Snapshot multi-spectral-line imaging for applications in dermatology and forensics

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Spectral image

- By definition, spectral image represents x-y distribution of spectral reflectance $R(\lambda) = I_r(\lambda)/I_o(\lambda)$, where $I_o(\lambda)$ – intensity of incident light at a specific single wavelength λ; $I_r(\lambda)$ – intensity of reflected light at the same wavelength
- Theoretically, spectral image = spectral line image (λ)
- In practice: spectral line → spectral band imaging

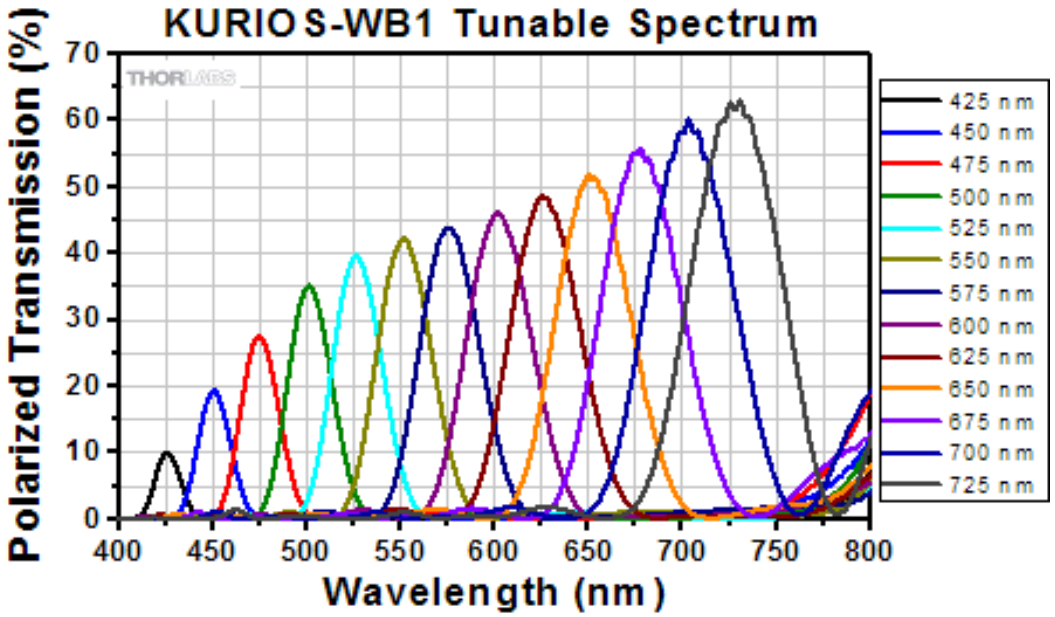
Hyperspectral & **multi**spectral imaging (images at a number of wavelengths bands)

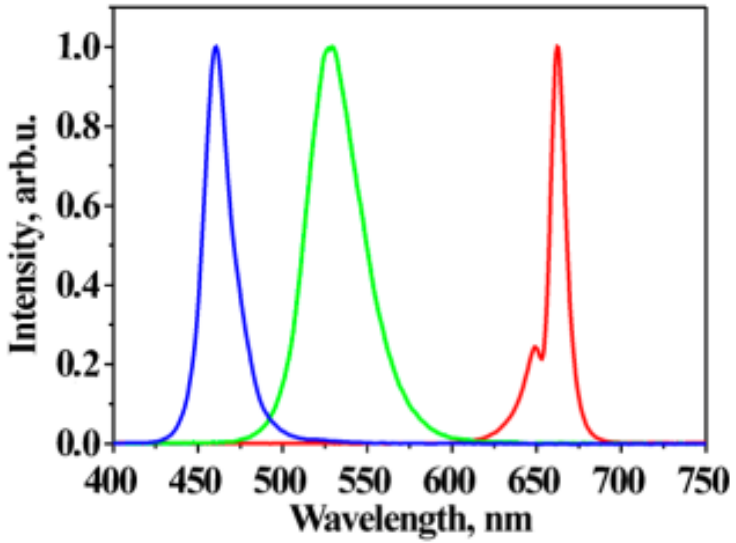
<u>Hyperspectral</u>:

adjacent overlapping spectral bands

<u>Multispectral</u>:

selected non-overlapping spectral bands

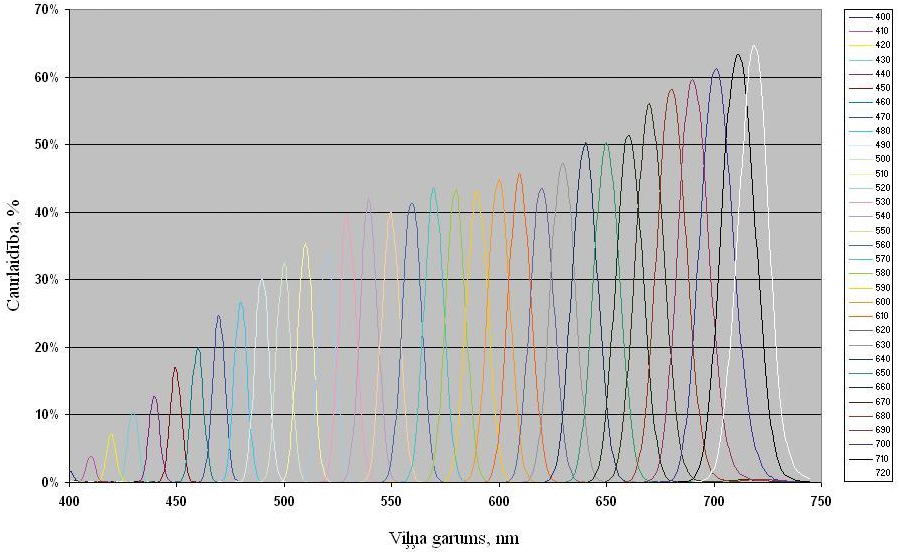




Multi-spectral-band imaging: drawbacks

- HSI (tens of k$)
  - Huge computing resources required
  - A number of spectral images non-informative
  - Typical spectral bandwidth

