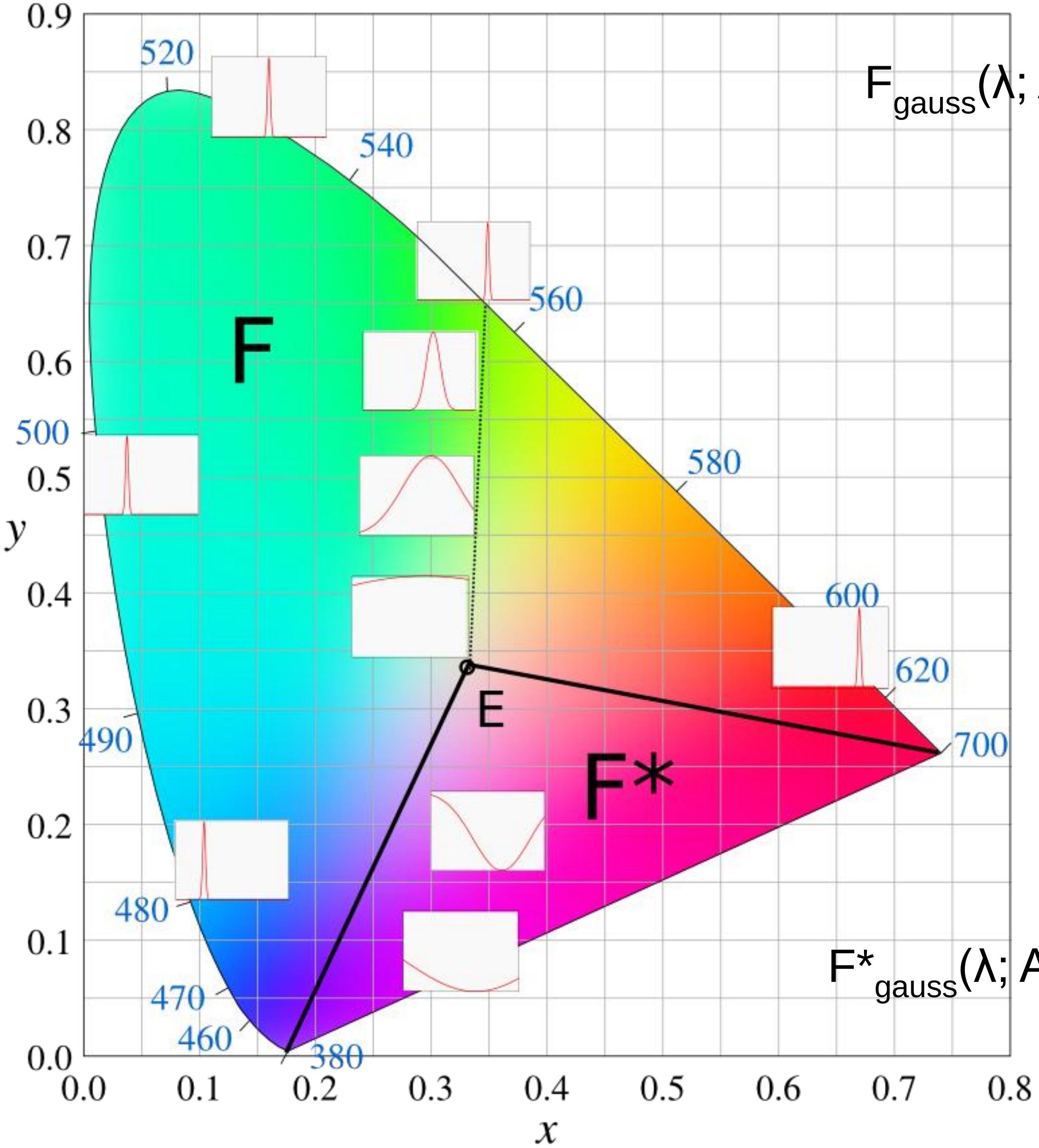
Do we have the metamers of all colours?

- For very small σ-s we have the spectral colours.
- For very large σ, we have neutral colour (“white”).
- For moderate σ we will get all the colours between the neutral colour and spectral colours.
- Problem: We have no magentas, purples!
- Solution: Use a different set of functions for “magentas”:

$$F^*_{gauss}(\lambda; A, \lambda_0, \sigma) = A - F_{gauss}(\lambda; A, \lambda_0, \sigma)$$

(upside down gaussians)

An example set of base functions: visualization



$$F_{gauss}(\lambda; A, \lambda_0, \sigma) = A \exp\left(-(\lambda-\lambda_0)^2 / (2\sigma^2) \right)$$

$$F^*_{gauss}(\lambda; A, \lambda_0, \sigma) = A - F_{gauss}(\lambda; A, \lambda_0, \sigma)$$

Calculation algorithm

Main steps of spectrum reconstruction for **one pixel:**

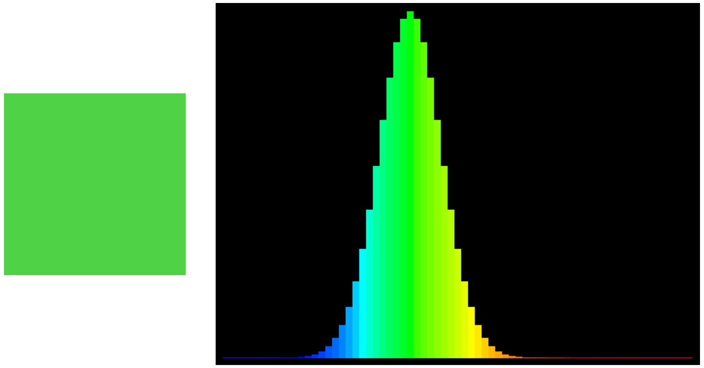
Initialization: Fill interpolation tables for F_{gauss} and F^*_{gauss}
(solve $\underline{c}_0 = \underline{c}(A, \lambda_0, \sigma)$ for a lot of $\underline{c}_0 = (r, g, 1 - r - g)$ triplets and store)

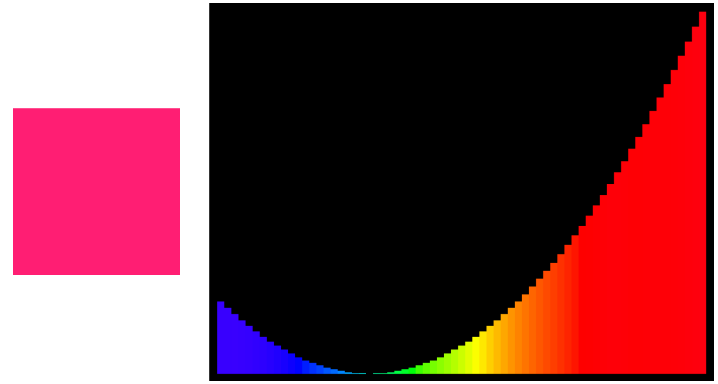
1. Get colour channels from pixel
2. Calculate linear (R, G, B) (using sRGB specification)
3. If ((G<R) && (G<B)) use table for F^*_{gauss} else use table for F_{gauss}
4. Calculate r = R/(R+G+B); g =G/(R+G+B)
5. A=(R+G+B)
6. Using the interpolation table, get λ_0 and σ

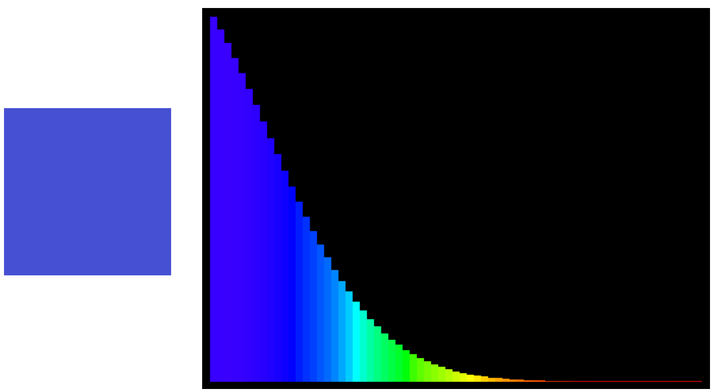
For a **whole picture**, steps 1. – 6. is repeated for all pixels and the reconstructed spectra is summed.

