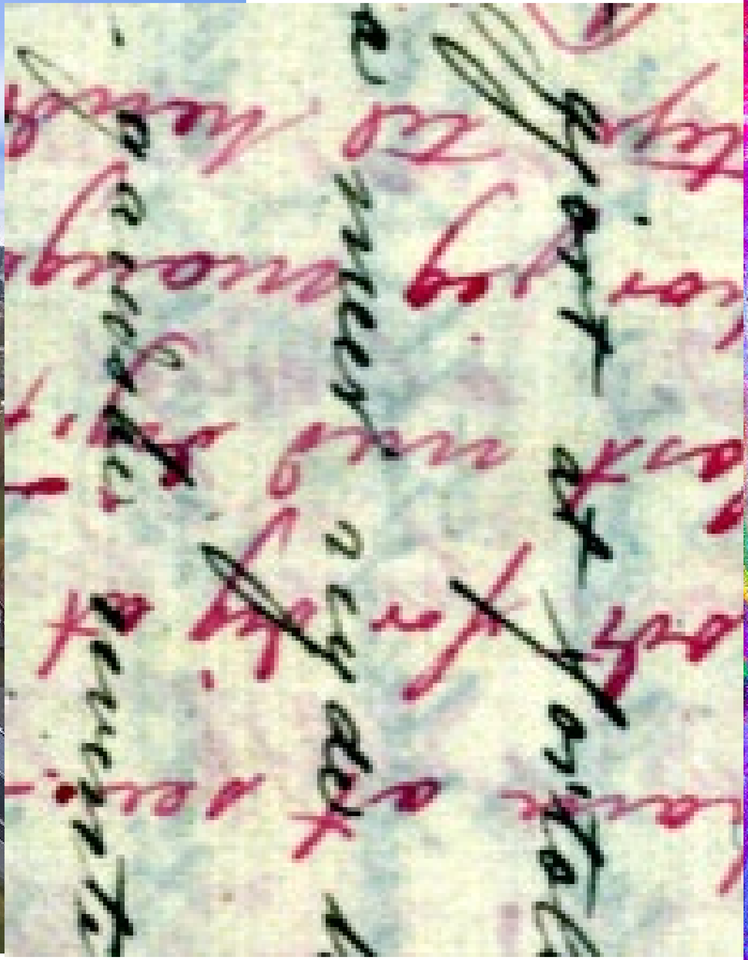


Spectral Imaging Research at the Colourlab

Jon Y. Hardeberg

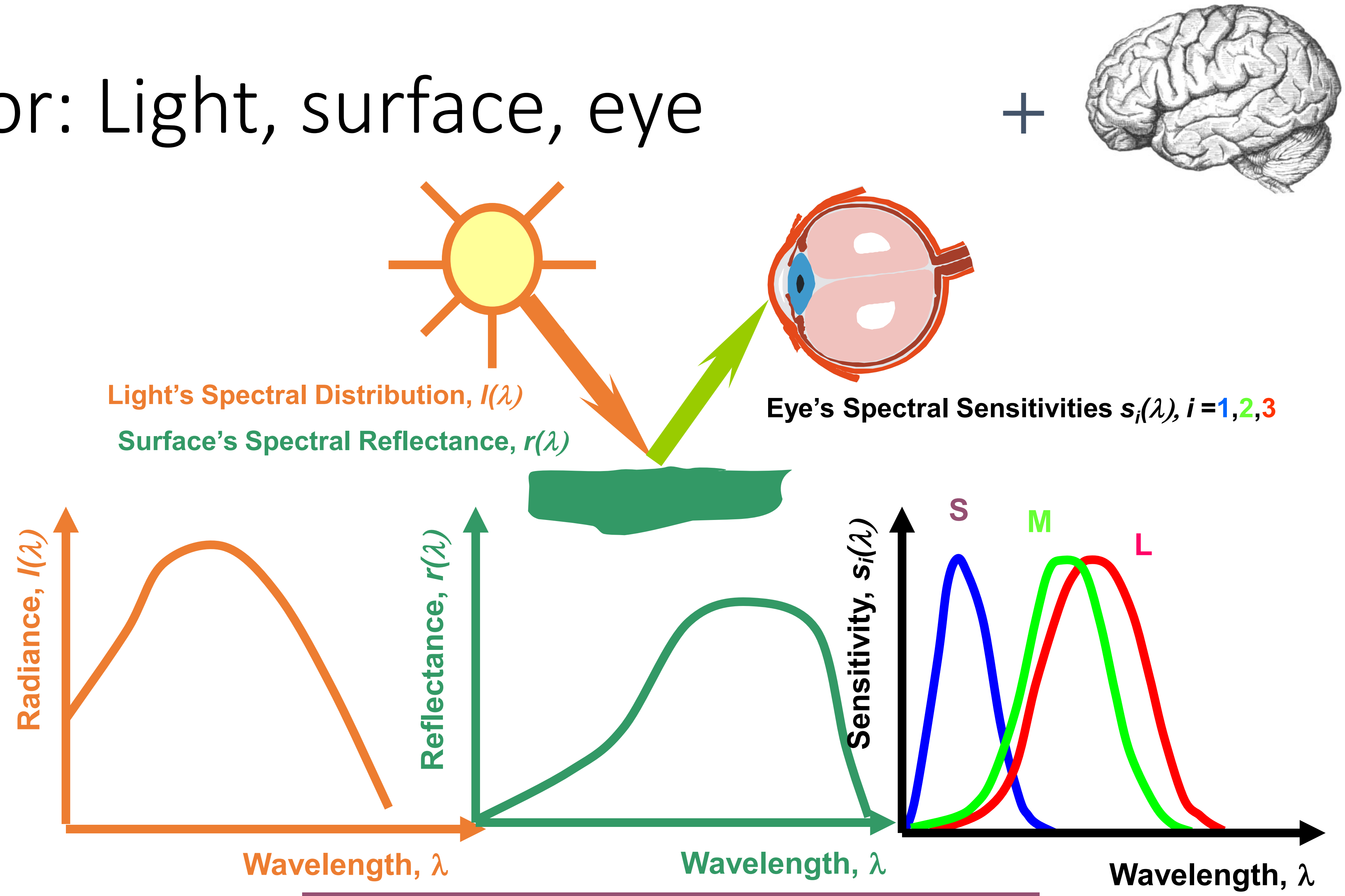
Colourlab, Department of Computer Science
NTNU – Norwegian University of Science and Technology
Spektralion AS
Gjøvik, Norway

