Laboratoire Electronique Informatique et Image

VISOR Seminar

Colorimetric characterization of displays and multi-display systems

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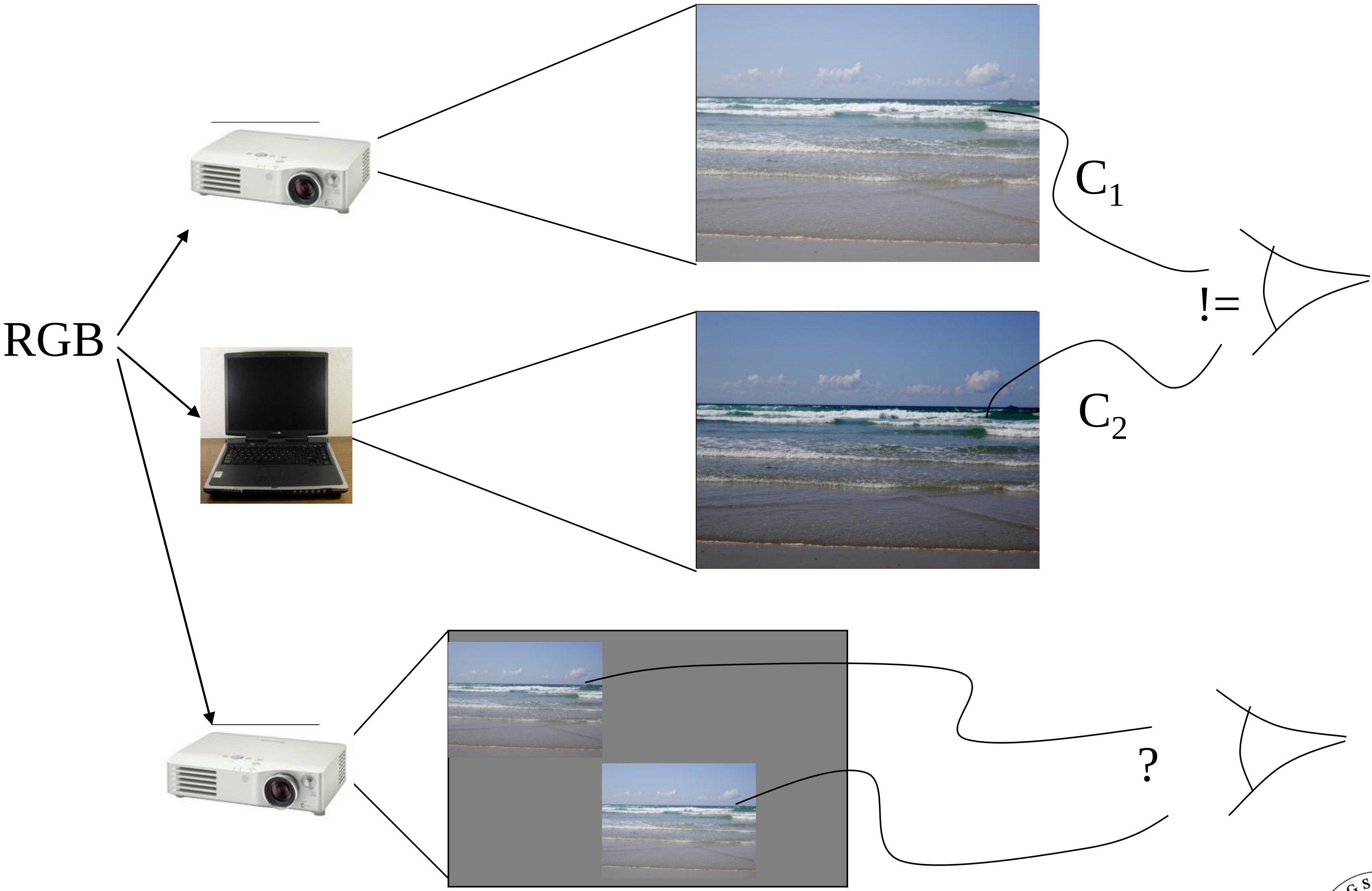
colorlab.no The Norwegian Color Research Laboratory

HØGSKOLEN I GJØVIK

GUC, Thursday, 16th December, 2009

Displays never reproduce
the same color
for the same input


RGB
C1
C2
!=
?

Who cares?

Duality
Professional vs Consumer

I am a good worker,

Give me more money!

Want to ask for more funding ?

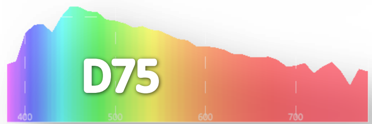
Consumer: aesthetic and intended meaning have to be preserved

I am a good worker,

Give me more

Get more work!

Consumer: aesthetic and intended meaning have to be preserved



Color rendering of multi-spectral images of art paintings under different illuminants

(Thanks Philippe Colantoni and the C2RMF)

Professional: The color rendering has to be perfectly accurate

Agenda

Agenda

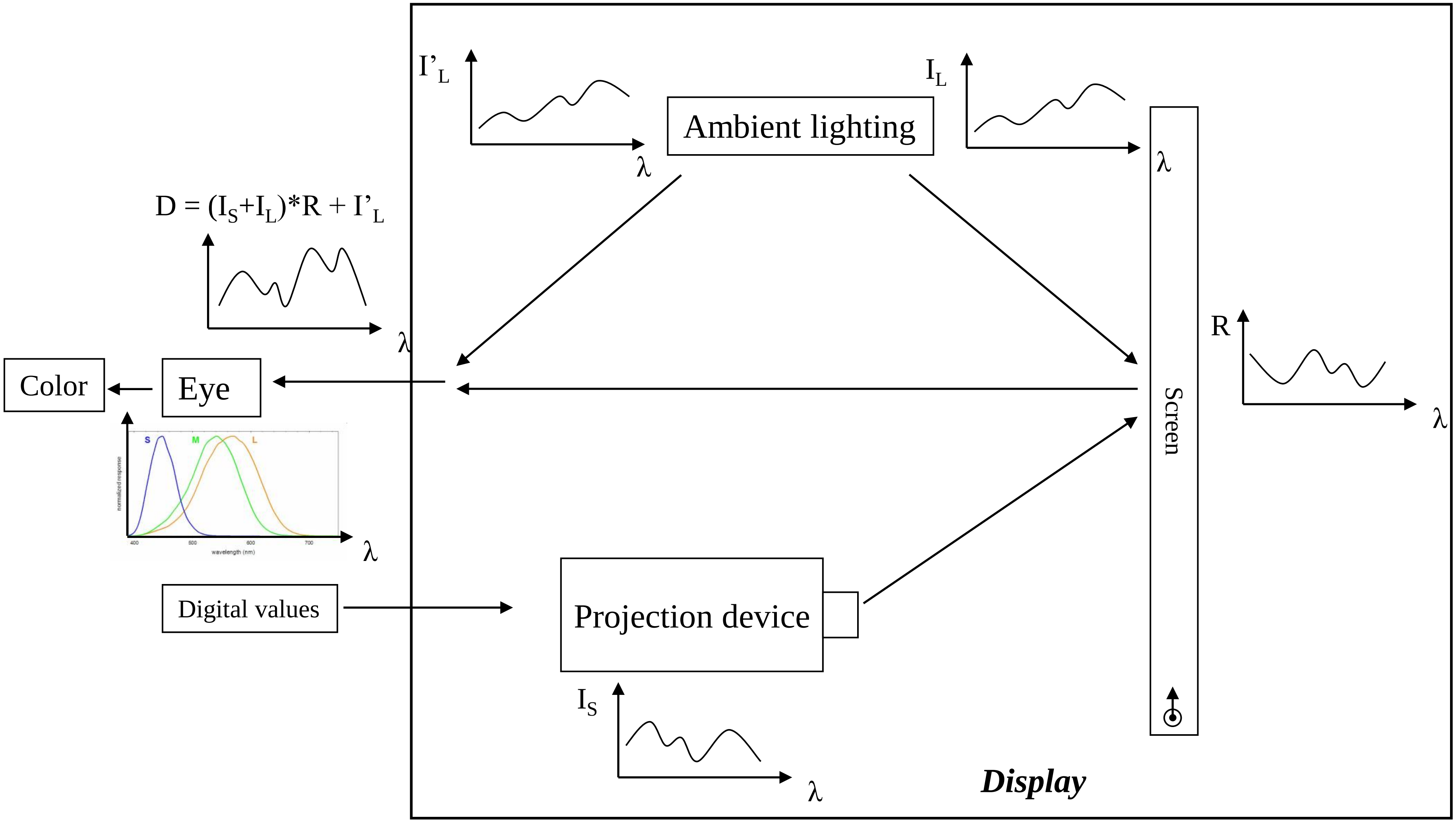
I. Display and color
   1. Definition
   2. Color metrology
   3. 6 dimensional function:
      i. Temporal stability (1D)
      ii. Spatial uniformity (2D)
      iii. Color (3D)
   4. Color characterization