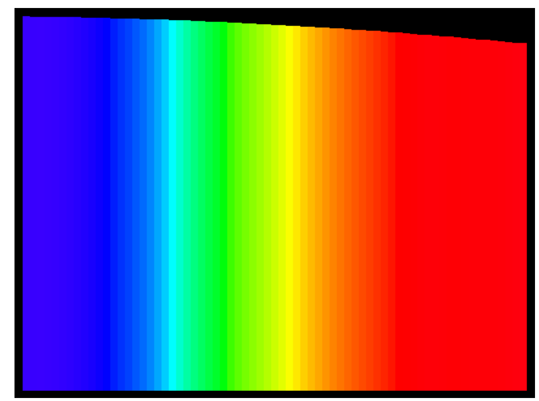
Algorithm was implemented for 3 set of base functions. (Gaussian, parabolic, piecewise constant functions)

Simple results: homogeneous pictures

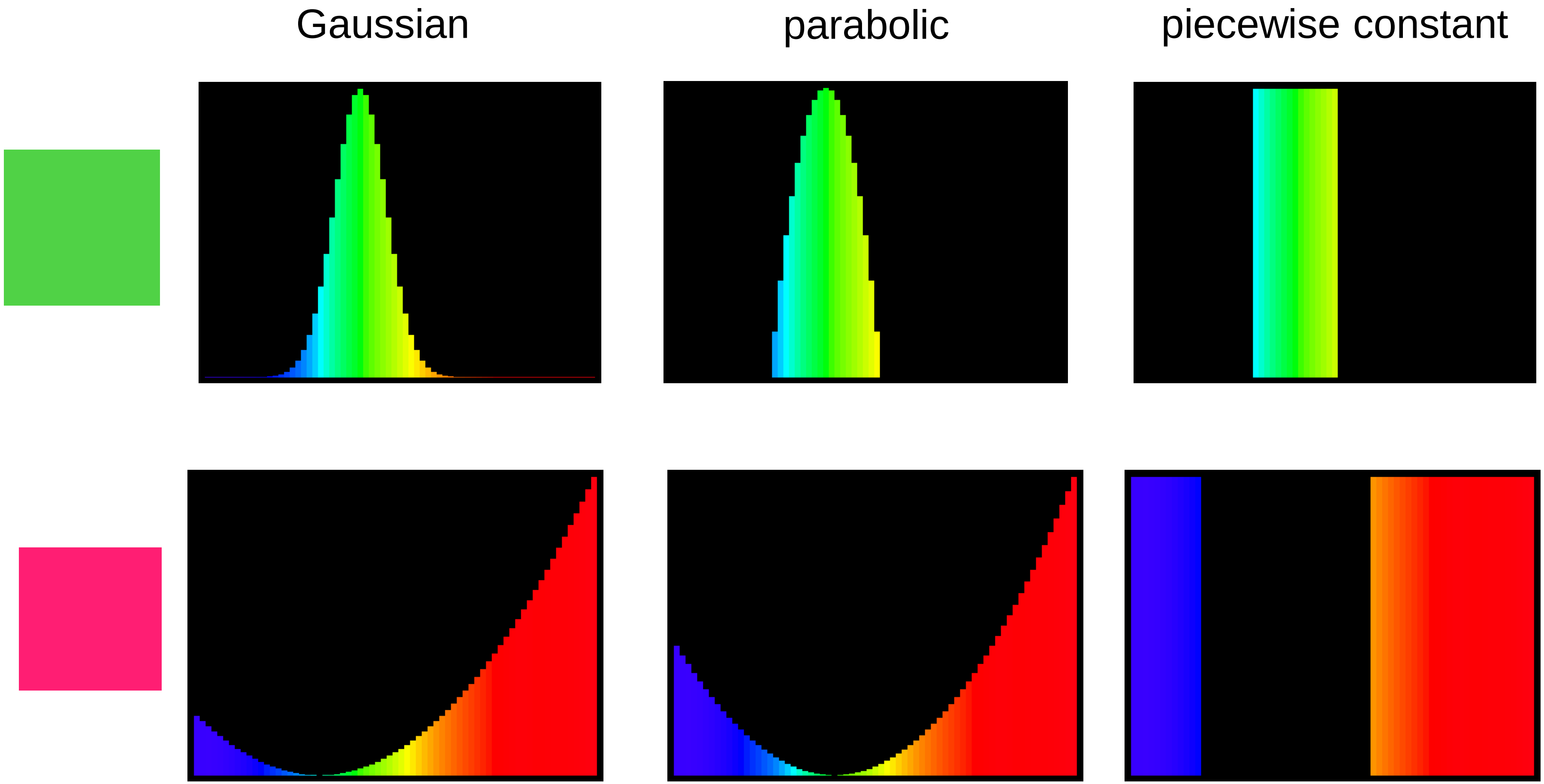




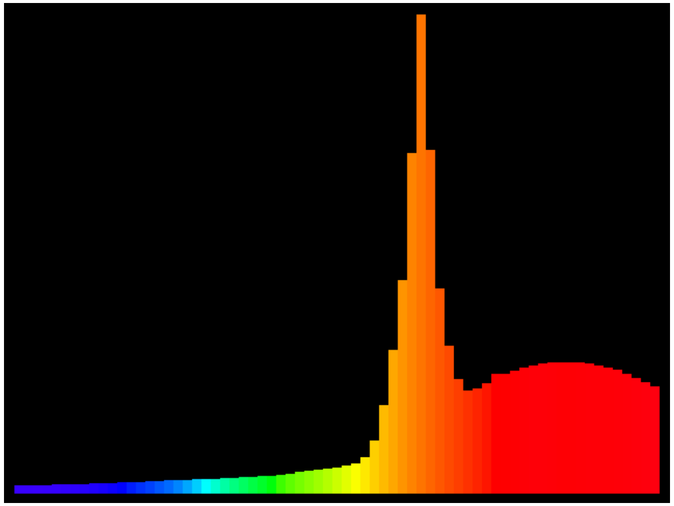




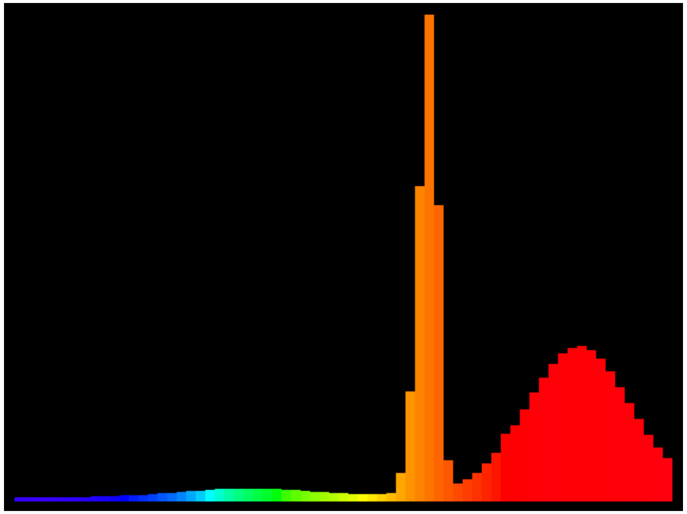
Simple results: different base functions