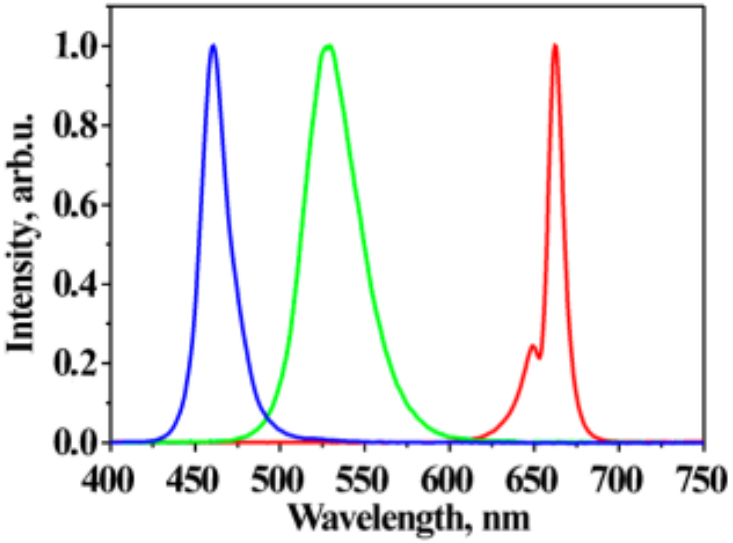
    ~ 10-20nm, overlapping bands → insufficient spectral purity
  - Acquisition time - tens of seconds to minutes → possible motion artefacts (*in-vivo*)
- MSI (<1k$)
  - Low spectral purity – typical spectral bandwidth ~ 20-50 nm
  - Acquisition time – seconds, *in-vivo* motion artefacts still possible



Challenge: how to minimize both spectral bandwidth and acqisition time of the spectral image set?

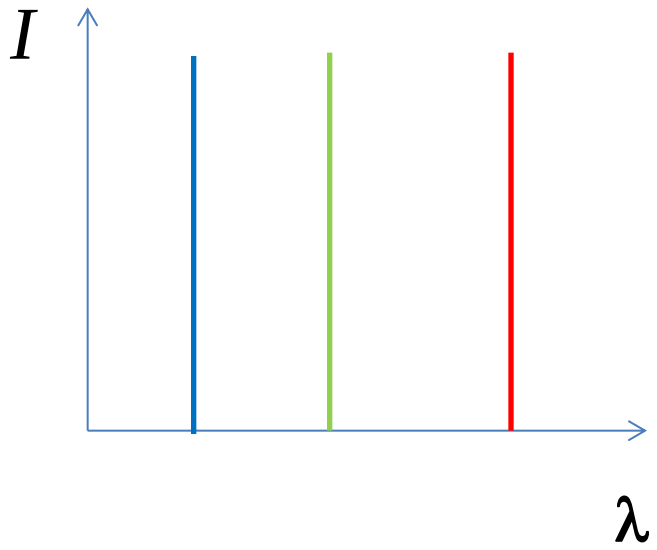
The main concept

Spectral band images



Sequential (t>>0)

Spectral line images



Single snapshot (t→0)

n =3 → n > 3

Why? Advantages:

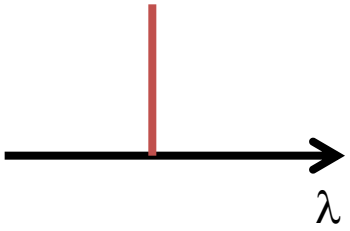
- Better spectral selectivity - limited by the spectral linewidth
- Improved imaging quality - avoided motion artefacts
- Simpler/faster image processing - dealing with numbers instead of integrals over the whole spectral bands

Multi-spectral-line imaging

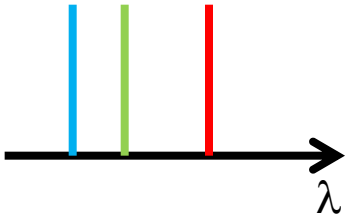
- Monochromatic (< 0.1nm) **single spectral line image** can be obtained if the object is illuminated by a single spectral line, e.g. emitted by laser
- 3 **monochromatic spectral images** from a **single-snapshot** RGB image data can be extracted if object is illuminated simultaneously at 3 laser wavelengths, and the RGB-band sensitivities of the image sensor are known → corrected R-, G- and B-band images*

Illumination spectra:

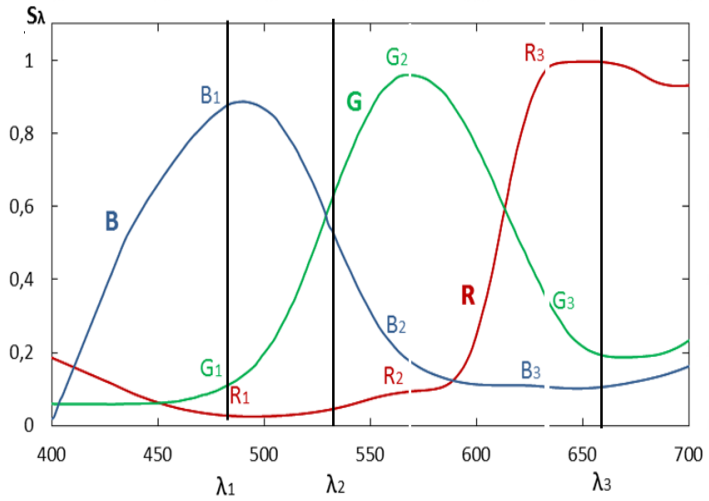
Single-wavelength



Triple-wavelength

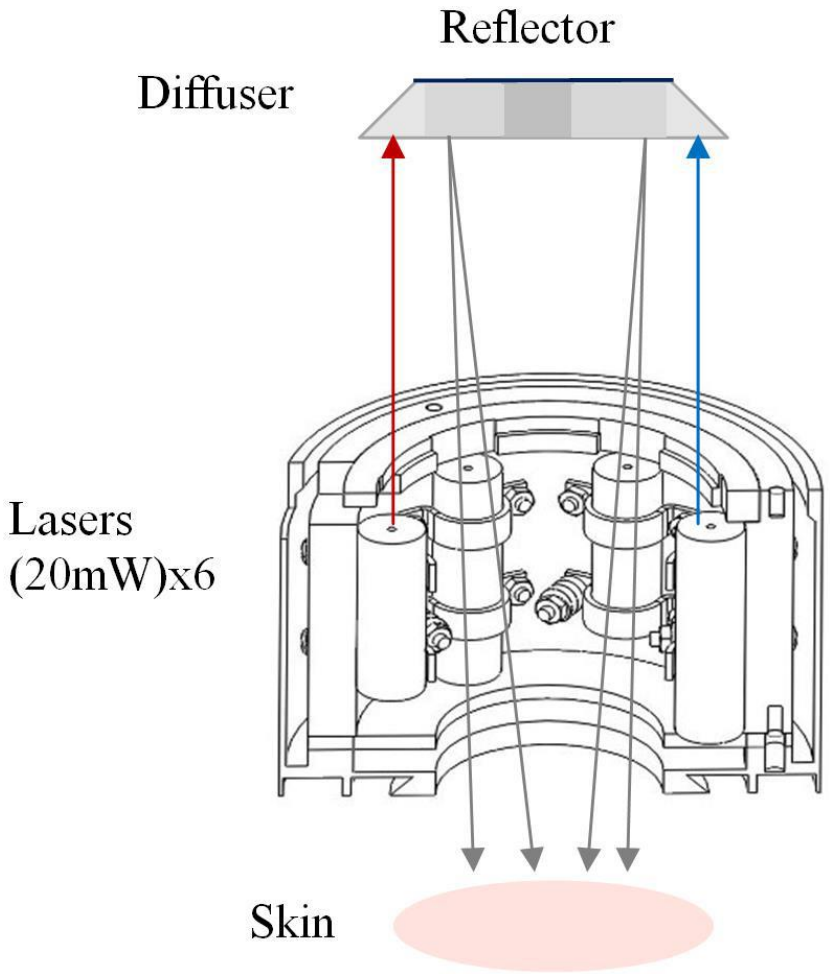


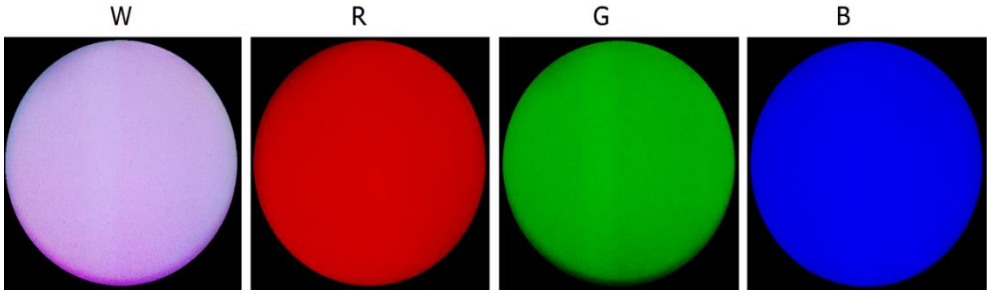
RGB sensitivities of the image sensor :



*) WO 2013135311 (A1), Method and device for imaging of spectral reflectance at several wavelength bands.

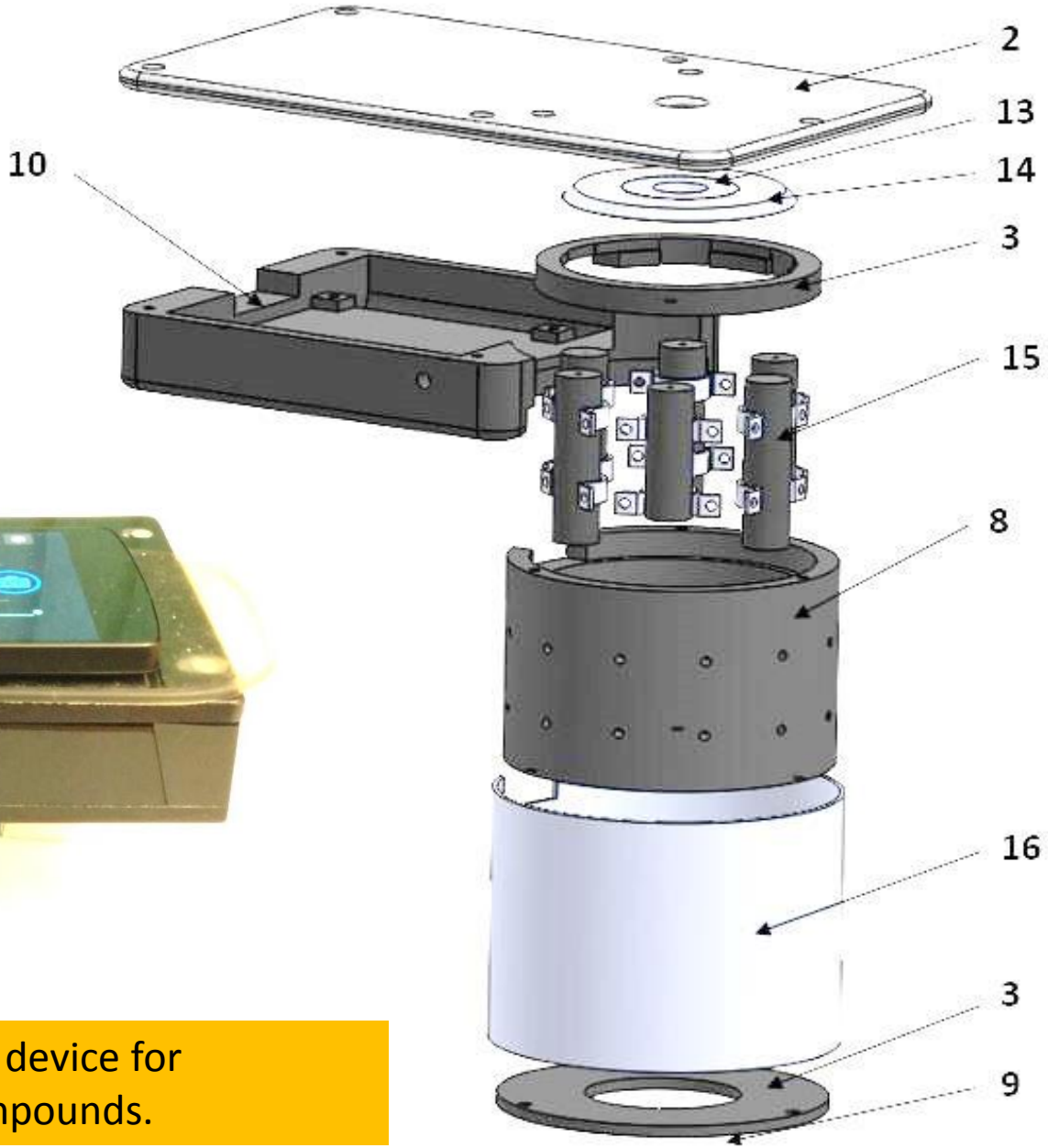
Laser illumination uniformity: flat ring-shaped diffusing reflector





Smartphone add-on triple wavelength laser illuminator:

448nm, 532nm, 659nm



WO 2017/012675 A1, Method and device for smartphone mapping of tissue compounds.