II. Point-wise colorimetric characterization

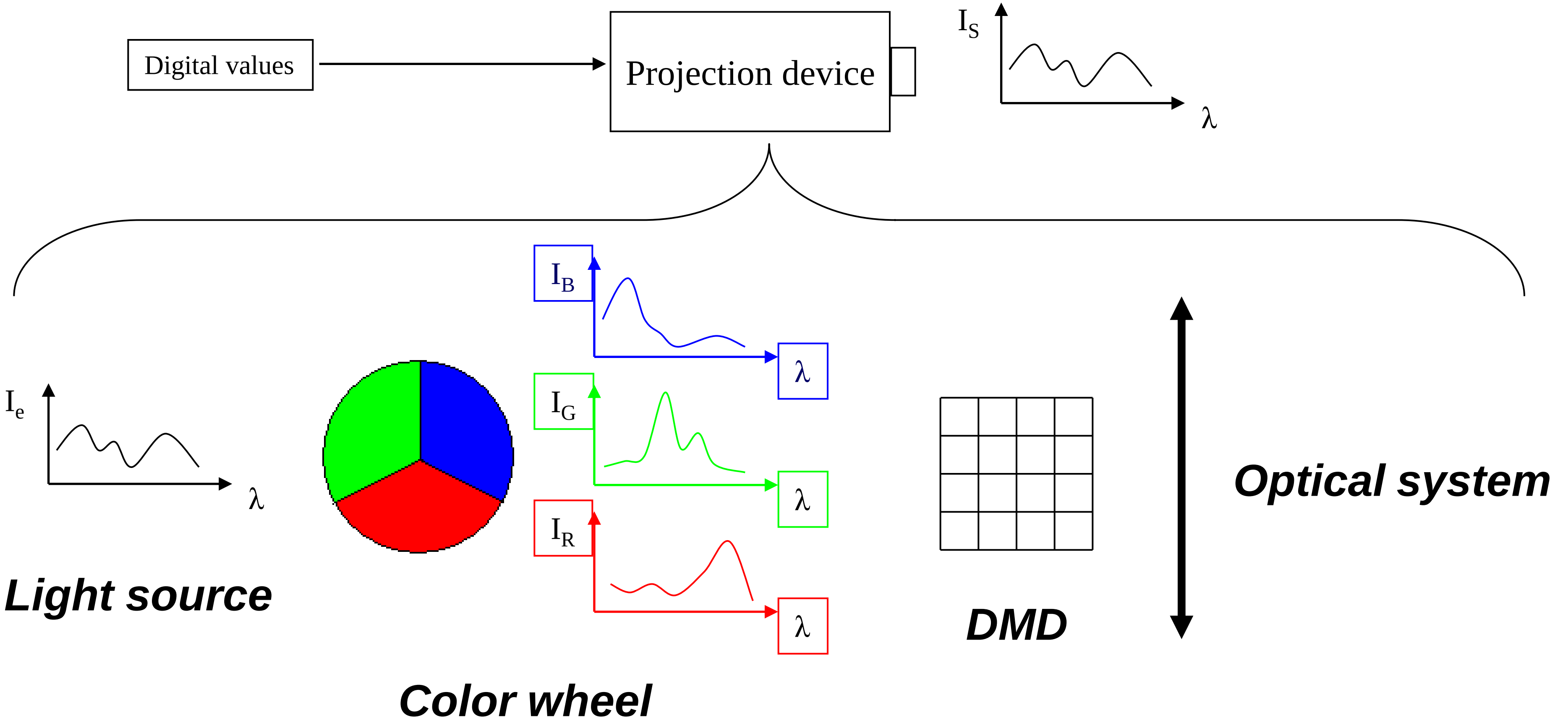
III. Spatial considerations

IV. Conclusion and perspectives

Display: Example of a projector



Digital color display device



Case of a DLP projection device

Measurement and color spaces

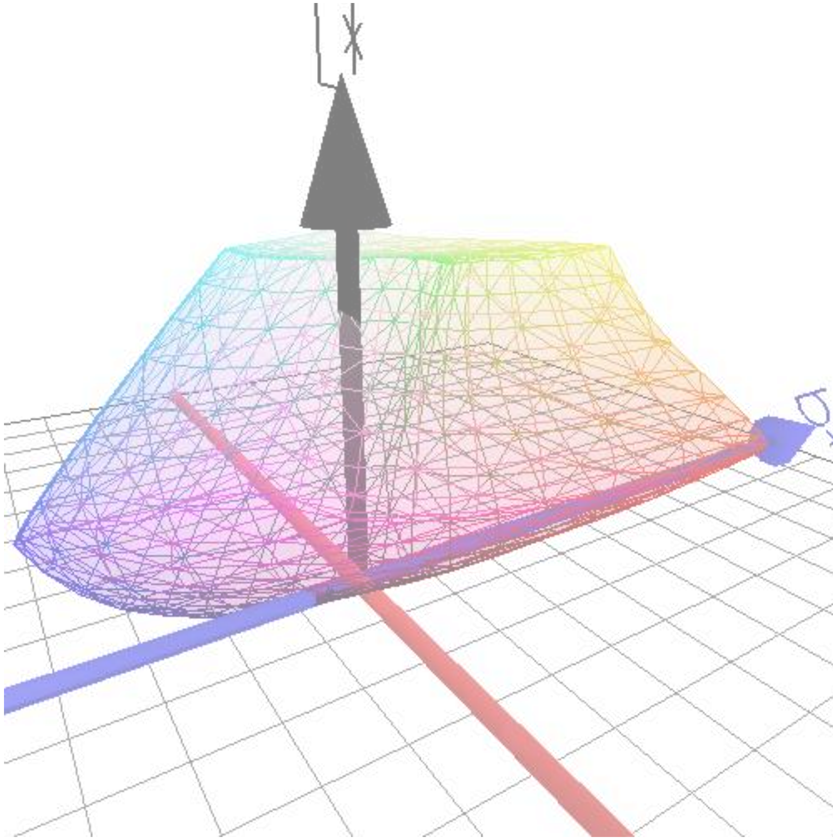
- Measurement
  - Spectral measurements & cone response curves
  - Intensity measurement considering filters that mimics the cone response curves

- Color spaces
  - Digital space: RGB
  - Reference color space: A space where we can describe the color relatively to a standard observer
    - Physically (CIEXYZ)
    - Relatively to white adaptation and perceptually uniform (CIELAB)

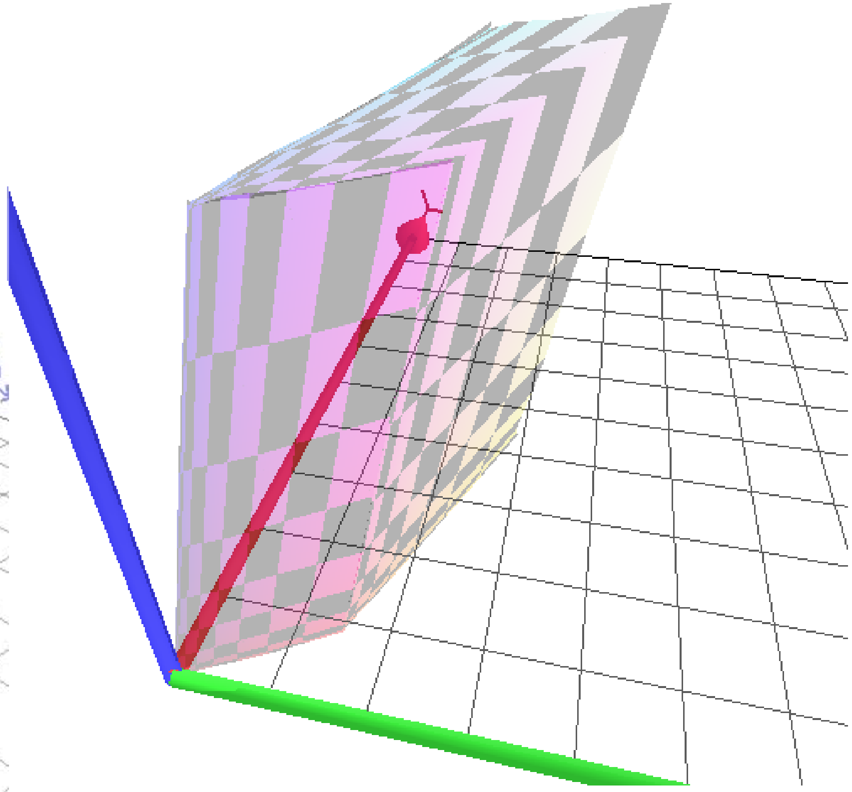
6D function

- Temporal stability (1D)
  - Often assumed to be stable
  - Display dependent
- Spatial uniformity (2D)
  - Often assumed to be uniform in chromaticity
  - Strong luminance shift
- Color (3D)
  - Display color gamut (Set of colors reproducible by a display)

Color gamuts



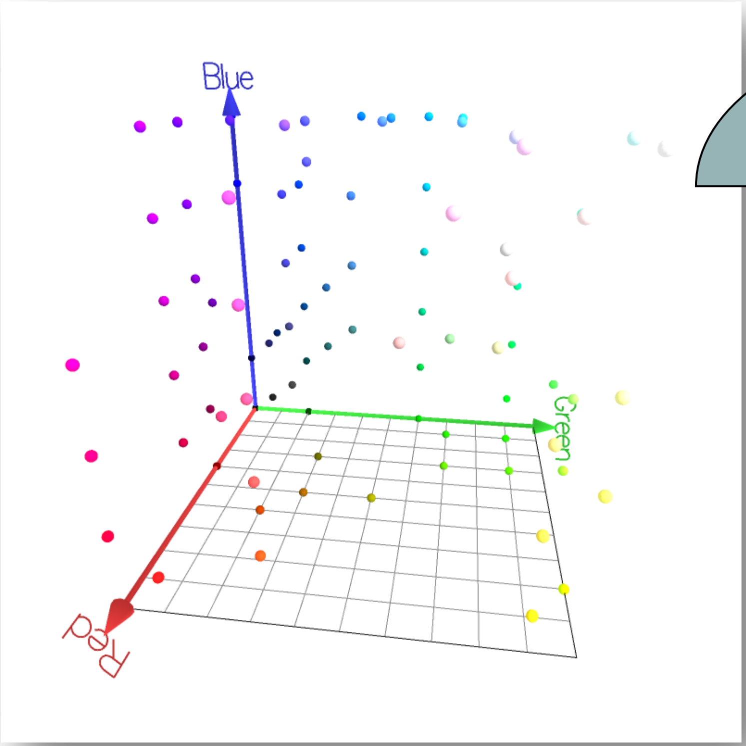
CIELAB



CIEXYZ

Color characterization

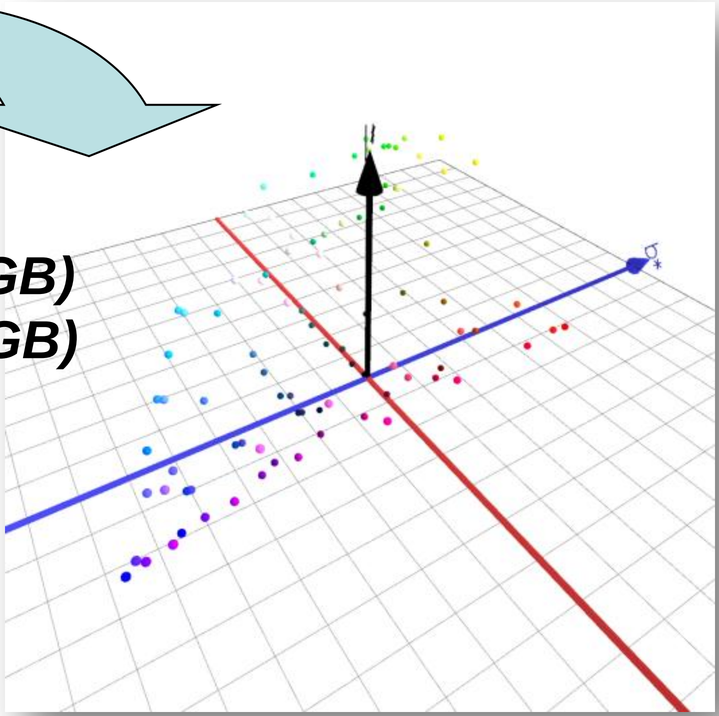
- A model that relates digital input and displayed color (in a reference color space)



Forward model

CIEXYZ = F(RGB)

CIELAB = F(RGB)

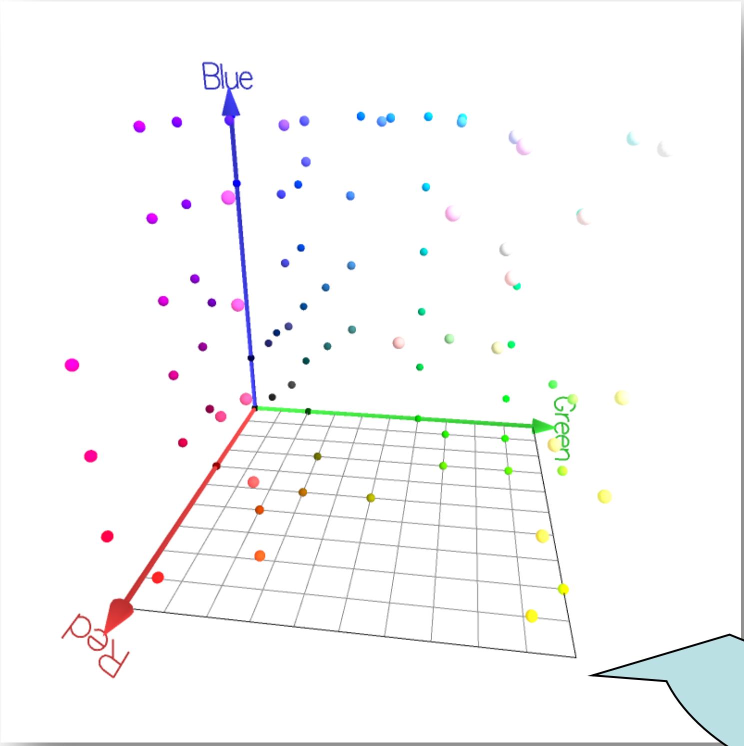


RGB

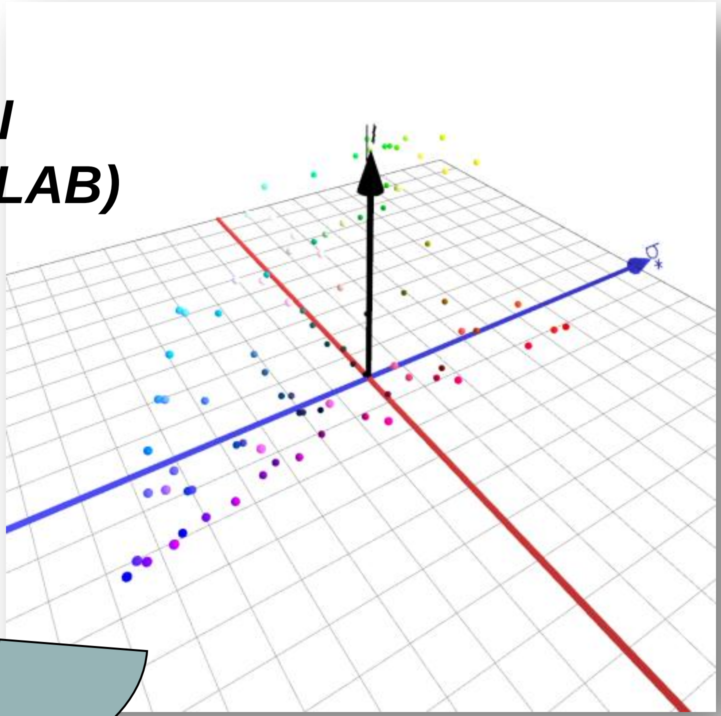
CIELAB

Color characterization

- A model that relates digital input and displayed color (in a reference color space)



Inverse model
RGB = F^{-1}(CIELAB)



RGB ***CIELAB***

Quality

- Metric $\Delta E^*_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$
- Quality criterion (Colorimetry)
  - Just Noticeable Difference

Quality

- Criteria in color imaging
  - Rules of thumb: Hardeberg (1999), Abrardo et al (1996)
  - Only a basis for evaluation, no exact or proved thresholds

ΔE^*_{ab}	Professional		Consumer
Considering	Mean ΔE^*_{ab}	Max ΔE^*_{ab}	Mean ΔE^*_{ab}
$- < 1$	good	good	good
$1 \leq - < 3$	acceptable		
$3 \leq - < 6$	not acceptable	acceptable	acceptable
$6 \leq -$		not acceptable	not acceptable

Agenda

Agenda

Consumer example

I am a good worker,

Give me more

Remember the sick looking guy and its funding ?