“Spectrum” of a photo

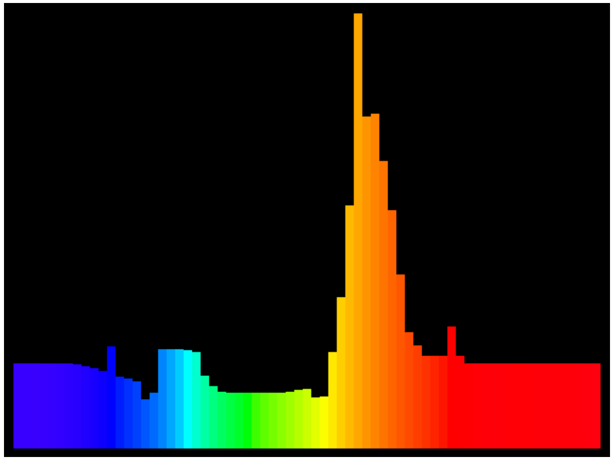


Reconstructed “spectrum”

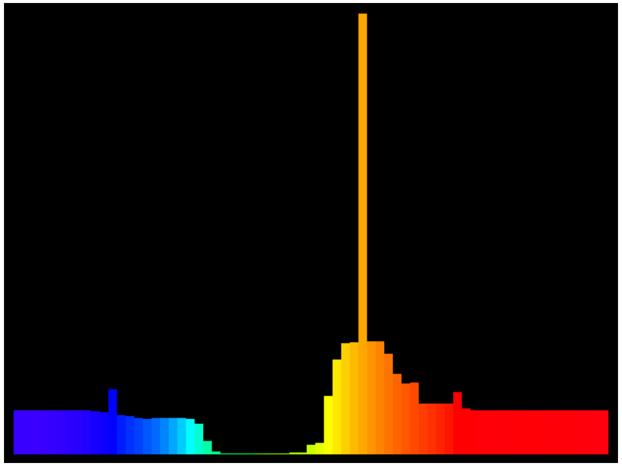


Sharpened “spectrum”

Original and fake documents



original



fake

Fake was produced with a colour photocopier.
Identical light source was used.

Improvements

Possible directions of improvements:

- Enhancement transformations
  (use only pixels with small σ, sharpening spectra of pixels, ...)
- Implement other base functions
- Investigation of possible applications

Main question:

Is there a more sophisticated way to find metamers
with good qualitative properties?

Such a method will be presented in the second part of this talk.

Principal component analysis

Let $\xi : \Omega \rightarrow \mathbf{R}^p$ a vector probability variable.

Expected value: $E(\xi) = m \in \mathbf{R}^p$.

Centralized: $\xi^* = \xi - m$.

Covariance matrix: $\operatorname{cov}(\xi, \xi) = \mathrm{V} \in \mathbf{R}^{p \times p}$.

Eigenvalues of covariance matrix V: $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_p \geq 0$.

Orthogonal and normalized eigenvectors belonging to the eigenvalues: $v_1, v_2, \ldots, v_p \in \mathbf{R}^p$.

Principal component analysis

Principal components of probability variable $\xi : \Omega \to \mathbf{R}^p$ are the following scalar probability variables:

$$\tau_i = v_i^T \cdot \xi^* , \qquad i = 1, 2, \ldots, p .$$

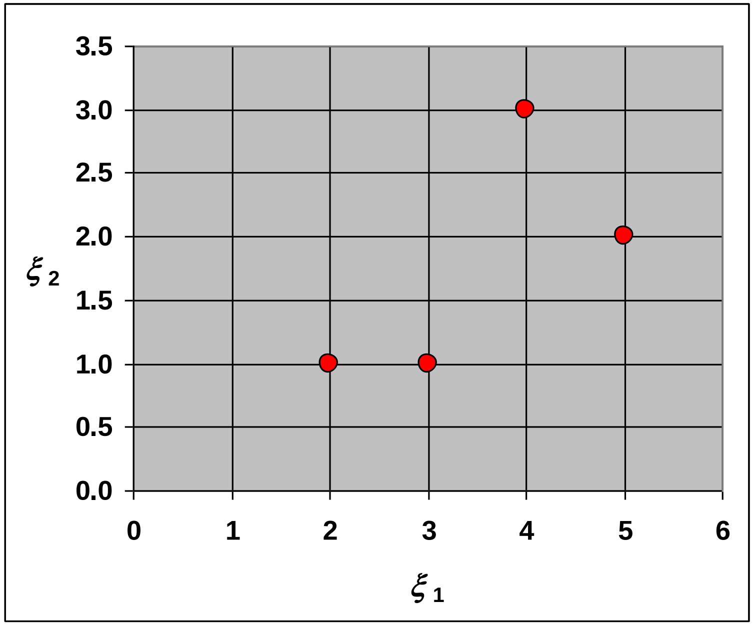
The most important property of the **principal components**:

$$\xi = \sum_{i=1}^{p} \tau_i \cdot v_i + m .$$

A simple example in two dimensions:

Let us assume that 4 measurements have been achieved:

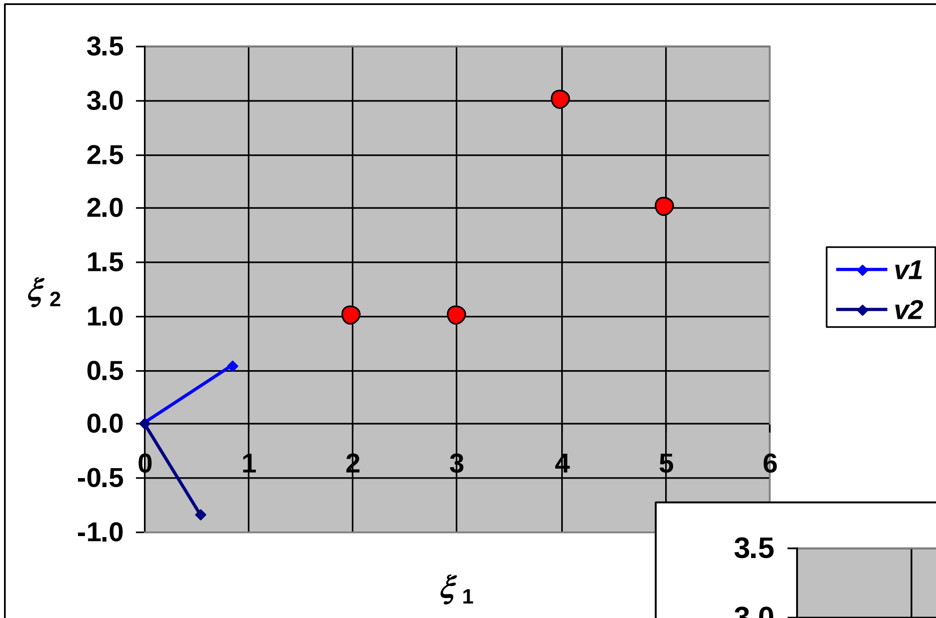
(2, 1); (3, 1); (4, 3); (5, 2).