Proof of concept - 1: mapping of skin chromophore distributions

BENIGN

MALIGNANT

Nevi

Melanoma

Seborrheic keratosis

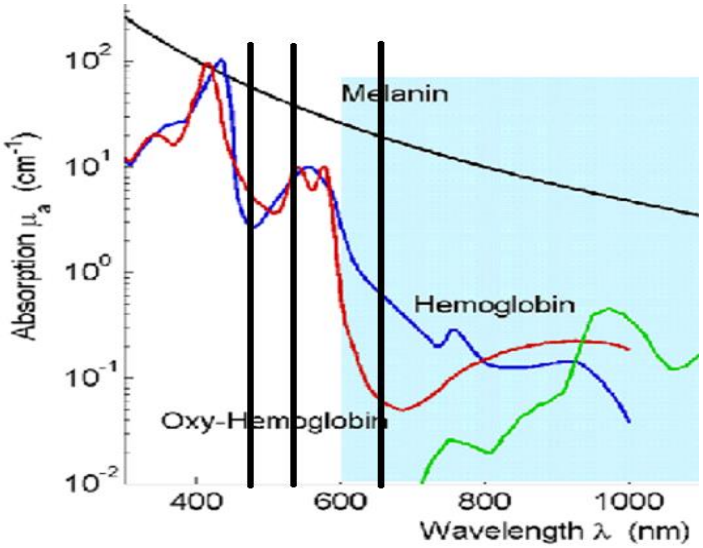
Basal cell carcinoma

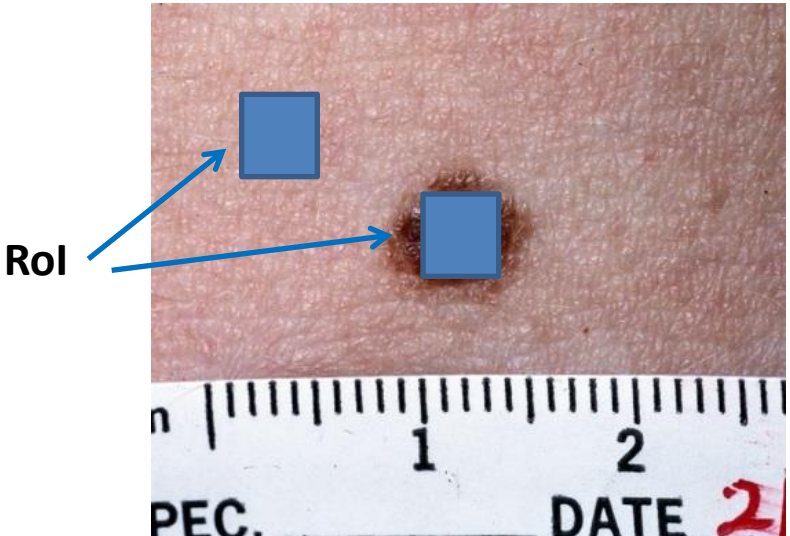
Hemangioma

Squamous cell carcinoma

Image processing: 3-chromophore model, Beer's law

$$\begin{cases} \ln\left(\frac{I_1}{I_{01}}\right) = -l_1\left(\Delta c_a \cdot \varepsilon_a(\lambda_1) + \Delta c_b \cdot \varepsilon_b(\lambda_1) + \Delta c_c \cdot \varepsilon_c(\lambda_1)\right) \\ \ln\left(\frac{I_2}{I_{02}}\right) = -l_2\left(\Delta c_a \cdot \varepsilon_a(\lambda_2) + \Delta c_b \cdot \varepsilon_b(\lambda_2) + \Delta c_c \cdot \varepsilon_c(\lambda_2)\right) \\ \ln\left(\frac{I_3}{I_{03}}\right) = -l_3\left(\Delta c_a \cdot \varepsilon_a(\lambda_3) + \Delta c_b \cdot \varepsilon_b(\lambda_3) + \Delta c_c \cdot \varepsilon_c(\lambda_3)\right) \end{cases}$$





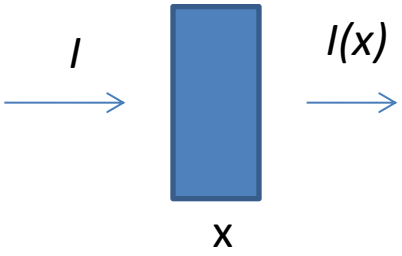
$k_j = \ln(I_j/I_{jo})$:

$$\Delta c_a = A_1 \cdot k_1 + A_2 \cdot k_2 + A_3 \cdot k_3$$
$$\Delta c_b = B_1 \cdot k_1 + B_2 \cdot k_2 + B_3 \cdot k_3$$
$$\Delta c_c = C_1 \cdot k_1 + C_2 \cdot k_2 + C_3 \cdot k_3$$

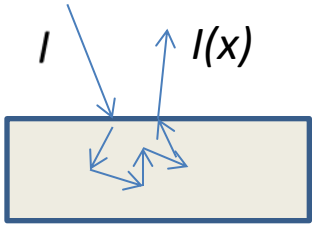
Problem: skin-remitted photon path length. Monte-Carlo simulations (*A.Bykov, Oulu*)

Slab absorption,

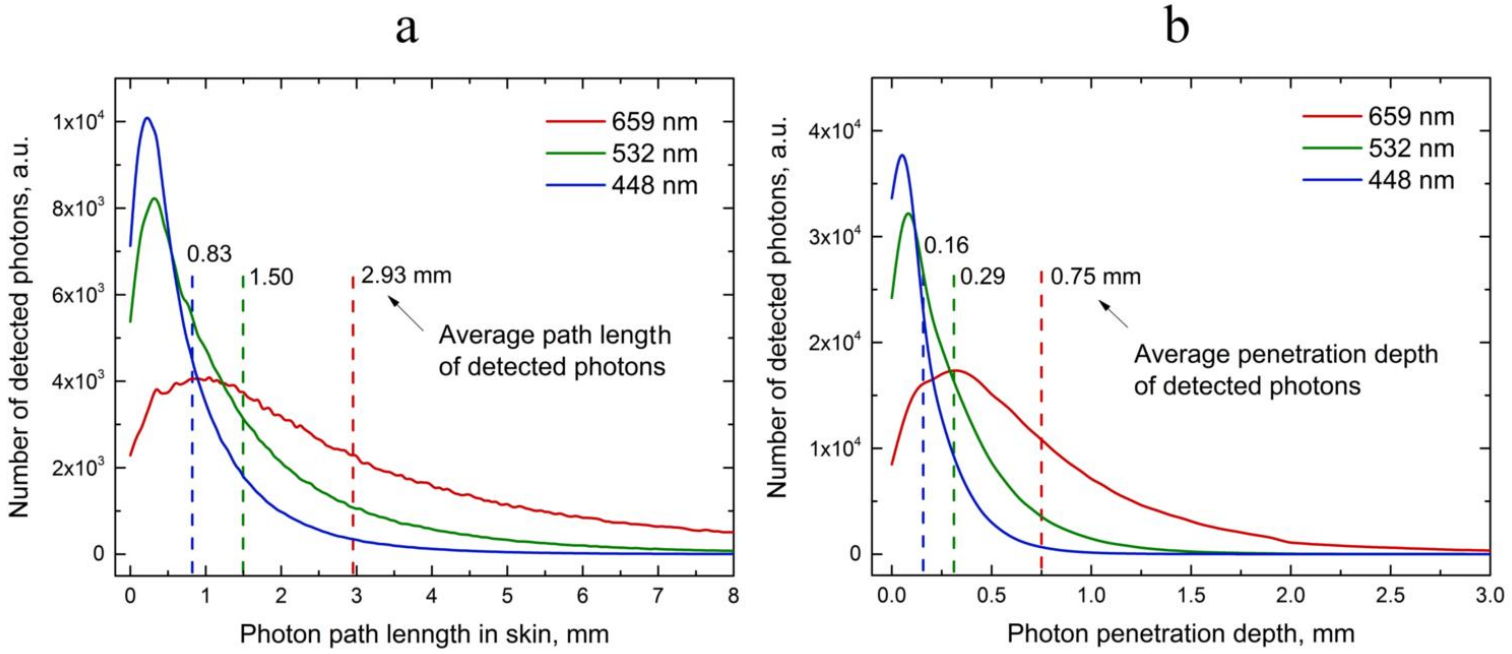
$$I(x) = I \exp(-kx)$$



Diffuse reflectance absorption:

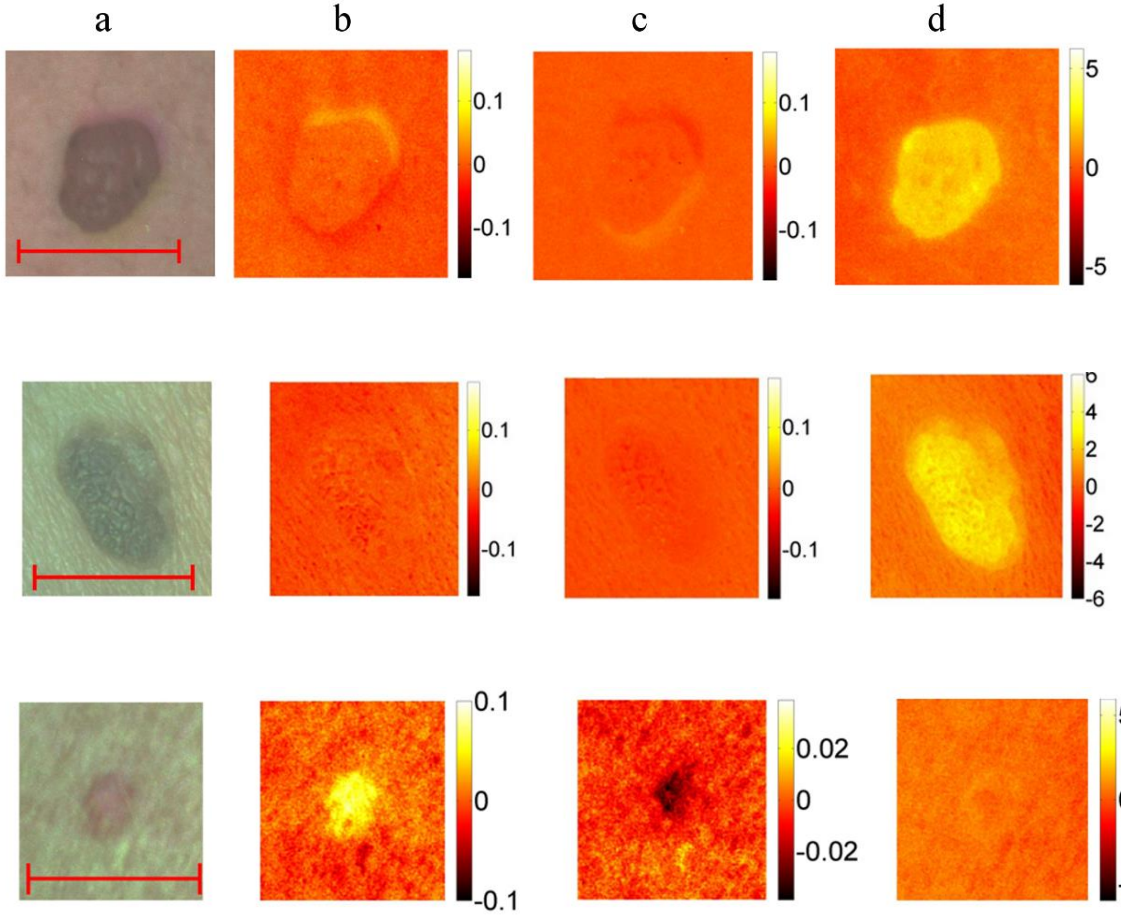


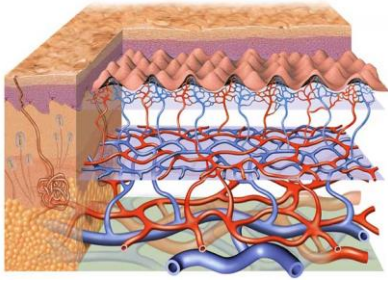
x = ?



(In progress – experimental determination by ps laser pulse propagation measurements: M.Osis et al., *Quant.Electron.*, Vol.49 (2019), Issue 1)

RGB images (a) and maps of chromophore content changes: b – oxy-haemoglobin, c – deoxy-haemoglobin, d – melanin.