No spectroradiometer, photometer or colorimeter at home
But most probably a camera

A simple model

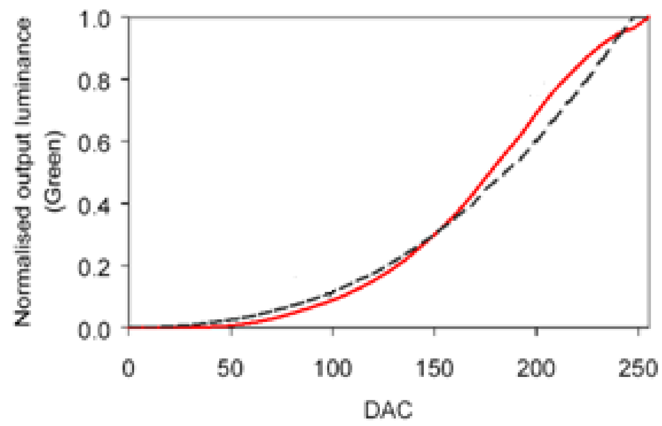
DAC (control) values — $d_r\ d_g\ d_b$

Luminance generation

Luminance levels (i.e. linearized RGB) — $Y_R\ \ Y_G\ \ Y_B$

Colorimetric transform

Tristimulus values — $X\ \ Y\ \ Z$



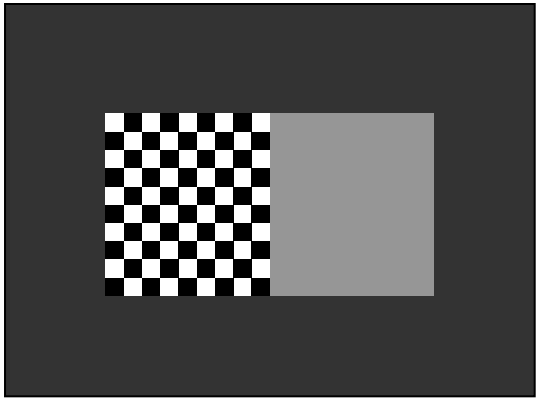
Suppose additivity and chromaticity constancy

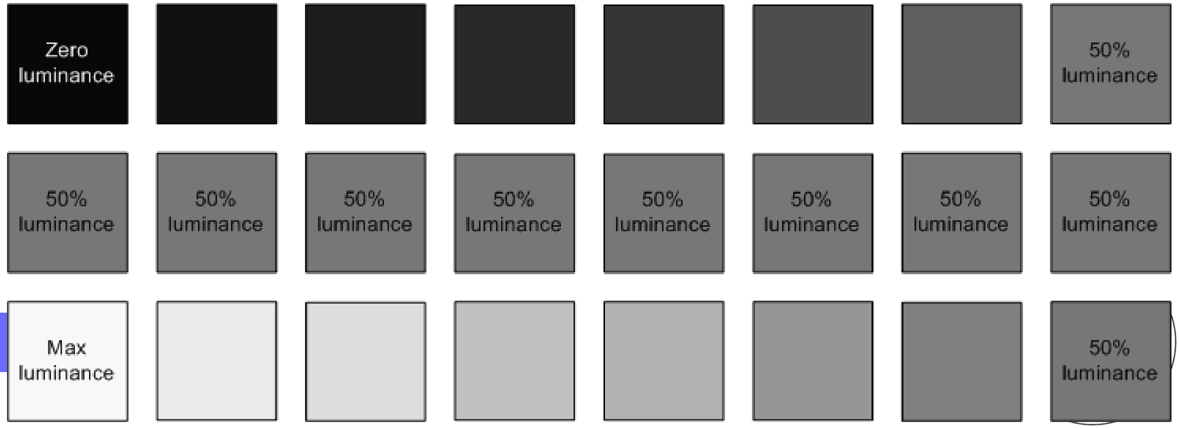
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} \times \begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix}$$

Camera-based response curve estimation

- Originally proposed by Bala et al (2006, 2007)

- 2 tasks
  - Estimating the camera response curve relatively to the display via one visual task
  - Using the camera as a relative photometer to estimate the projector response curve





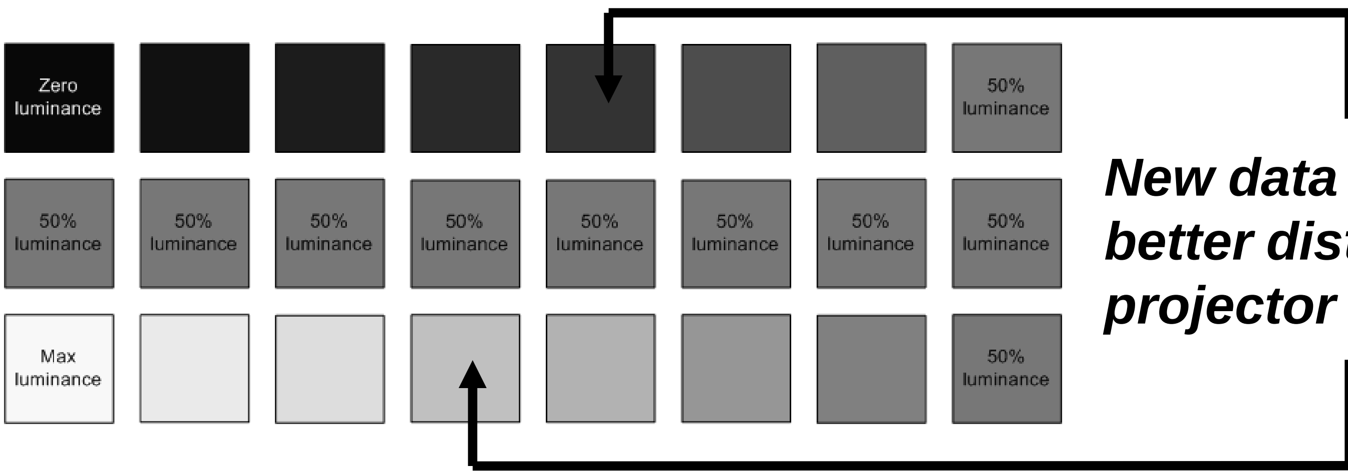
Proposal

- Adding more visually determined levels
  - Increase the accuracy of the camera response curve estimation
- Individual estimation of each primary
  - Projector response curve can vary severely between channels

Mikalsen, E. B., Hardeberg, J. Y. and Thomas, J.-B. (2008), ***Verification and extension of a camera-based end-user calibration method for projection displays***, *in* 'CGIV'.

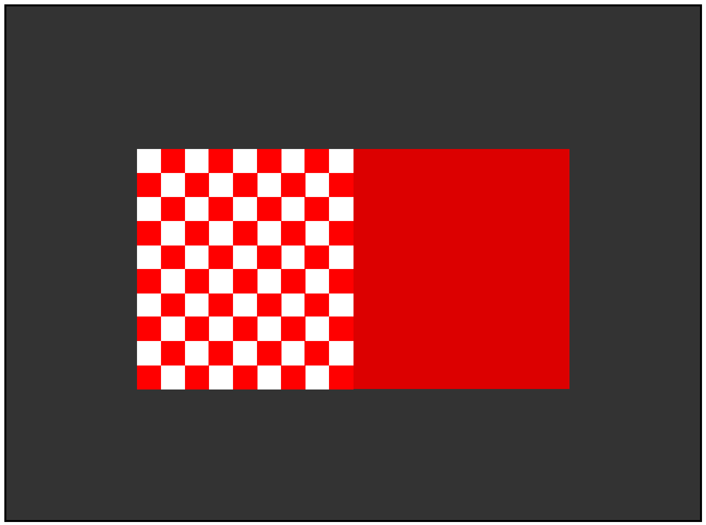
Improvement: Adding visual matching point

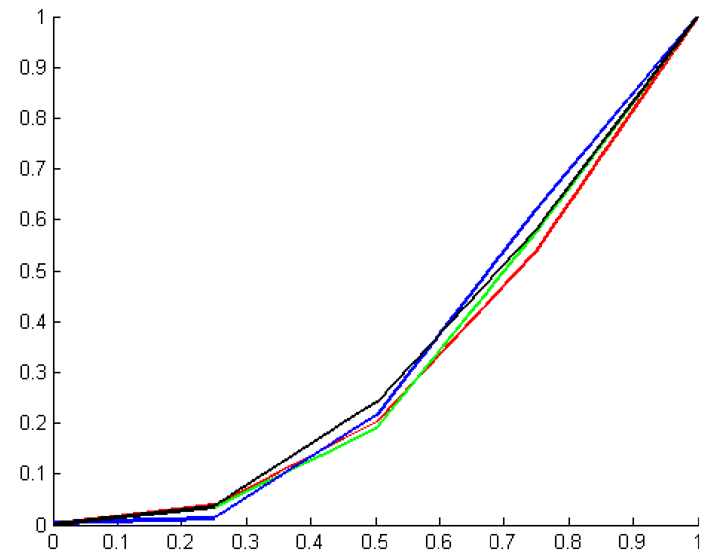
Adding two new luminances (25% and 75%) to determine the camera response curve



New data for the camera and better distribution for the projector

Improvement: Individual channel estimation





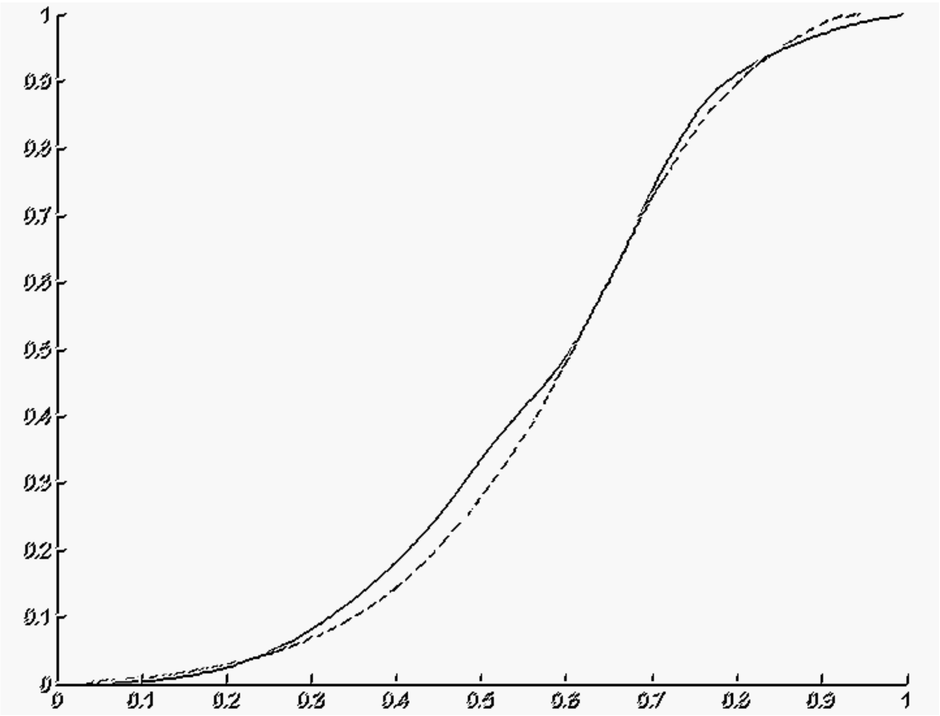
Individual estimation of R, G and B channel response curves