$$\lambda_1 = 1{,}6541$$

$$\lambda_2 = 0{,}2834$$

A simple example in two dimensions:



$$\lambda_1 = 1{,}6541$$

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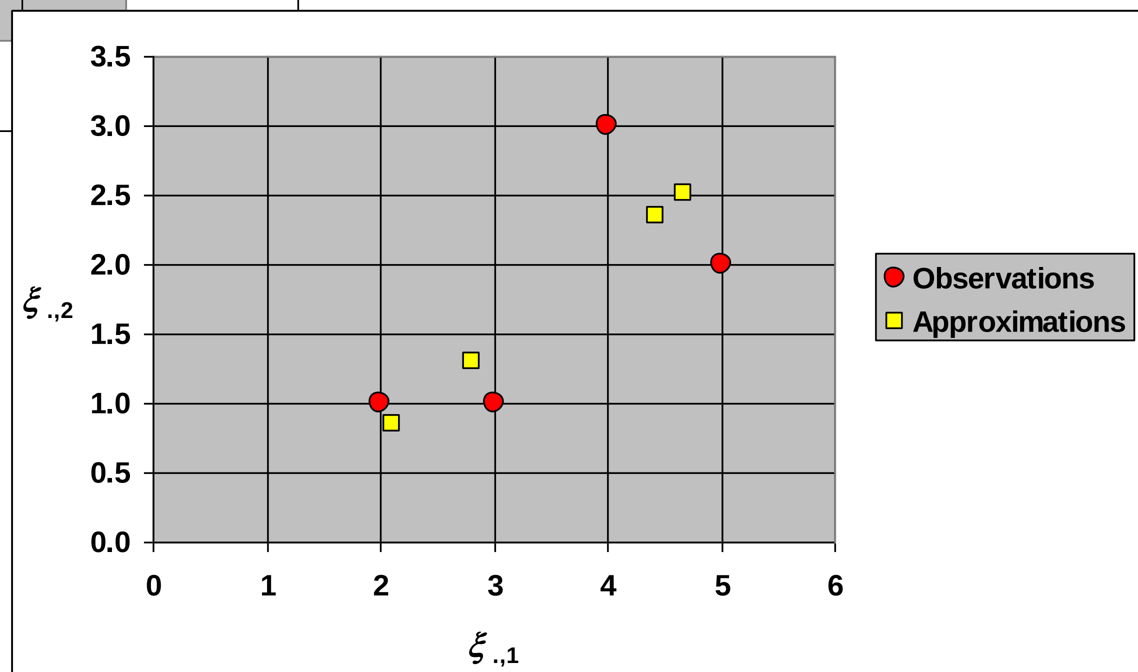
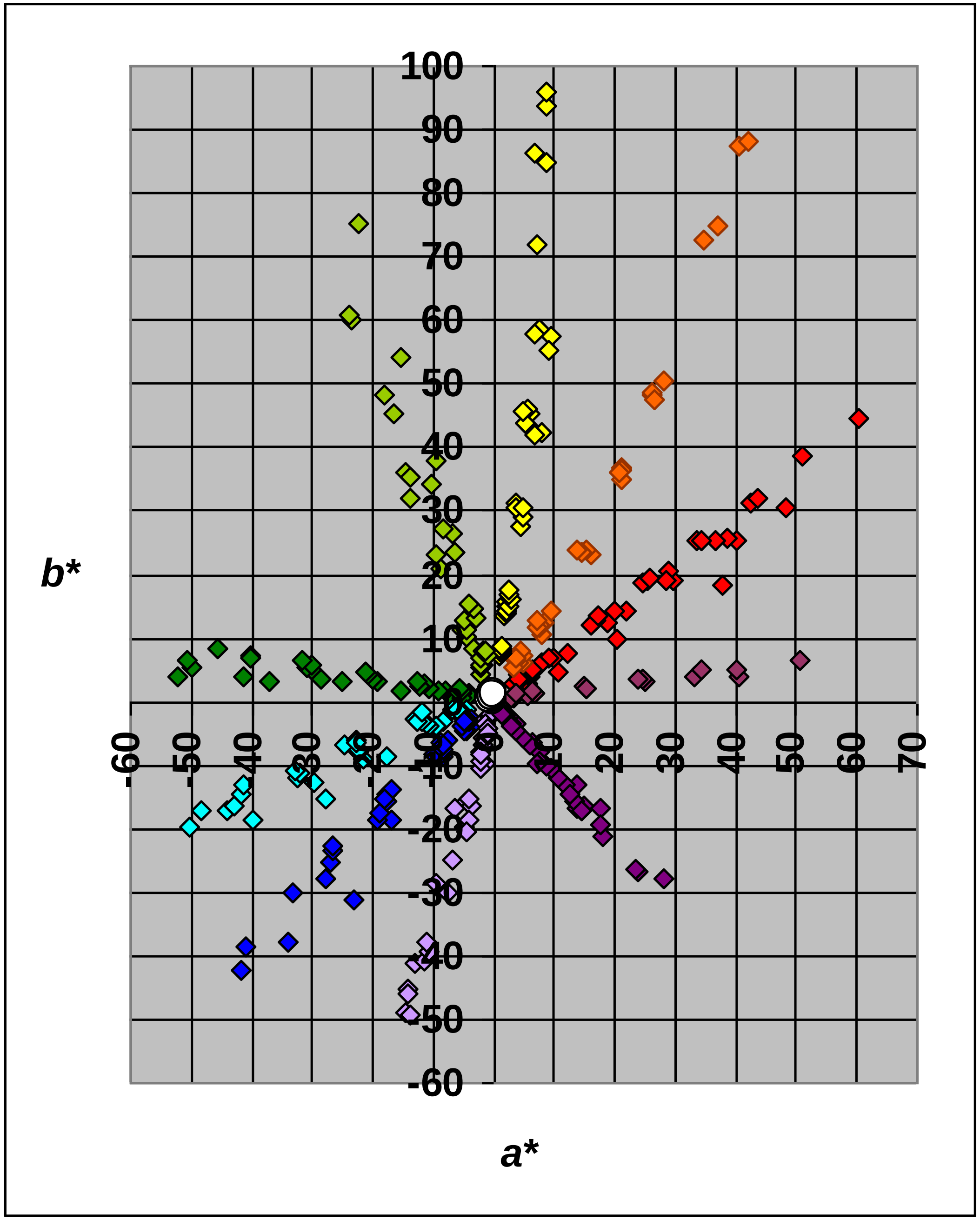
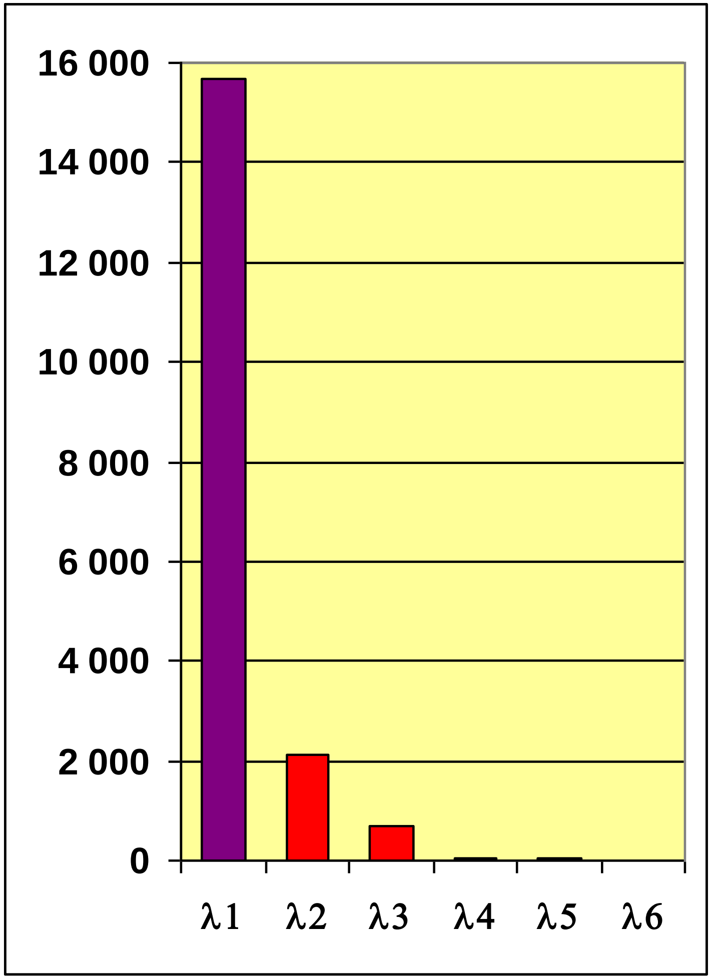
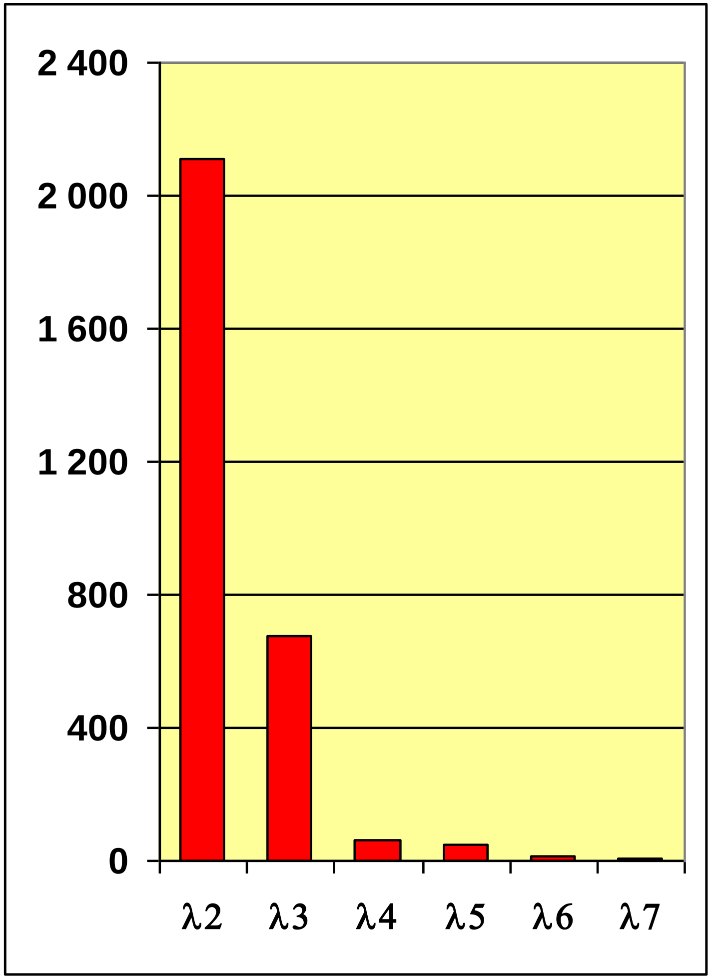