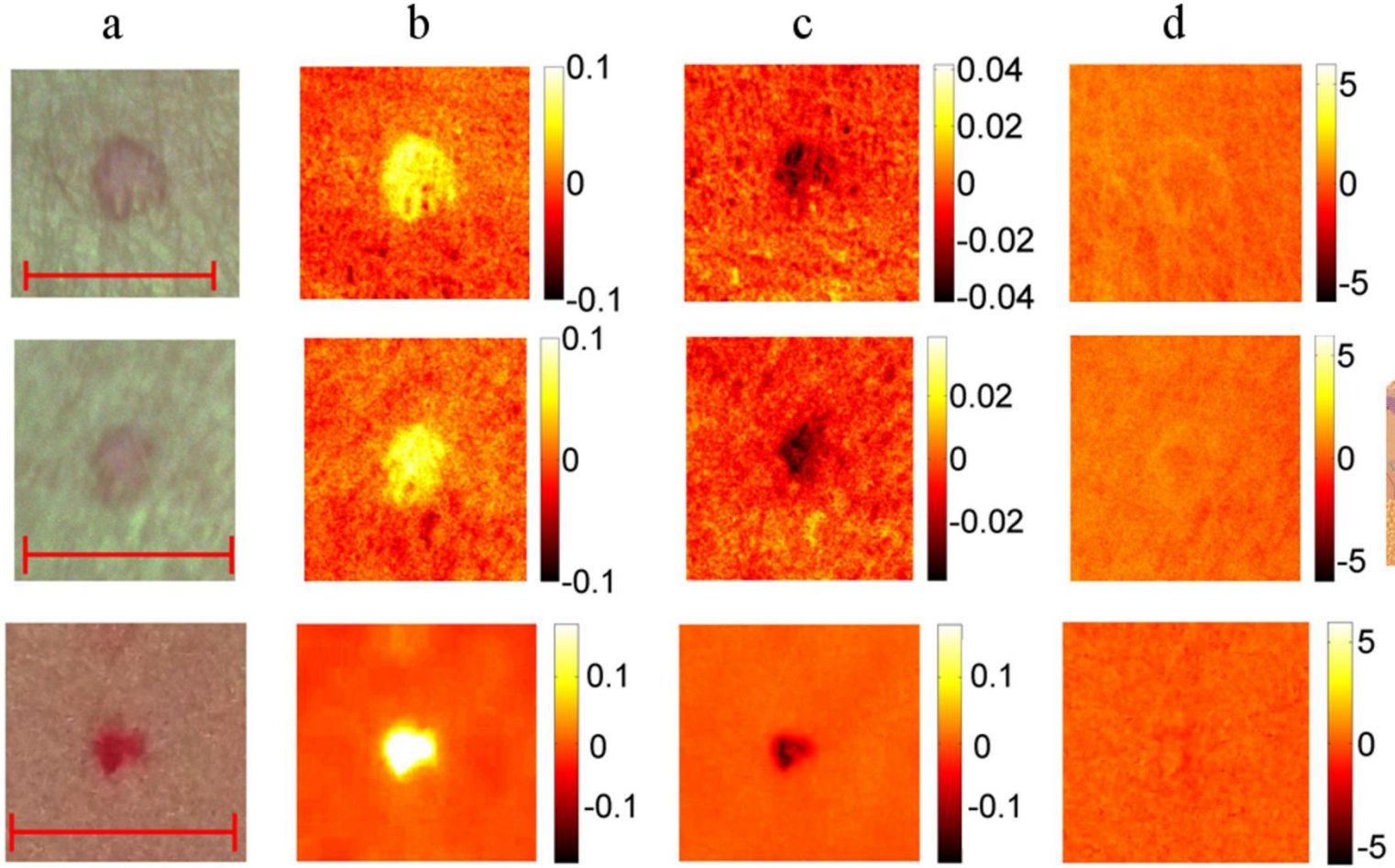


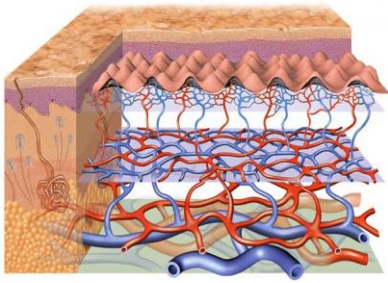


J.Spigulis, I.Oshina, A.Berzina, A.Bykov, “Smartphone snapshot mapping of skin chromophores under triple-wavelength laser illumination”, *J.Biomed.Opt.*, **22**(9), 091508 (2017).

RGB image (a) and maps of chromophore content changes for 3 vascular hemangiomas:

b – oxy-hemoglobin, c – deoxy-hemoglobin, d – melanin



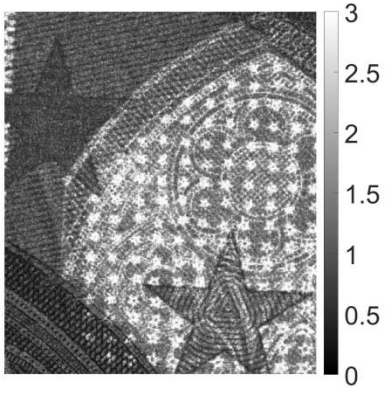


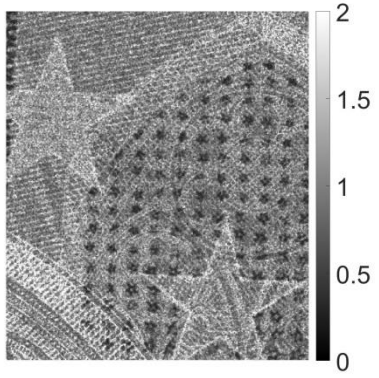
Proof of concept - 2:
color pigment differences in counterfeits

Counterfeit banknotes: from Bank of Latvia

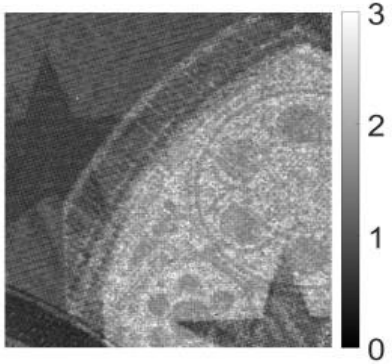
LATVIJAS BANKA

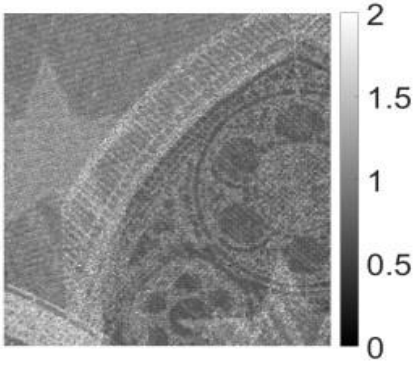
Preliminary results: increased sensitivity by ratios of spectral line images involving blue 448 nm