Projector response curves can be significantly different from channel to channel

Results

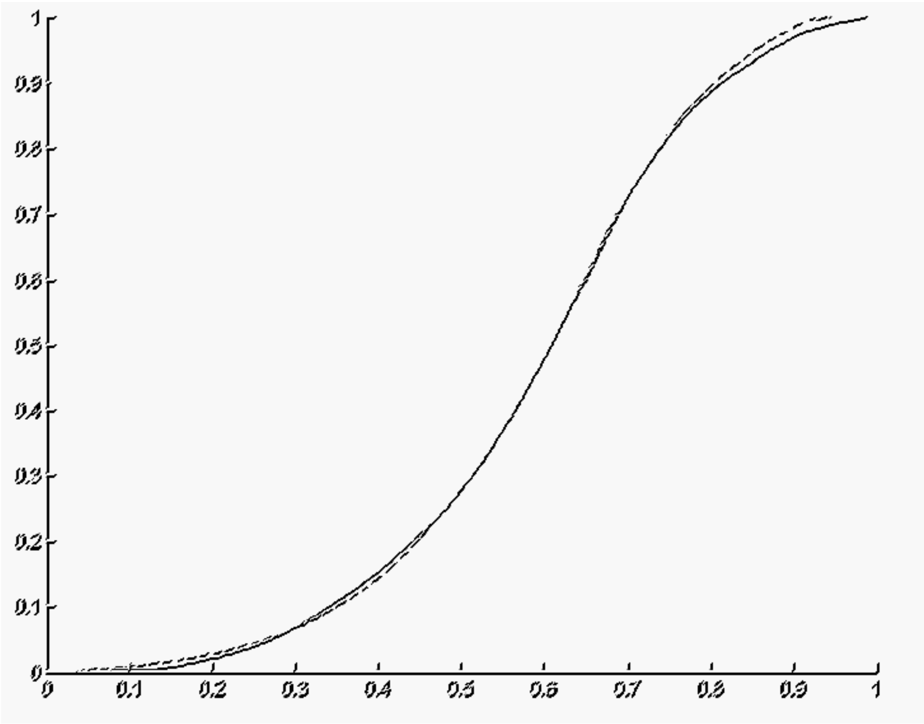
- Projector response curve estimation

Gray 1 (Original method)



ΔL = 1.82

Gray 3



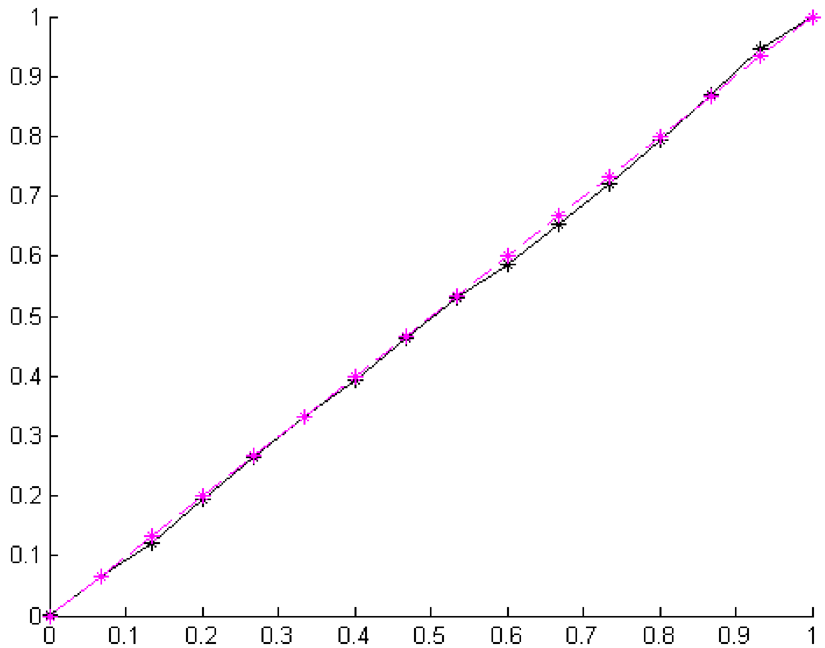
ΔL = 0.65

Measured response in dashed line: We improved the estimation

Results

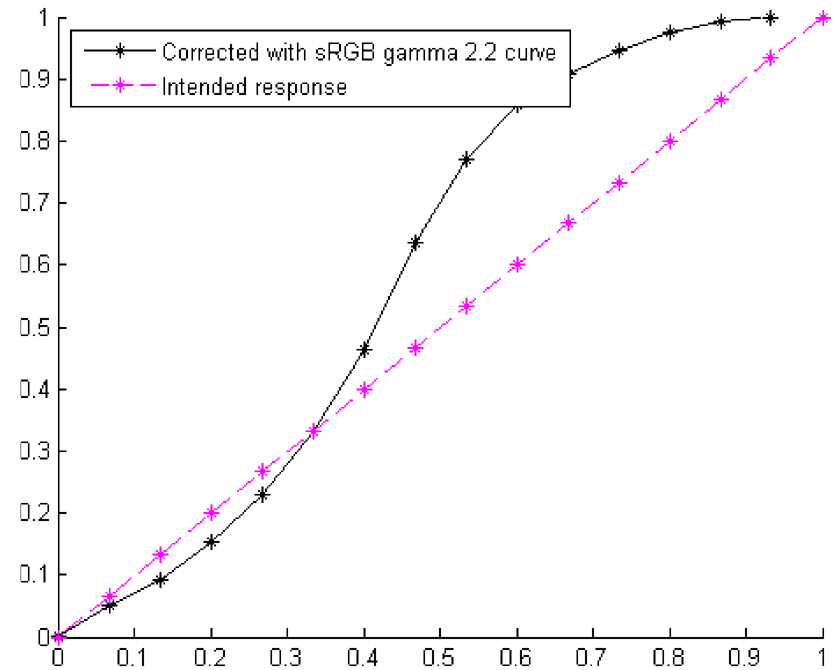
- Correction compared with sRGB

Gray 3 matching point



ΔL = 0.60

sRGB

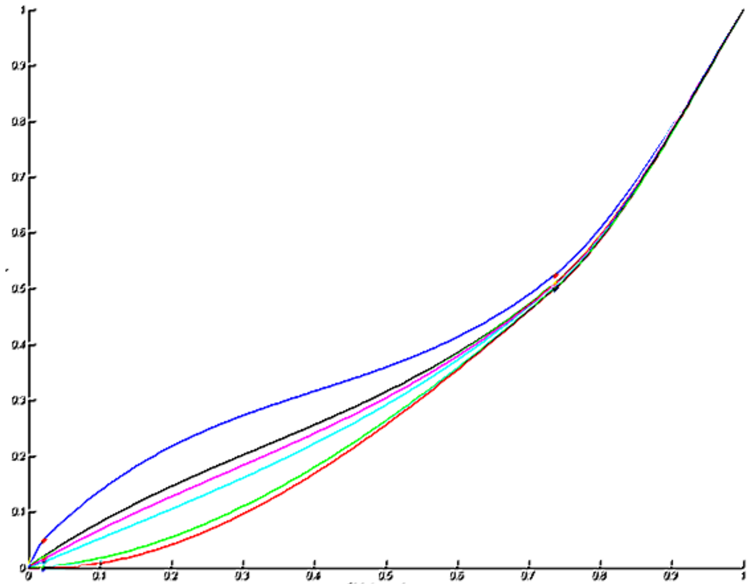


ΔL = 10.53

Perfect correction in pink

Discussion

- Black level estimation
  – Bala and Braun (2006): Flare of about 2% in dim condition
  – Mikalsen et al (2008): Flare estimation is of major importance: We measured it



Consequences of using several estimation of the black offset while using cubic spline for the interpolation

Conclusion

- We increased the accuracy of the method
- Some combinations camera/projector do not work
  - Dynamic range

Agenda

I. Display and color

II. Point-wise colorimetric characterization

1. Consumer
   i. Response curve estimation
2. Professional
   i. Model based on polyharmonic splines and inversion
3. Classification

III. Spatial considerations

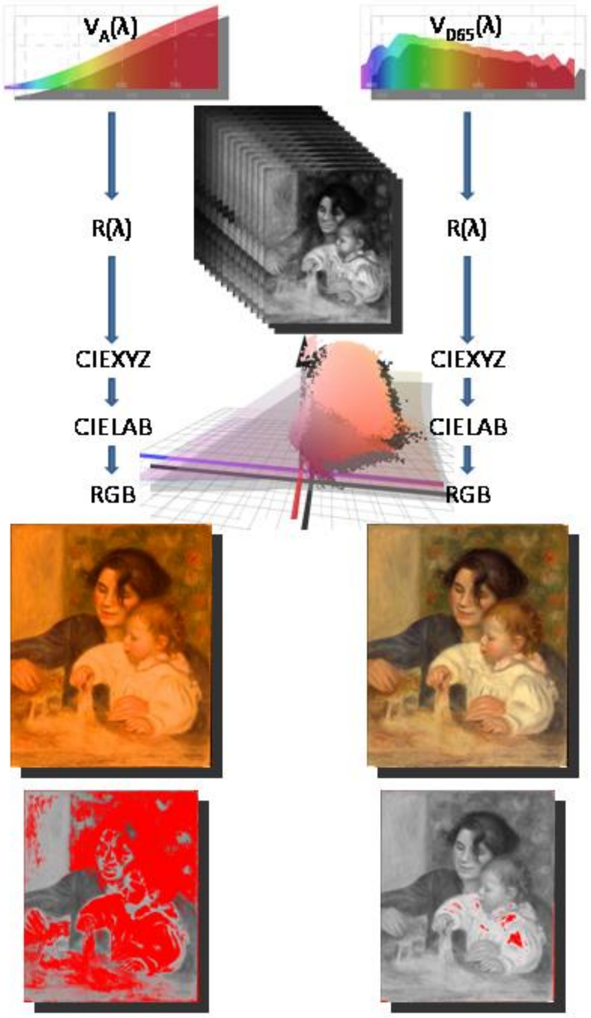
IV. Conclusion and perspectives

Professional

If you investigate art paintings:
You have a controlled environment, a high quality monitor, a spectroradiometer, a super computer, a high quality GPU, etc.

Professional application

- Color rendering of multi-spectral images under different illuminants



Visualizing paintings under different illuminants give some information of interest for experts.

3D Look Up Table

- Technology independent
- Empirical method
  - Number of measurements used to describe the whole transform

3D Look Up Table

- Defined by
  - A given number of data
  - A pattern for data distribution
  - An interpolation method

Proposal

- Iterative refinement of the forward model data set
- Give more freedom to the model parameters
- Optimize the data distribution for the inversion

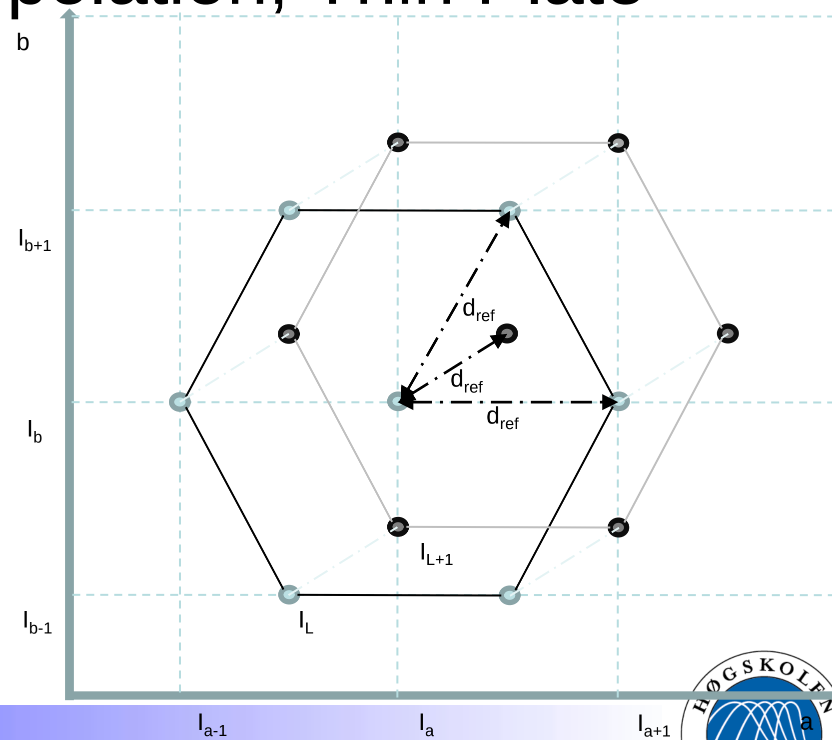
Colantoni, P. and Thomas, J.-B. (2009), ***A color management process for real time color reconstruction of multispectral images***, *in* ‘Lecture Notes in Computer Science’, *16th SCIA*.

Thomas, J.-B., Colantoni, P., Hardeberg, J. Y., Foucherot, I. and Gouton, P. (2008*a*), “***A geometrical approach for inverting display color characterization models***”, *in JSID* , Vol. 16.

Thomas, J.-B., Colantoni, P., Hardeberg, J. Y., Foucherot, I. and Gouton, P. (2008*b*), ***An inverse display color characterization model based on an optimized geometrical structure***, *in* ‘proc. SPIE’.