Distribution of 373 real Munsell-samples in the a^*b^*-plane of the CIELAB system.

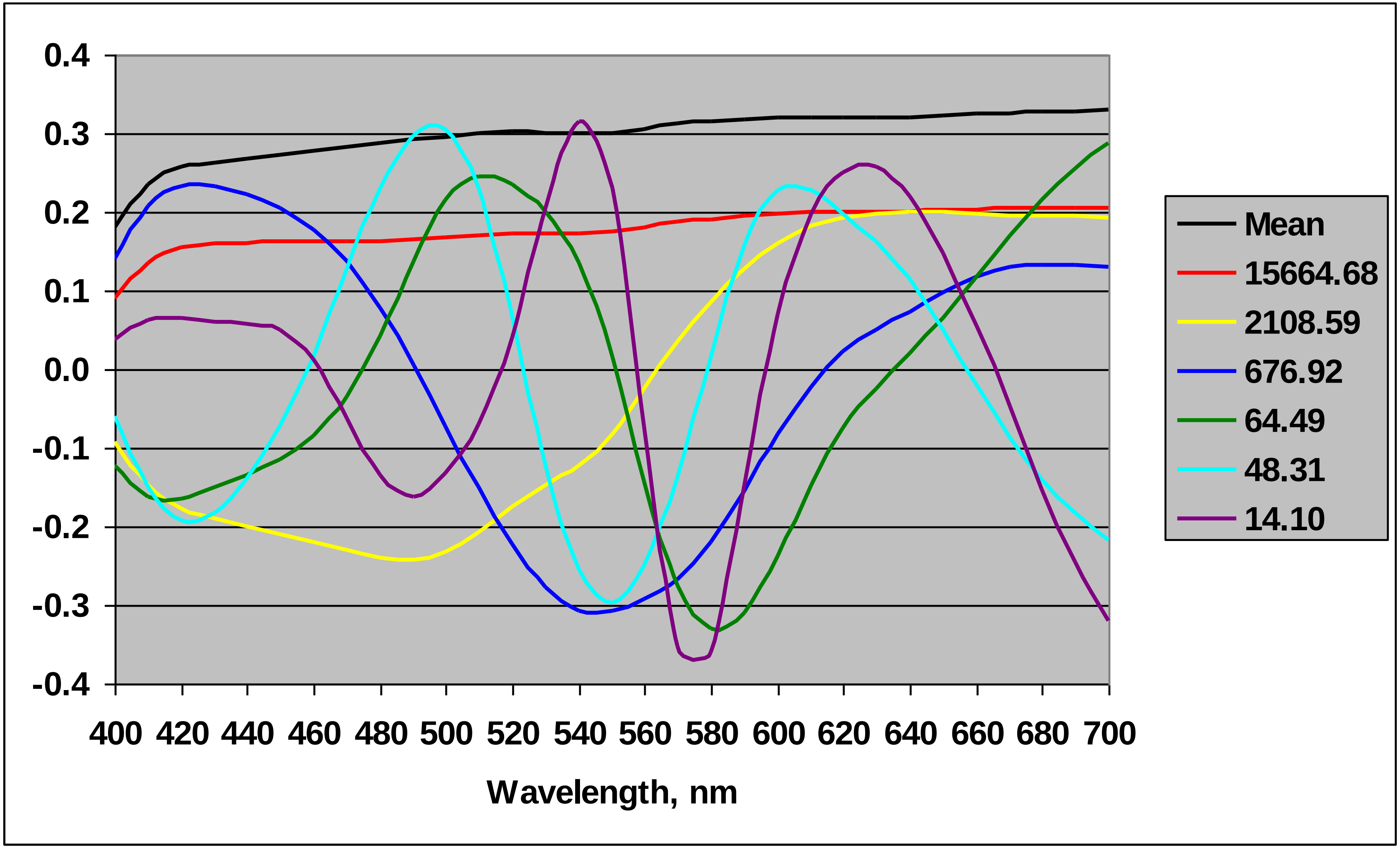


Eigenvalues of the 373 Munsell-samples

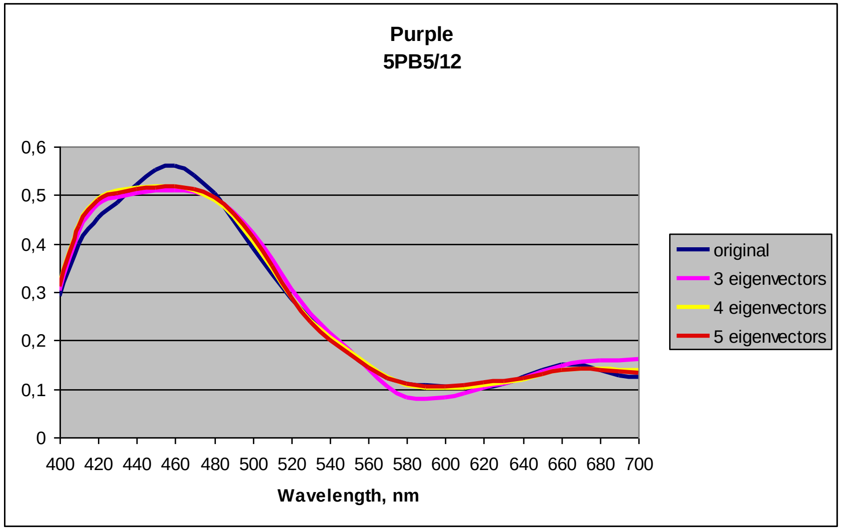


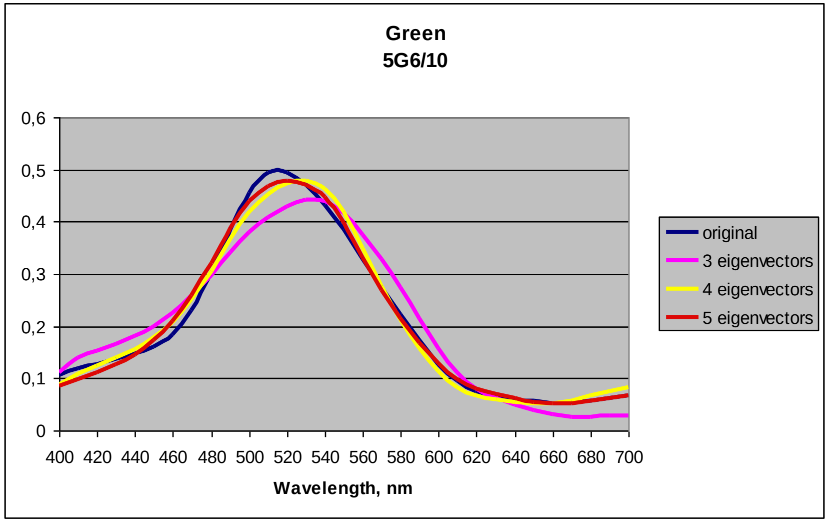


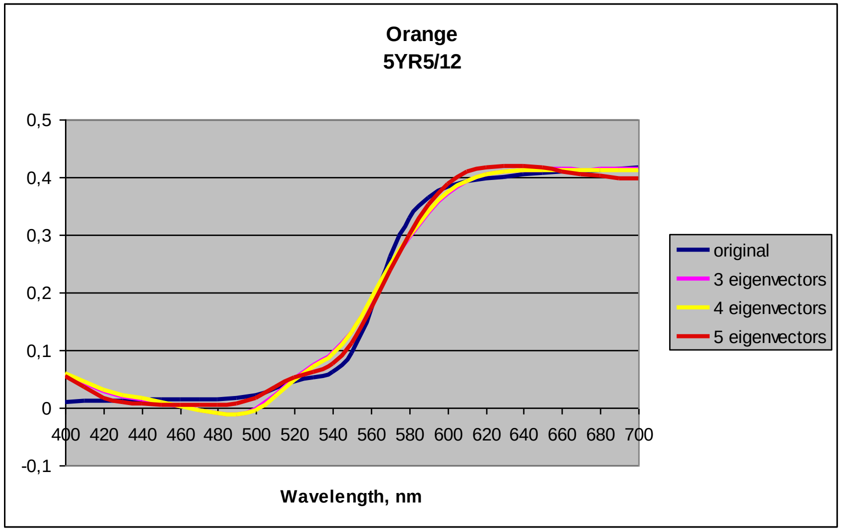
The mean vector and eigenvectors belonging to the first 6 eigenvalues