Real





Fake

RGB

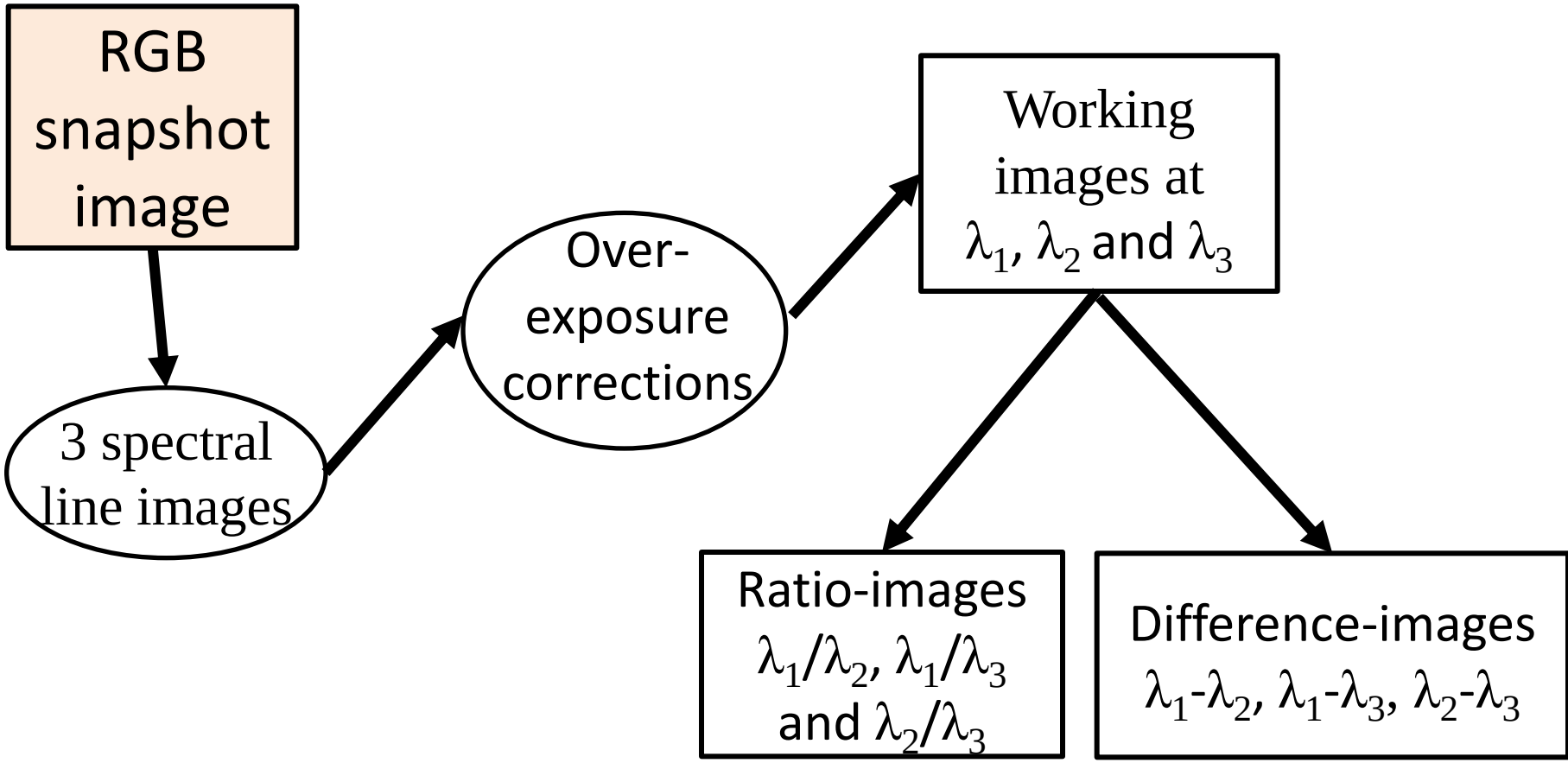
659/448nm

448/532nm

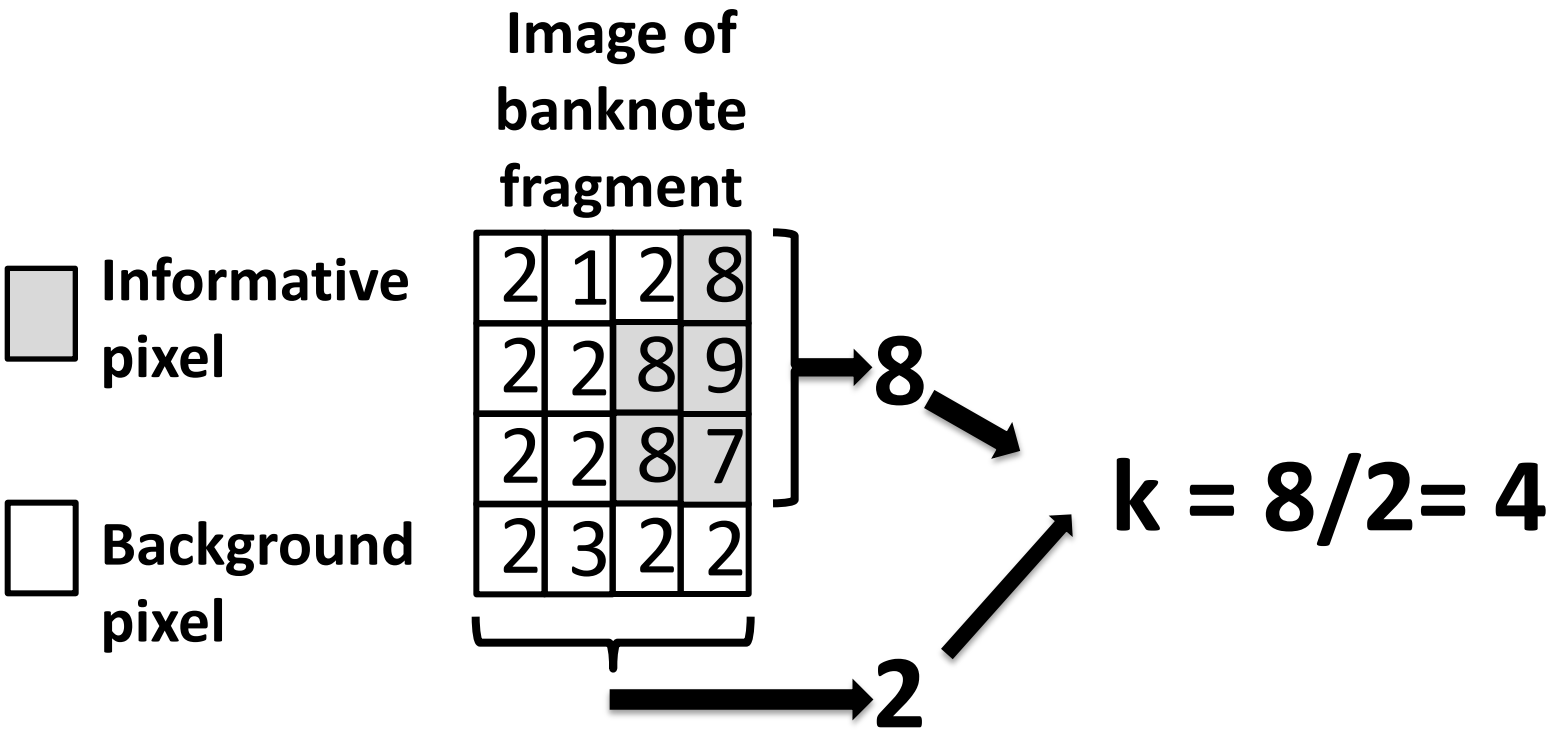
More detailed study: samples of EUR 20 and EUR 50 banknotes

	Authentic	**Counterfeit**			
		Jet-printed	Offset-printed	Copied	Other
EUR 20 (new version)	7	2	-	2	3
EUR 20 (old version)	2	-	10	-	3
EUR 50 (new version)	15	1	-	-	2
EUR 50 (old version)	3	-	1	-	7
In total:	**58**				

Image processing



Numerical comparison: k-factor



Mean pixel values over the selected RoI are calculated/divided

k-values of the same fragment of 50 EUR banknotes

1,60
1,50
1,40
1,30
1,20
1,10
1,00
0,90
0,80
0,70

λR λG λB λR/λG λR/λB λG/λB λR-λG λR-λB λG-λB

Autentiskas Strūklas printeris Nekategorizētas

M: counterfeit sensitivity parameter (reliability)