Forward model

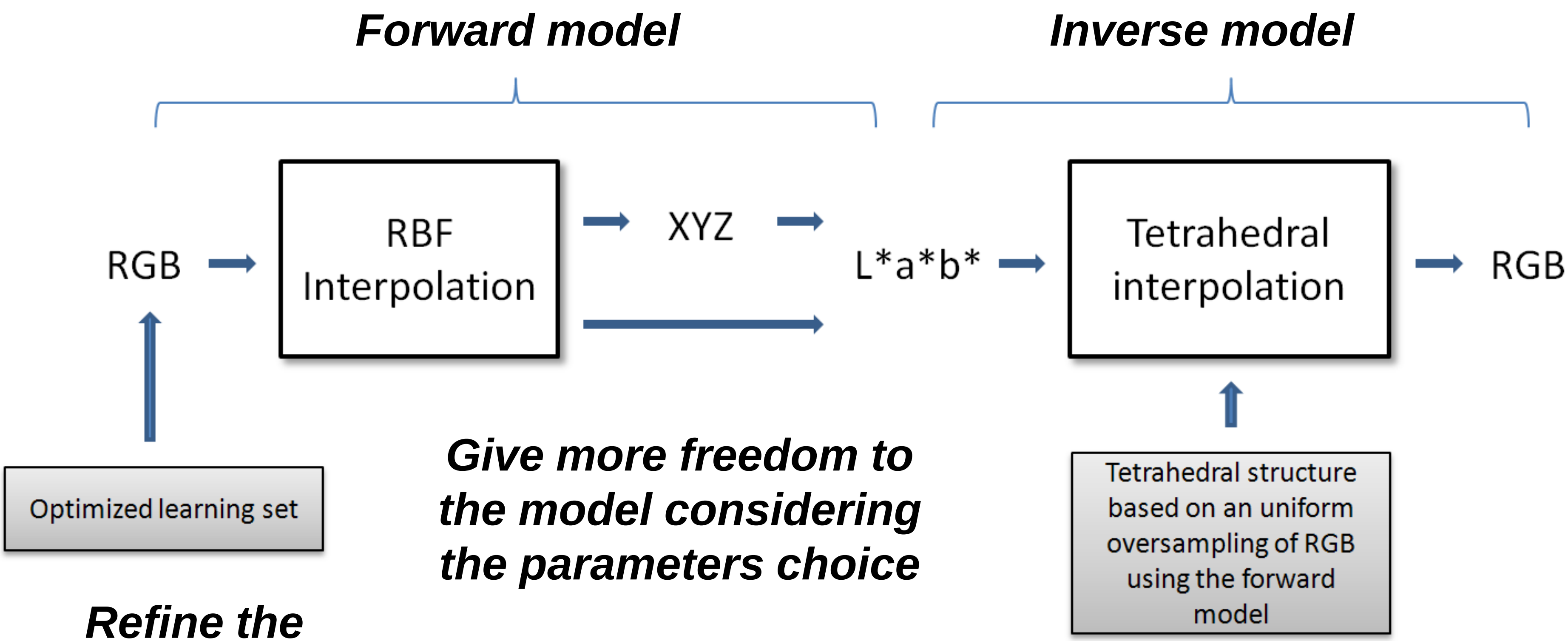
- Forward model proposed by Stauder et al (2006, 2007)
- Radial Basis Function interpolation, Thin Plate Spline kernel
- Regular hexagonal pattern in CIELAB



Inverse model

- Based on an inversion method proposed by Stokes (1997)
  - Creating data for inversion by using the forward model
- Tetrahedral linear interpolation

Overview



Give more freedom to the model considering the parameters choice

Refine the optimized learning data set

Optimize the tetrahedral structure for the inversion

Iterative refinement of the optimized data set

Temporary model based on a few measurement

↓ ***Generate***

A RGB data set to measure that fits the geometrical pattern in a reference space

↓

Measure of one RGB value

↓

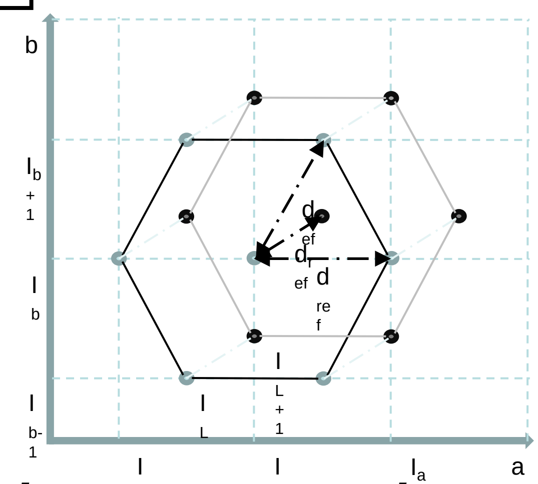
Store data

↓

Actual model

Store data → ***Generate*** → ***New temporary model*** → ***Regenerate more accurately the rest of the data set to measure*** → ***A RGB data set to measure***

Until all RGB data has been measured



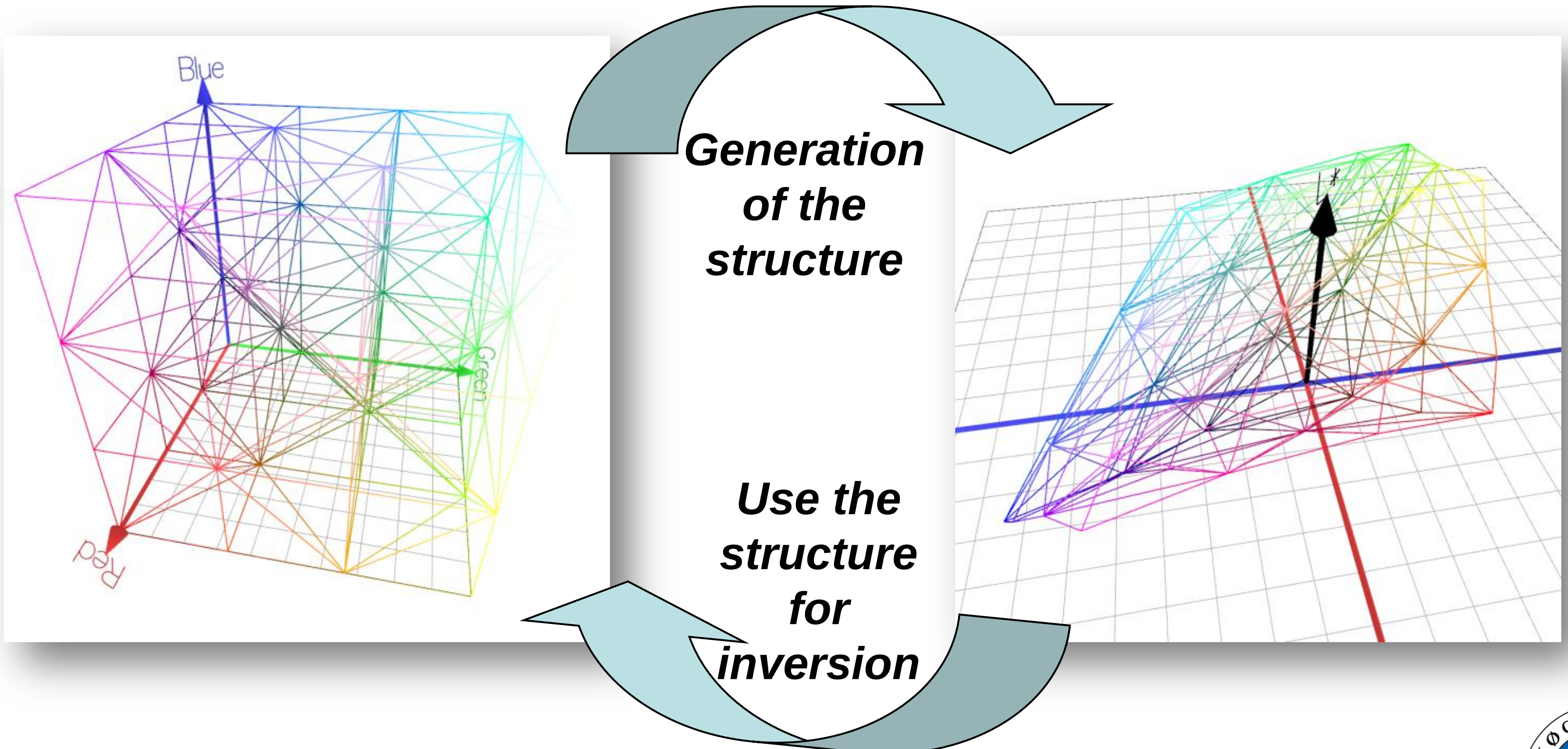
Parameters choice

- Parameters to optimize
  - Kernels: Biharmonic (r), Triharmonic (r^3), Thin Plate Spline ($r^2\log(r)$ and $r^2\log(r^2)$)
  - Smoothing factor: 0 => interpolation, !=0 => approximation
  - Color space target: CIEXYZ or CIELAB

- Brute force approach
  - Cost function: mean(ΔE^*_{ab}) x Standard deviation(ΔE^*_{ab})

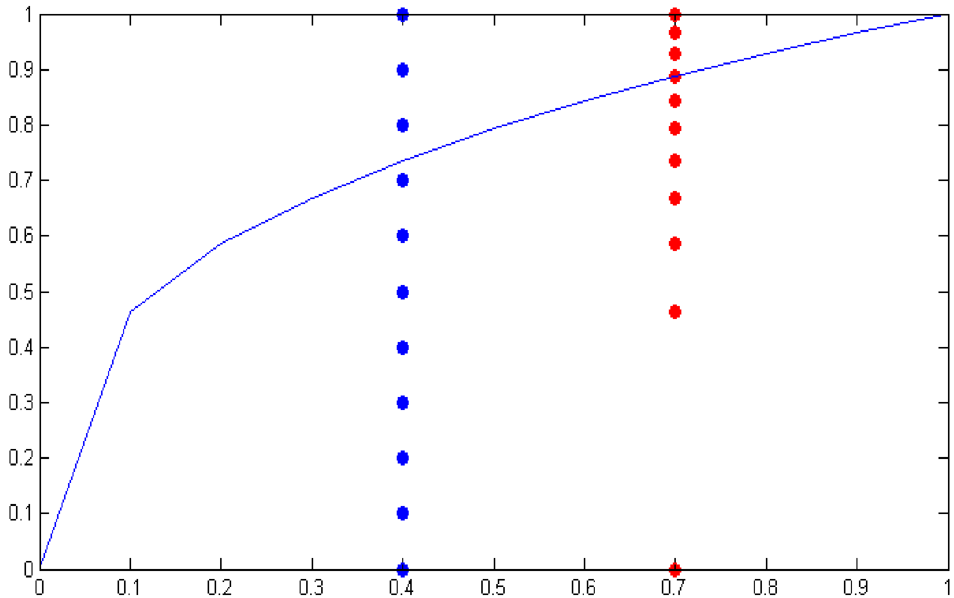
Inversion not optimized

- Original inverse model based on a regularly spaced grid in RGB



Problem of distribution

- CIELAB = F(RGB) is not linear
- Tetrahedral linear interpolation: the accuracy is not the same everywhere in the color space



Plot of a cubic root function (such as in CIELAB transform)

Linearly distributed data (mimic RGB)

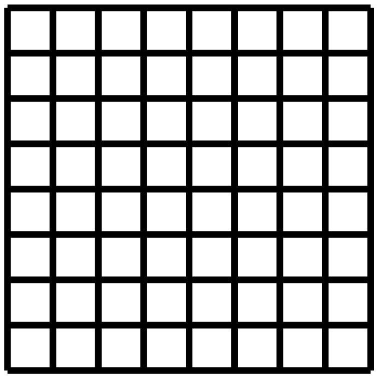
Data set used for the interpolation (mimic CIELAB)

Data redistribution

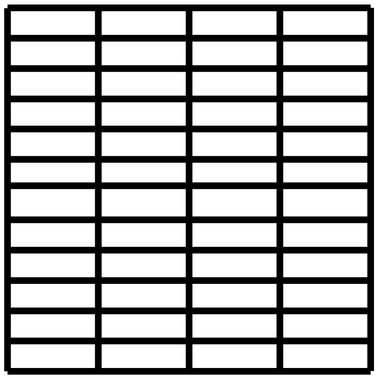
- We proposed different methods for global redistribution
- Other methods exist (Dianat (2006), Groff (2000), etc.)
- Better map of CIELAB or better accuracy on a training set

Data redistribution

- Only a different data number along R, G and B axis
  - Same training data set as for the forward model
  - Same criterion (mean(ΔE^*_{ab}) x Standard deviation(ΔE^*_{ab}))



Regular grid data in RG plane



Redistributed data in RG plane

Results

- Forward: 216 color patches
- Inverse: 36x36x36 data
- Compared with a uniform grid

Results

	Forward model		Inverse model	
	ΔE Mean	ΔE Max	ΔRGB Mean	ΔRGB Max
Optimized	0.332	1.075	0.00311	0.01267
Uniform	0.435	1.613	0.00446	0.01332

CRT monitor Mitsubishi SB2070

	Forward model		Inverse model	
	ΔE Mean	ΔE Max	ΔRGB Mean	ΔRGB Max
Optimized	1.057	4.985	0.01504	0.1257
Uniform	1.313	9.017	0.01730	0.1168

LCD monitor HP2408w

display device	ΔE Mean	Mean(ΔE STD)	ΔE Max
SB2070 - CRT Mitsubishi	0.234267	0.159998	1.55088
HP2408w - LCD Hewlett-Packard	1.93712	1.35595	10.8971

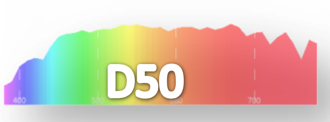
Repeatability

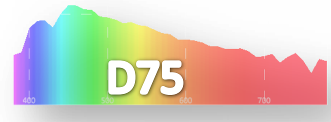
Results

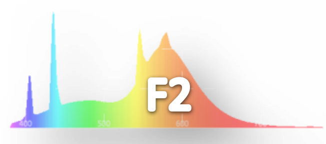
	Forward model		Inverse model	
	ΔE Mean	ΔE Max	ΔRGB Mean	ΔRGB Max
EIZO CG301W (LCD)	0.783	1.906	0.00573	0.01385
Sensy 24KAL (LCD)	0.956	2.734	0.01308	0.06051
DiamondPlus 230 (CRT)	0.458	2.151	0.00909	0.06380

Results on other monitors, professional performance on all

II. Point-wise color characterization: Professional







Agenda

Classification

- Based on our results
  - Several displays
  - Several models (PLCC*, PLVC, GOGO, Bala, Polyharmonic splines)

Thomas, J.-B., Hardeberg, J. Y., Foucherot, I. and Gouton, P. (2007), ***Additivity based LC display color characterization***, *in GCIS'07*.