Reconstruction of known spectral reflectance functions



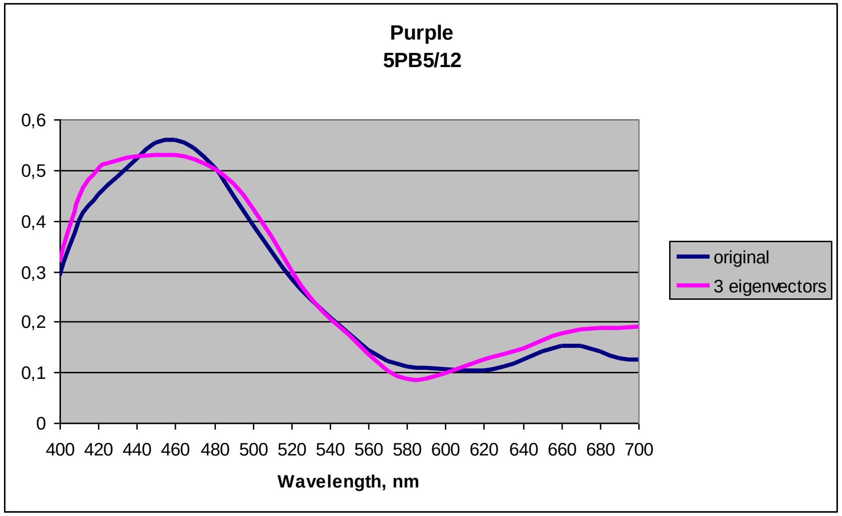


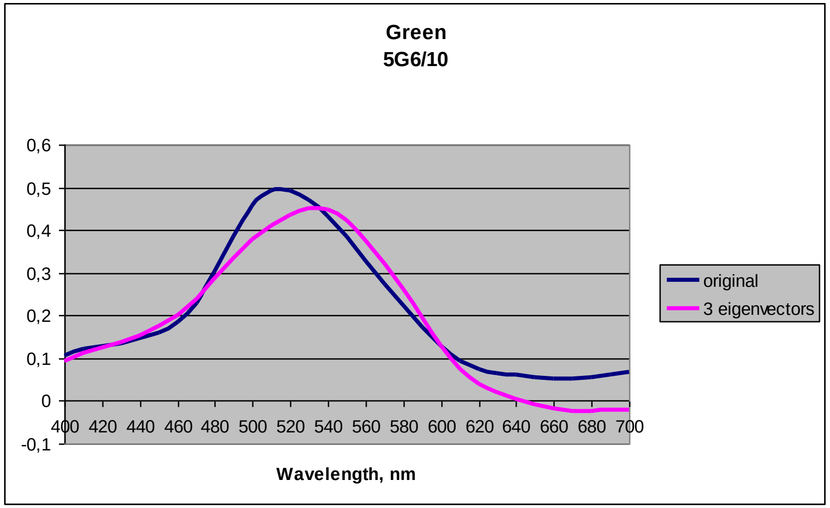


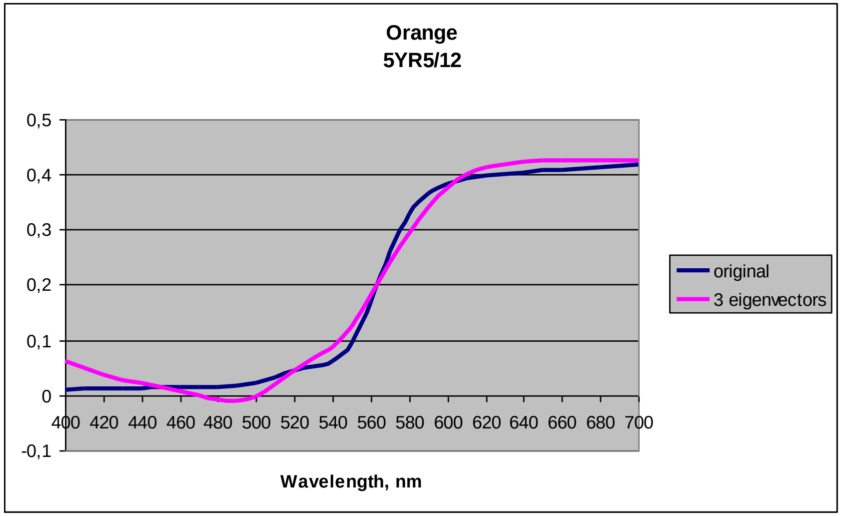
Original reflectance: known.

Basis: least squares' method.

Generating metameric pairs by the eigenvectors





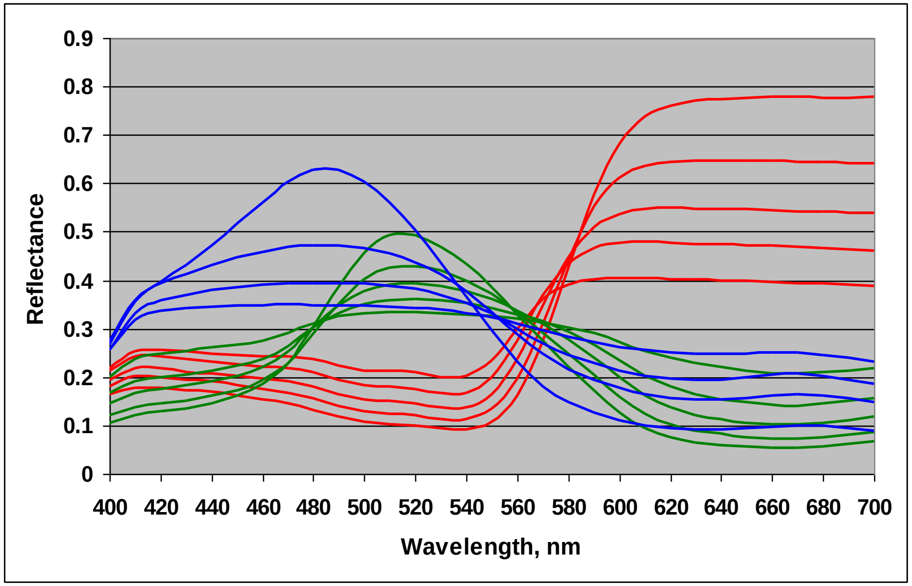


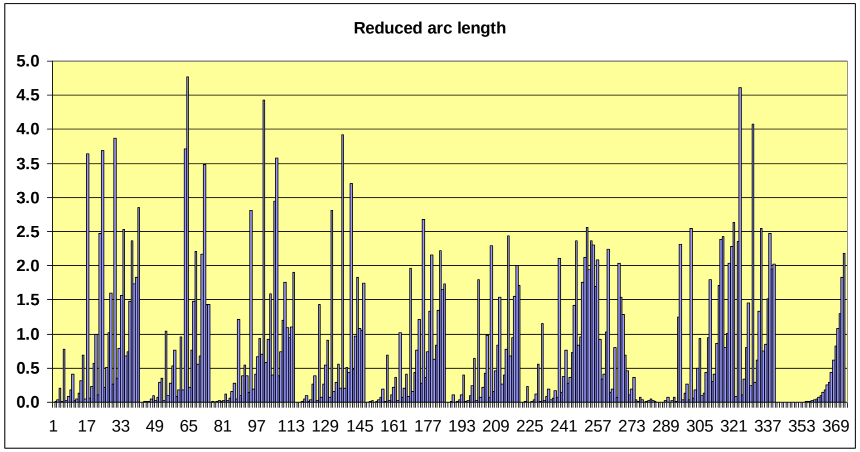
Original reflectance: not known.

Basis: tristimulus values (*XYZ*).

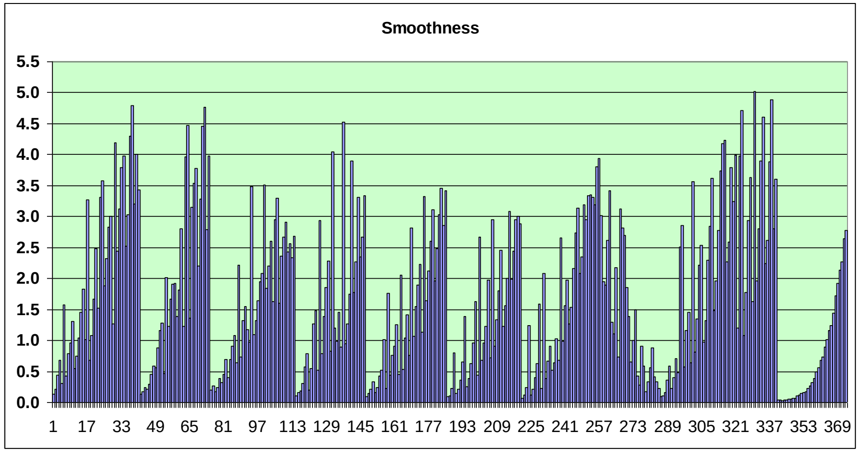
Problems: no metamerism or negative values.