NTNU Colourlab SPEKTRALION

Outline

- Introduction to multi- and hyperspectral imaging
- Some examples of recent research at the Colourlab

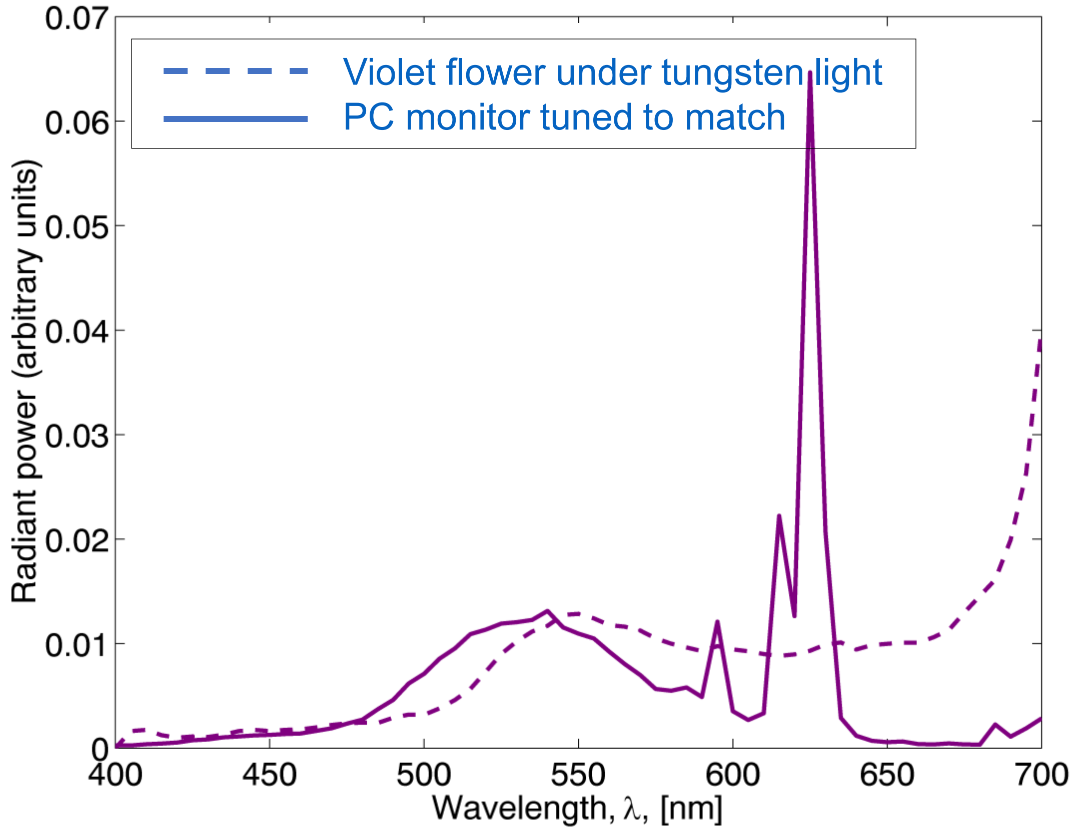
Color: Light, surface, eye

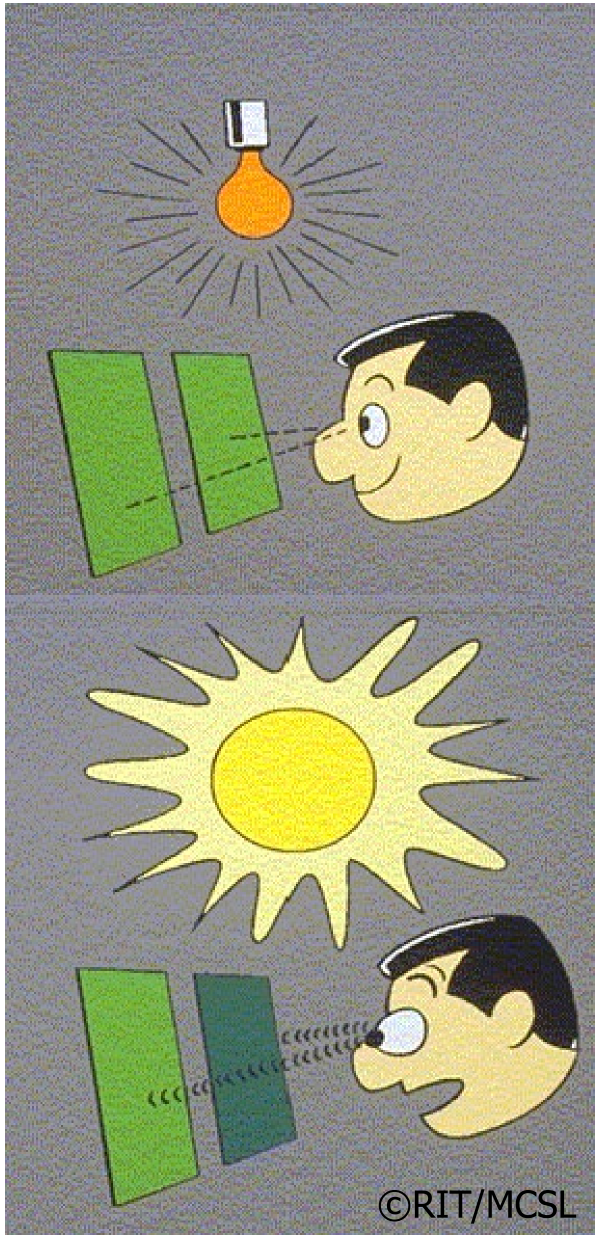


$$c_i = \int_{\lambda_{\min}}^{\lambda_{\max}} l(\lambda) r(\lambda) s_i(\lambda) d\lambda, \quad i = 1, 2, 3$$

Metamerism

- Metamers: Different light spectra having the same colour