Thomas, J.-B., Hardeberg, J. Y., Foucherot, I. and Gouton, P. (2008), "***The PLVC color characterization model revisited***", *Color Research & Application* , Vol. 33.

Colantoni, P. and Thomas, J.-B. (2009), ***A color management process for real time color reconstruction of multispectral images***, *in* 'Lecture Notes in Computer Science', *16th SCIA*.

Mikalsen, E. B., Hardeberg, J. Y. and Thomas, J.-B. (2008), ***Verification and extension of a camera-based end-user calibration method for projection displays***, *in* 'CGIV'08'.

Classification

PLVC	Bala	PLCC*	Polyharmonic splines	GOGO
54 (XYZ) measures	1 to 3 visual tasks times 1 to 3 pictures	54 (Y) measures 3 (XYZ)	216 (XYZ) measures	4 to 54 (Y) measures 3 (XYZ)
Technology dependent	Technology dependent	Technology dependent	Technology independent	CRT
Professional or Consumer	Consumer	Professional or Consumer	Professional	Consumer

The efficiency of a model is dependent on several factors: the number of measurements, the nature of the data to measure, the computational cost, its accuracy, etc.

It depends strongly on the display

Agenda

I. Display and color
II. Point-wise colorimetric characterization
III. Spatial considerations
   1. Why ?
   2. Evaluation
      i. Common approach
      ii. Global 3D approach
   3. Conclusion
IV. Conclusion and perspectives

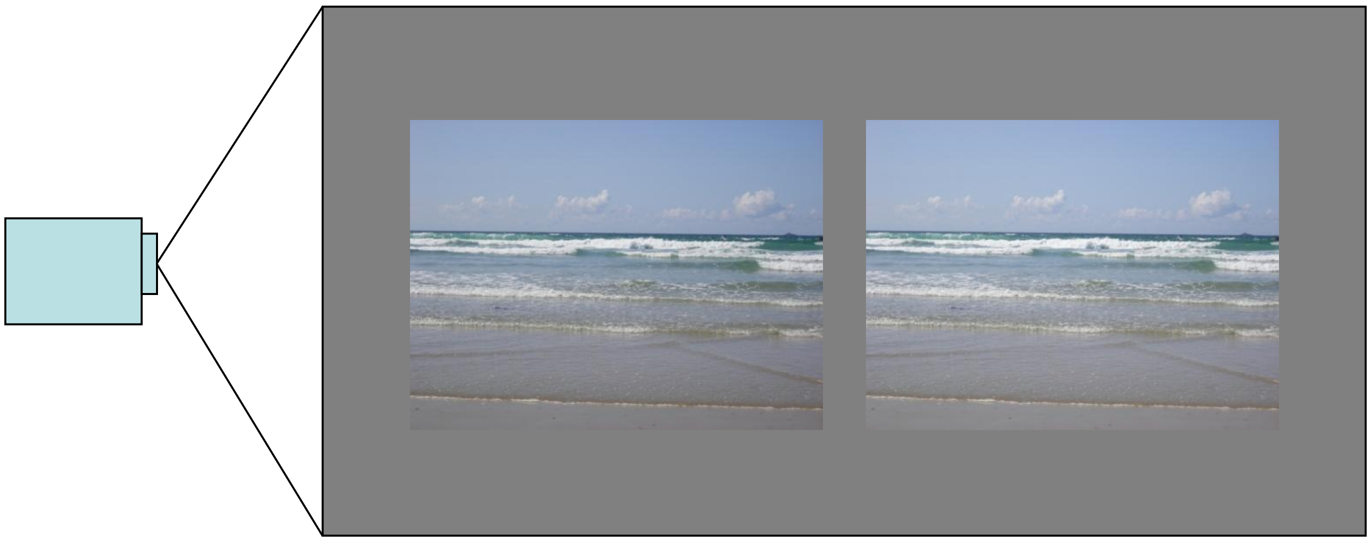
Why spatial characterization ?

- Need of visual uniformity for multi-display systems

Multi-projector systems show a strong non-uniformity
Image from Majumder (2005)

Why spatial characterization ?

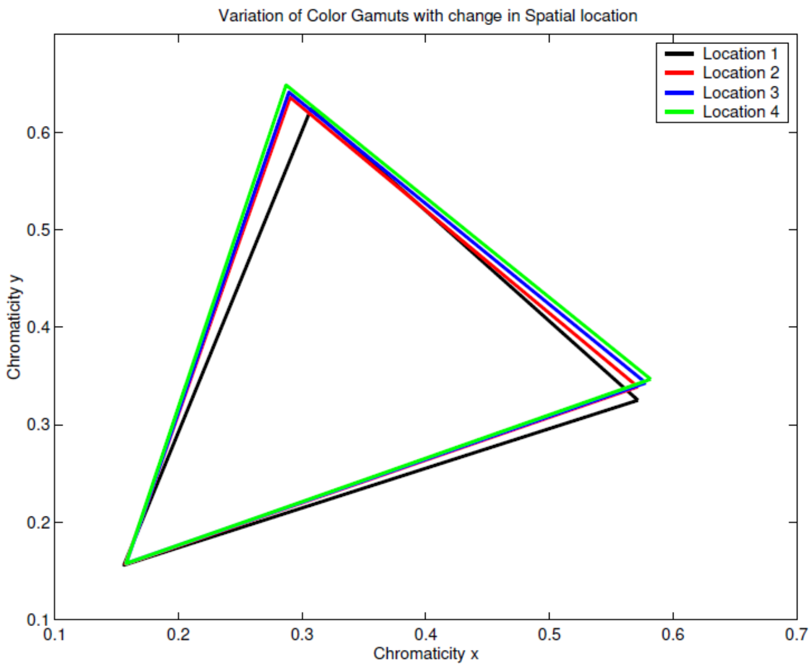
- Need of colorimetric uniformity and colorimetric control for psychovisual experiments



Tell me when you see a difference between these two images.

Proposal

- Assumption of chromaticity spatial homogeneity for many applications

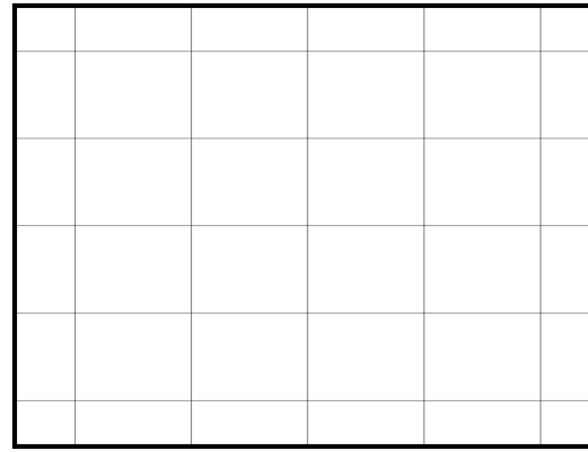


Majumder and Stevens
IEEE Transactions on Visualization and Computer Graphics (2004)

Gamut in the chromaticity plane at several locations across one display

- These gamuts are as different as different displays

Evaluation



- Common approach
  - Measurement of a color patch at several locations
- Global approach
  - 3D gamut comparison between several locations
- Global reference white: the highest luminance point

Thomas, J.-B. and Bakke, A. M. (2009), ***A colorimetric study of spatial uniformity in projection displays***, *in* ‘Lecture Notes in Computer Science’, ‘CCIW’09’.

Major measured color difference

LCD1					
ΔE^*_{ab}	1	2	3	4	5
1	9.26	5.24	2.80	2.93	7.53
2	7.89	4.14	1.41	1.81	7.26
3	6.61	4.41	0.00	1.05	5.14
4	9.57	5.10	1.89	1.95	3.68
5	11.64	7.97	6.05	5.75	6.64

LCD2					
ΔE^*_{ab}	1	2	3	4	5
1	6.80	3.80	1.70	3.45	7.36
2	6.77	3.07	0.00	2.82	6.75
3	7.03	2.92	1.97	2.02	5.07
4	5.76	5.44	4.84	4.44	6.11
5	8.07	7.94	7.13	8.57	10.17

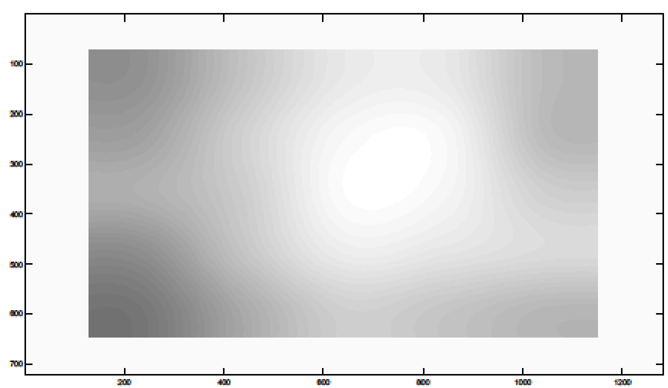
DLP					
ΔE^*_{ab}	1	2	3	4	5
1	21.71	17.60	14.88	15.36	19.09
2	21.58	15.45	12.40	12.78	17.73
3	19.97	12.00	7.20	9.97	16.36
4	18.52	8.94	1.92	5.16	13.11
5	18.18	7.92	0.00	1.25	11.97

- ΔE^*_{ab} on 3 displays (2 LCD and 1 DLP)
  - Of about 10 units from the center to an angle
  - Up to about 20 units between 2 locations
- Only due to luminance?