Mathematical tools for using more than 3 eigenvectors



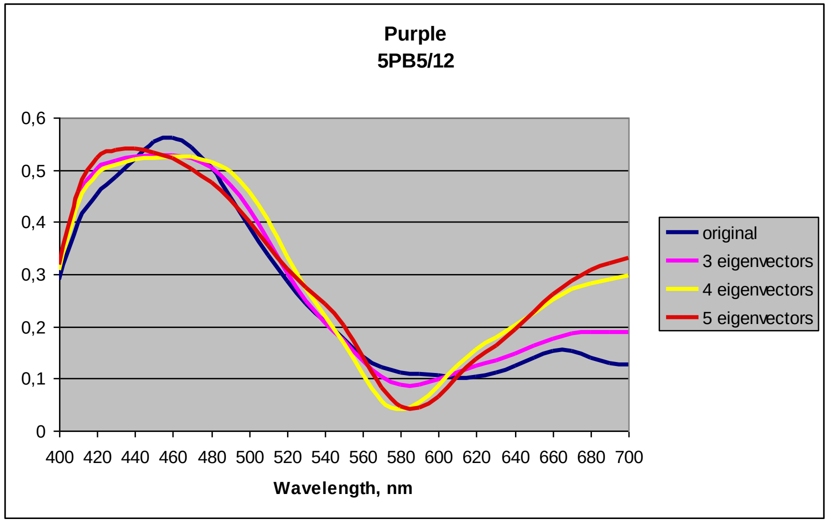


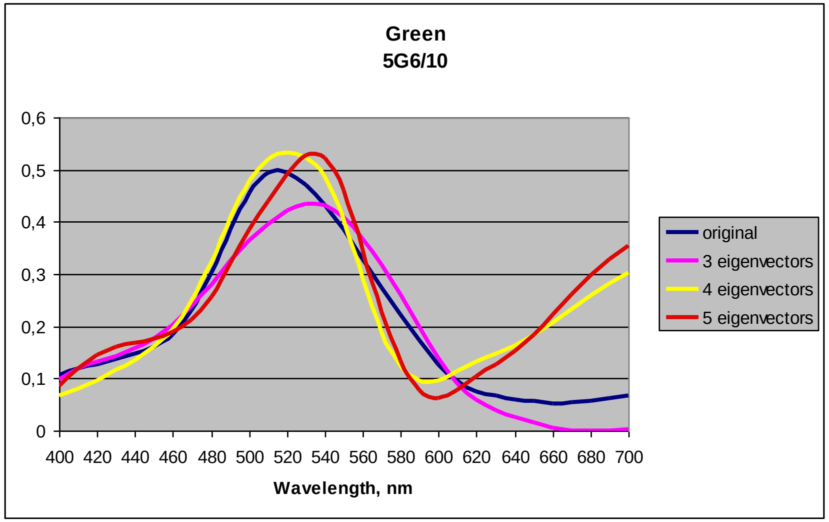
Length of the curve of the function (first derivative).

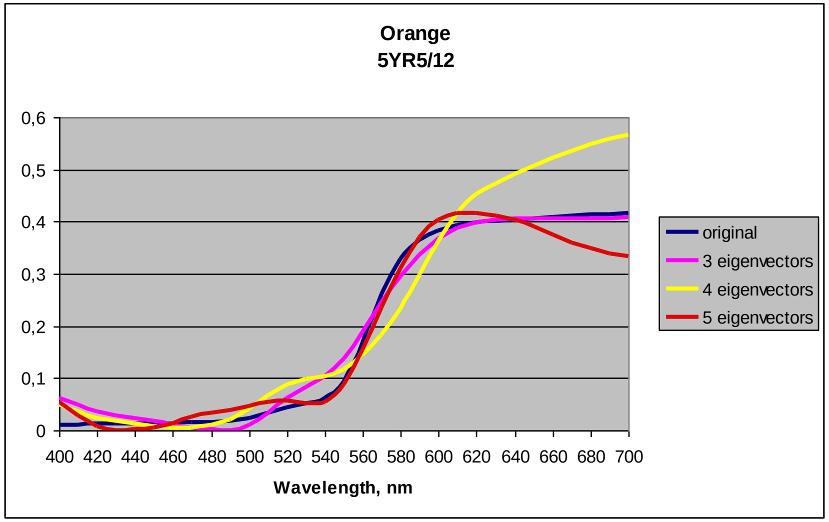


Smoothness of the function (second derivative).

Generating metameric pairs by the eigenvectors







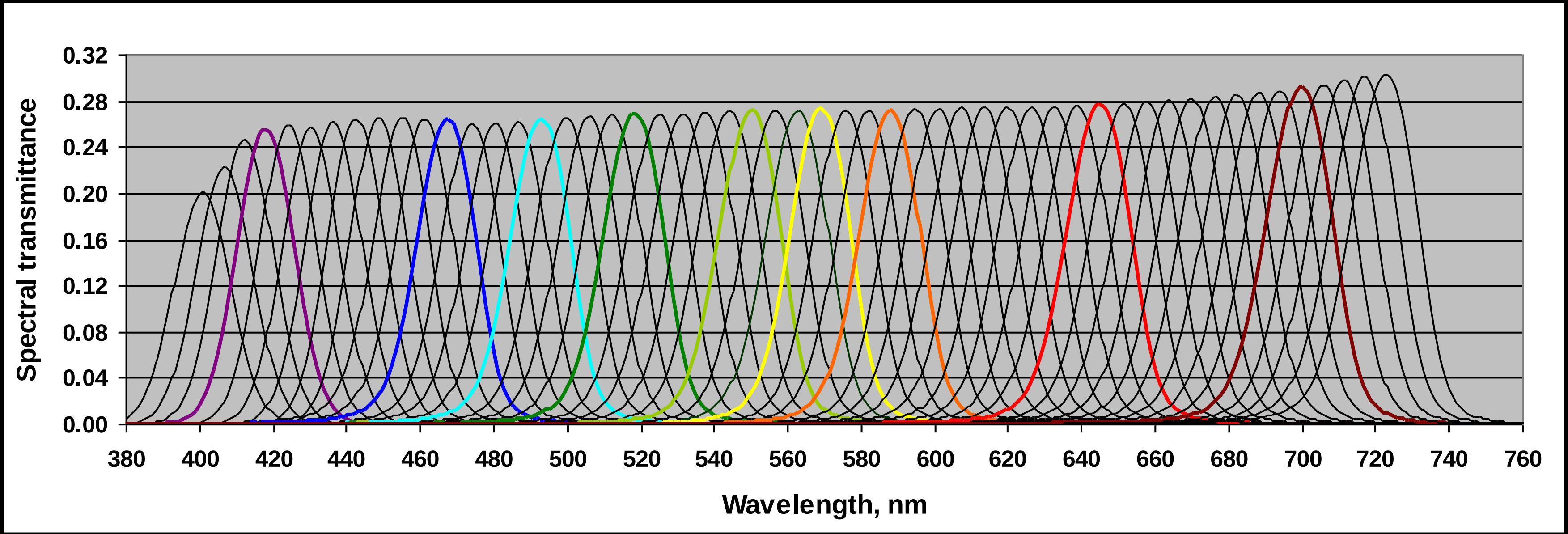
Original reflectance: not known.

Basis: tristimulus values (*XYZ*), curve length and smoothness.

Problem: no unique solution.

Further mathematical properties???

Direct method: Interference filter wedge placed in the output aperture of an integrating sphere



Indirect method: Measuring an appropriate set of color samples with known spectral reflectances and determining model functions for the spectral sensitivities of the camera.

Thank you for your attention!