Value difference

Total uncertainty

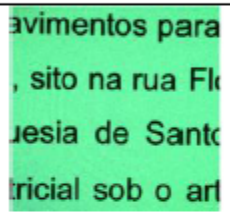
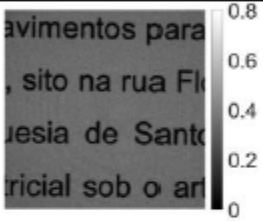
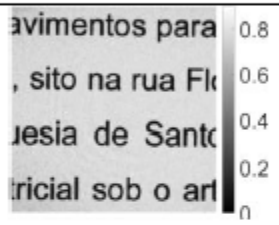
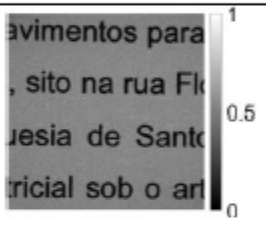
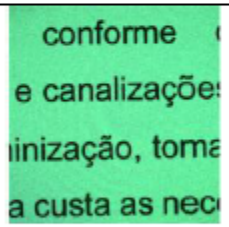
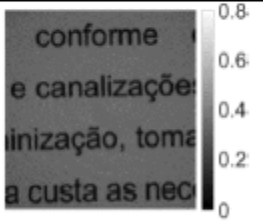
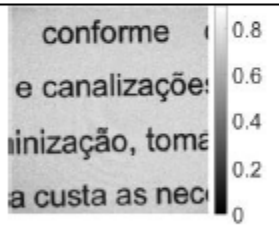
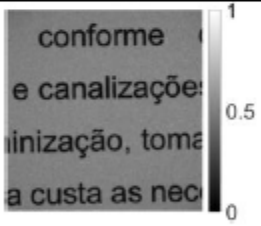
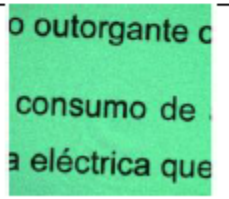
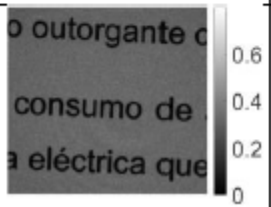
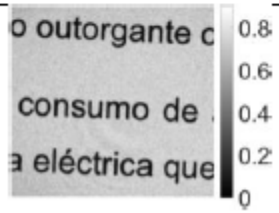
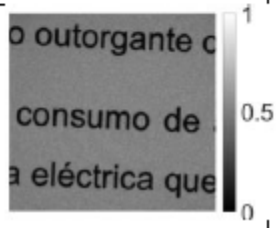
$$M = \frac{(|k_i - k_{iaut}|) - (\Delta k_i + \Delta k_{iaut})}{k_i}$$

Reliability: jet-printed vs other

Counterfeit method	Processing method	M
other	λ_R/λ_B	81.5%
other	λ_R-λ_B	64.3%
other	λ_B	51.2%
Jet printer	λ_B	49.4%
Jet printer	λ_G	43.6%
other	λ_G	40.4%
Jet printer	λ_R	39.7%
other	λ_R	37.6%
other	λ_R/λ_G	29.2%
Jet printer	λ_R/λ_G	25.3%
Jet printer	λ_R/λ_G	24.3%
Jet printer	λ_G/λ_B	23.5%
Jet printer	λ_R/λ_B	23.0%
Jet printer	λ_G-λ_B	22.6%
Jet printer	λ_G-λ_B	21.1%
Jet printer	λ_G/λ_B	21.0%

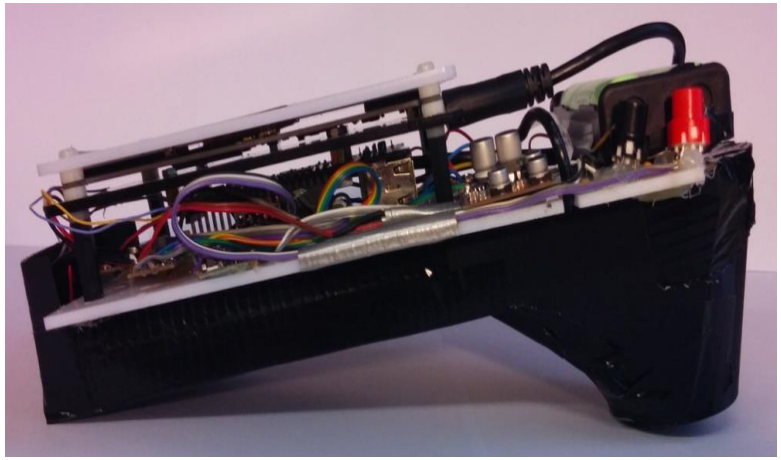
3 spectral line approach for document counterfeit detection

Table 1. Spectral line images and the respective normalized printed letter values for the three pages (
standard deviations).

Page No.	RGB image with three lasers	659 nm	Mean printed text values	532 nm	Mean printed text values	448 nm	Mean printed text values
1			0.029 ± 0.015		0.078 ± 0.035		0.051 ± 0.004
2			0.042 ± 0.017		0.098 ± 0.036		0.063 ± 0.004
3			0.028 ± 0.015		0.073 ± 0.033		0.051 ± 0.004

Under development: n > 3

- Up to 6 spectral line images by d**ouble-snapshot** RGB imaging technique, each snapshot under different 3λ–combined illumination*
- Quality improvement of the monochromatic spectral images by **laser speckle removal** **
- First switchable **4λ and 5λ** laser illuminator prototypes created →
- **Current project**: 4-wavelengths images by RGB-NIR camera under combined 450-520-660-850nm illumination



*) LV 15106 B. Method and device for mapping of chromophores under illumination by several laser lines.
**) WO 2018/177565 A1. Device for speckle-free imaging under laser illumination.

Summary

- Snapshot multi-spectral-line imaging concept implemented in a triple-wavelengths prototype device
- This imaging approach tested for skin tissue chromophore mapping and fake money detection
- Chromophore distribution in pigmented and vascular skin malformations: physiologically feasible results obtained
- Counterfeit EUR banknote studies: the blue line 448nm images and combinations of red 659nm and blue (λ_R/λ_B , $\lambda_R-\lambda_B$) found to be most sensitive
- Potential for document forgery detection demonstrated
- Further improvements for n > 3 in progress

Acknowledgements

- Supported by all team members of Riga Biophotonics lab
- Forensic study inspired by COST CA16101 action «Multi-Foresee»
- Special thanks to the Money Technology Department, Bank of Latvia for sharing the counterfeit EUR banknotes
- Financially supported by the Latvian Council of Science, grant # lzp-2018/2-0006

Multi-Foresee

FLPP
FUNDAMENTĀLIE UN LIETIŠĶIE PĒTĪJUMU PROJEKTI

Thank You!

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- http://home.lu.lv/~spigulis