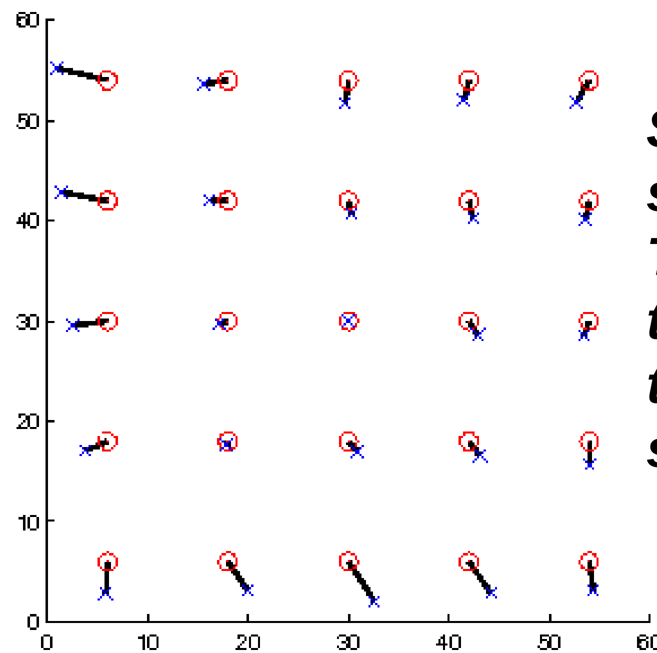
Lightness and Chroma are varying

LCD1											
ΔL^*	1	2	3	4	5	ΔC^*	1	2	3	4	5
1	-8.92	-4.85	-1.61	-1.60	-5.55	1	5.09	2.46	2.29	1.99	2.49
2	-7.66	-3.72	-0.37	-0.36	-5.55	2	4.68	1.78	1.36	1.81	1.97
3	-6.42	-4.09	0.00	-0.58	-3.74	3	3.53	0.87	0.00	1.65	1.56
4	-9.29	-4.77	-1.29	-1.91	-2.81	4	2.37	0.40	1.39	1.80	2.31
5	-11.27	-7.02	-3.78	-4.64	-5.84	5	3.16	3.41	4.73	3.77	1.91

Difference in lightness and chroma



Spatial lightness shift



Spatial chroma shift: The circles are the references, the cross the shift

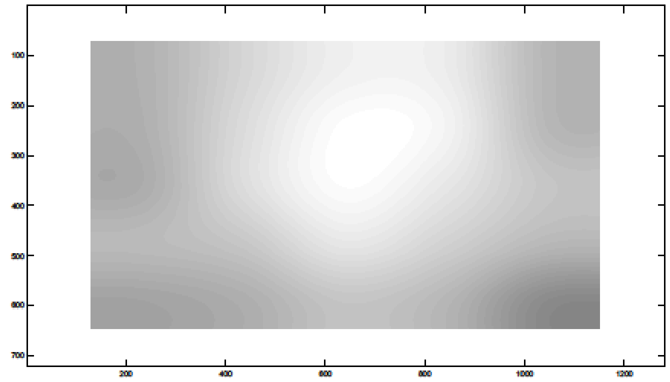
Lightness and Chroma are varying

LCD2

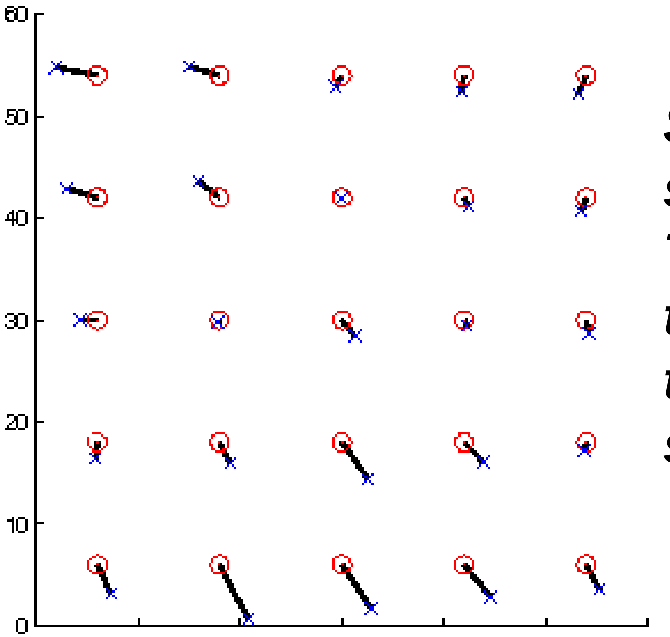
ΔL^*	1	2	3	4	5
1	-6.49	-3.43	-1.14	-1.53	-6.09
2	-6.63	-2.93	0.00	-0.90	-5.96
3	-6.90	-2.85	-0.11	-2.00	-4.78
4	-5.71	-4.68	-1.94	-3.79	-5.89
5	-7.59	-6.75	-4.82	-6.09	-9.66

ΔC^*	1	2	3	4	5
1	4.13	3.09	1.26	1.63	2.03
2	3.17	2.68	0.00	0.92	1.38
3	1.67	0.24	1.97	0.66	1.35
4	1.60	2.32	4.44	2.77	0.78
5	3.18	6.03	5.25	4.18	2.76

Difference in lightness and chroma



Spatial lightness shift

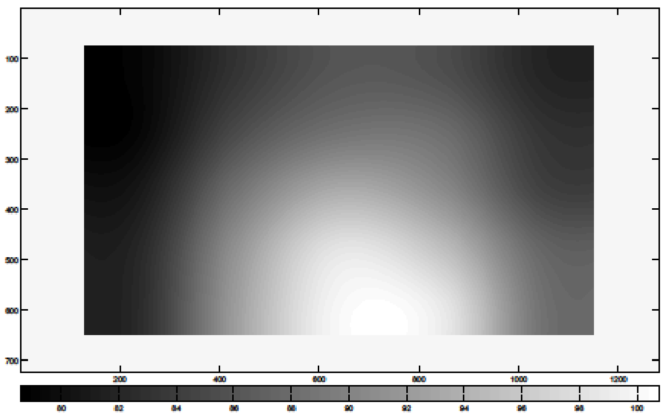


Spatial chroma shift: The circles are the references, the cross the shift

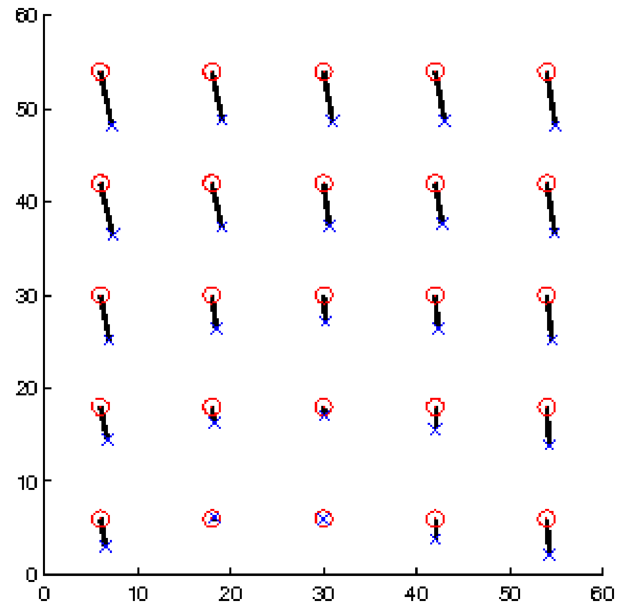
Lightness and Chroma are varying

DLP										
ΔL^*	1	2	3	4	5	ΔC^*	1	2	3	4	5
1	-20.88	-16.72	-13.84	-14.40	-18.14	1	5.97	5.37	5.47	5.47	5.92
2	-20.90	-14.79	-11.49	-11.83	-16.80	2	5.68	4.85	4.65	4.44	5.40
3	-19.39	-11.46	-6.63	-9.29	-15.60	3	4.94	3.62	2.81	3.56	4.81
4	-18.06	-8.61	-1.68	-4.87	-12.63	4	3.53	1.70	0.92	2.41	4.09
5	-17.77	-7.62	0.00	-1.21	-11.58	5	3.01	0.31	0.00	2.18	3.85

Difference in lightness and chroma



Spatial lightness shift



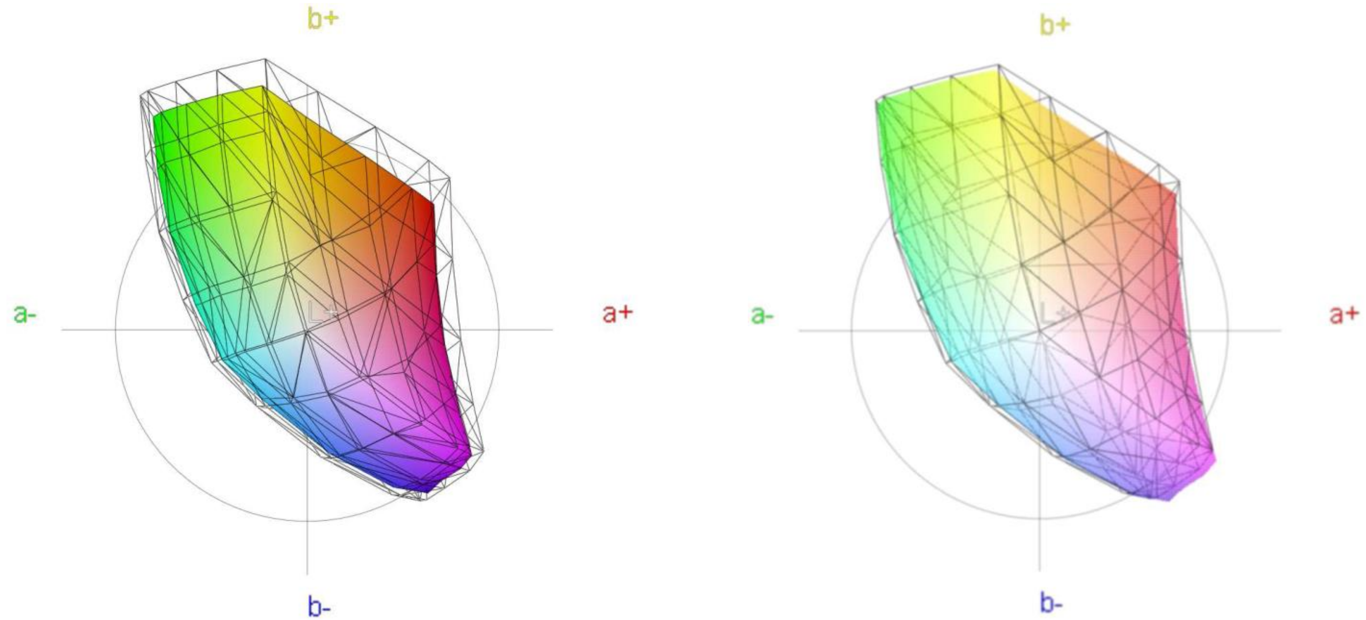
Spatial chroma shift: The circles are the references, the cross the shift

Conclusion

- The assumption that considers the color shift as negligible does not hold

Global approach

- Gamut volume comparison: Bakke et al (2006)
  - Gamut global difference
  - Percentage of gamut mismatch for each position compared with the reference.



Local white point vs global white point

- After lightness adjustment there is still a noticeable difference

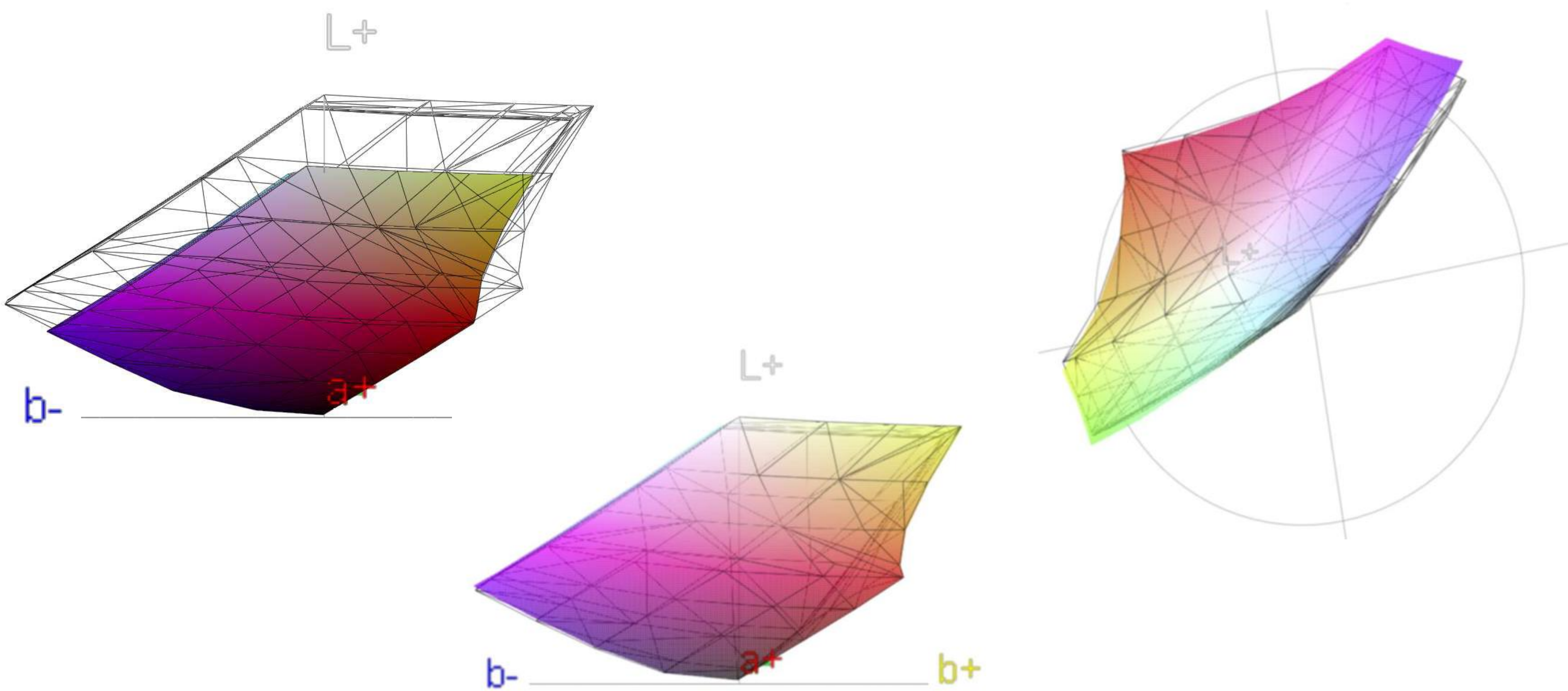
Gamut mismatch

Gamut mismatch, global white point				Gamut mismatch, local white point			
LCD1							
%	1	3	5	%	1	3	5
1	27.23	4.90	17.08	1	9.57	3.30	5.72
3	23.92	0.00	16.15	3	7.49	0.00	5.53
5	32.66	9.48	13.50	5	7.90	2.07	4.09
LCD2							
%	1	3	5	%	1	3	5
1	24.84	5.83	19.75	1	9.42	2.48	4.46
3	20.18	0.00	18.79	3	6.00	0.00	2.40
5	29.75	11.01	20.82	5	5.98	1.98	2.48
DLP							
%	1	3	5	%	1	3	5
1	52.36	38.02	41.06	1	8.51	6.86	6.91
3	47.73	18.29	36.28	3	7.96	3.92	6.38
5	43.22	0.00	26.93	5	6.62	0.00	4.87

Global approach

- Relative mismatch comparable to the error introduced when using a simple convex hull as gamut boundary descriptor
- 2.75% inter-device difference at the reference position for the two LCDs.
- Compared with 9.57 or 9.42% intra-device difference

Visualization



Example: DLP

52.36% gamut mismatch mainly due to the luminance shift, but still 8.51% while compensating for it

Conclusion

- Assumptions broken:
  - Intra-difference larger than inter-difference
  - Luminance correction might not be enough
- Need to define spatial color characterization models

Agenda

I. Display
II. Point-wise colorimetric characterization
III. Spatial considerations
IV. Conclusion and perspectives
   1. Summary of contributions
   2. Point-wise color characterization
   3. Spatial color characterization

Summary of contributions

- Display point-wise color characterization
  - Study of models on today technologies
  - Improvement of some models
    - Distribution of data
- Display spatial common assumptions
  - Evaluation
  - Critic

Point-wise characterization

- Consumer vs Professional
  - Color characterization depends on the need
  - The consumer aims to reach the professional "style"
  - Algorithms are designed: need user-friendly specific (free?) software

    (Direct application)

- Quality
  - Metric and criteria: Is a rule of thumb based on ΔE^*_{ab} enough?

    (Applied research)

Spatial color characterization

- Objective colorimetric spatial characterization
  (Applied research)

- Spatial ICC profiles including a shading table?
  (Direct application)

Spatial color characterization

- Subjective, perceptual spatial uniformity
  - Limit of colorimetry
  - Metric and criteria of spatial uniformity
  - Image quality
    - The content will influence the perceived uniformity

(Applied and fundamental research)

Personal bibliography related to this thesis

Journals:

The PLVC display color characterization model revisited, Jean Baptiste THOMAS, Jon HARDEBERG, Irène FOUCHEROT, Pierre GOUTON, Color Research & Application., 33 (6), pp. 449-460, 2008.

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Spatial non-uniformity of color features in projection displays: A quantitative analysis, Jean-Baptiste Thomas, Arne Magnus Bakke, Jérémie Gerhardt, submitted to Journal of Imaging Science and Technology, in review process.

Conferences:

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Verification and extension of a camera-based end-user calibration method for projection displays, Espen MIKALSEN, Jon HARDEBERG, Jean Baptiste THOMAS, Proc. CGIV 2008, IS&T, Terrassa, Spain, pp. 575-579, 2008.

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Takk for oppmerksomheten

THANKS FOR YOUR ATTENTION

Merci de votre attention

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QUESTIONS ?

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Fonds social européen

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UNIVERSITÉ DE BOURGOGNE

Bourgogne Conseil régional

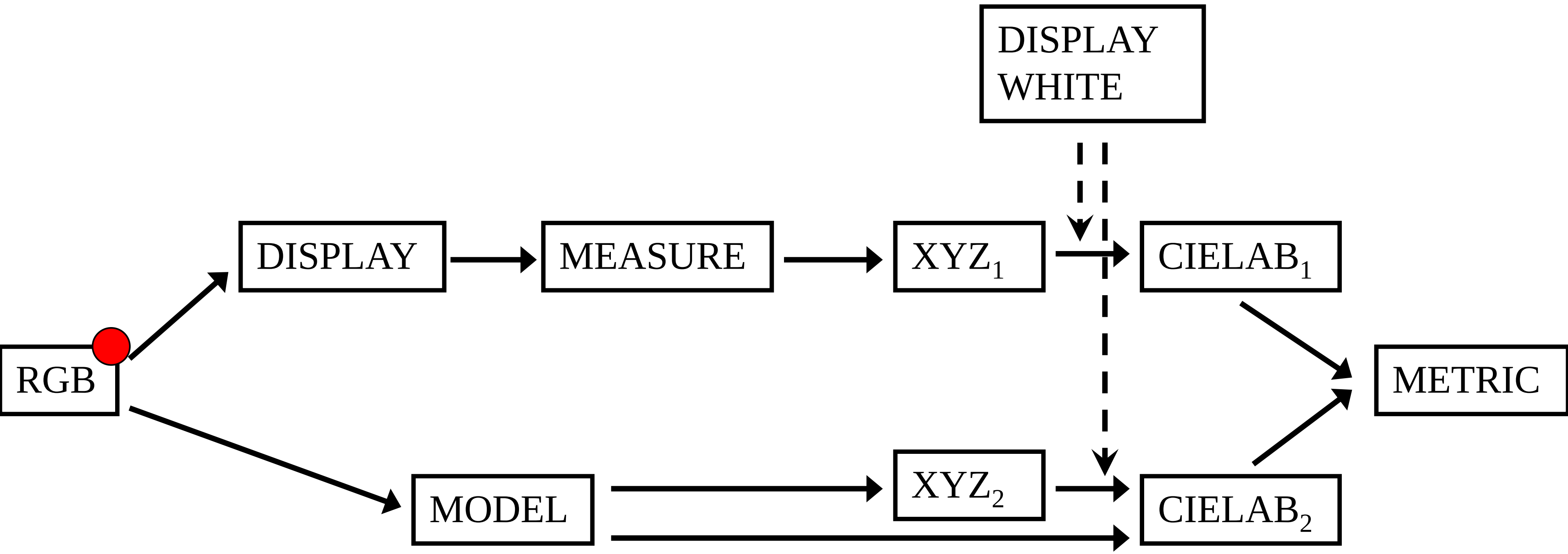
colorlab.no

The Norwegian Color Research Laboratory

Color metrology

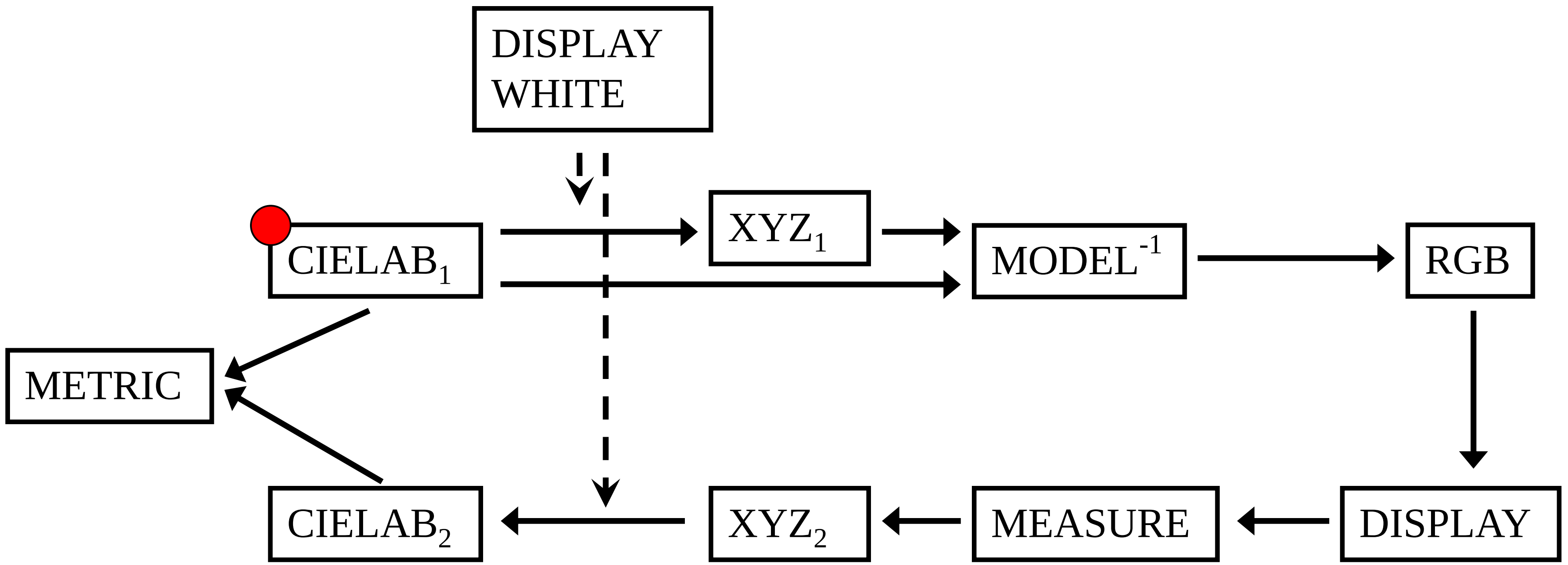
- Metric
  - Choice of $\Delta E^*_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$
  - Easy to compare with other works (most of works presents ΔE^*_{ab}, some works 94, 00)
  - Standards in ΔE^*_{ab} (as far as I know)
  - No specific parameters to tune
  - Always more severe than ΔE^*_{94}, ΔE^*_{00}

Evaluation: Forward



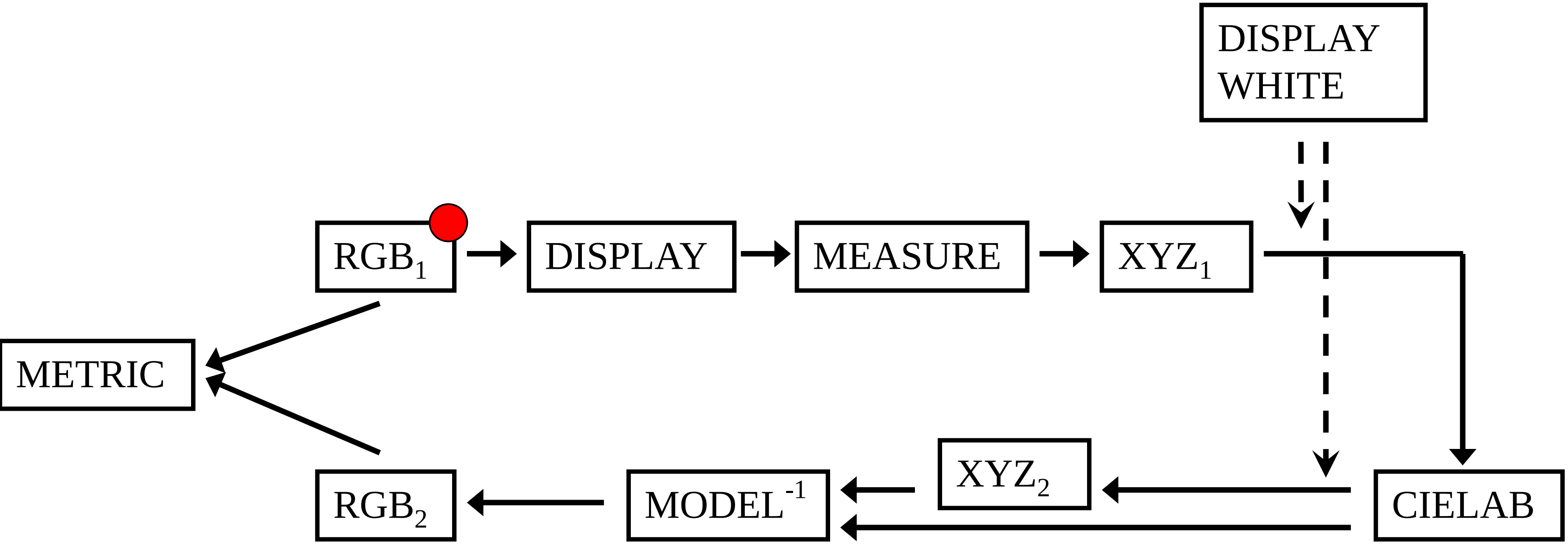
Evaluation of a forward model scheme

Evaluation: Inverse 1



Perceptual evaluation of the inverse model

Evaluation: Inverse 2



Evaluation of the model inversion