Metamerism: A curse and a blessing!

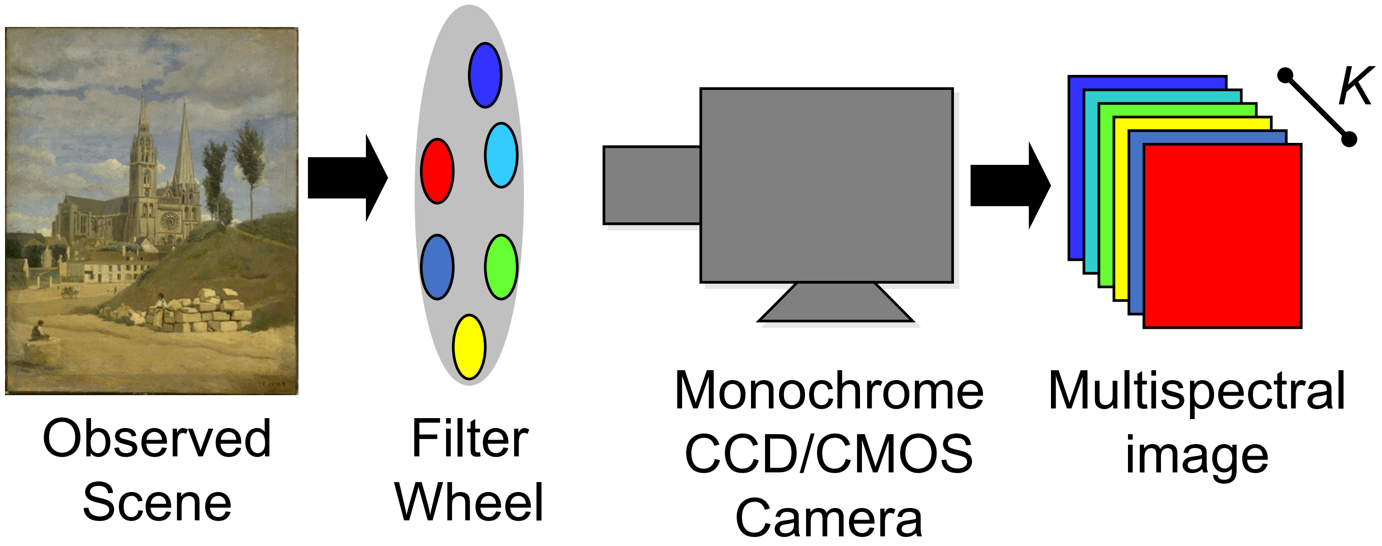
Spectral imaging: why?

For many applications, spectral reflectance can be more appropriate information than color

- An object's color:
  - *f(light, surface, eye/sensor)*
  - *N=3* numbers
- An object's spectral reflectance:
  - *f(surface)*
  - Continuous function of wavelength
  - Can be adequately described by *N* variables
- Spectral imaging can overcome the problems of metamerism

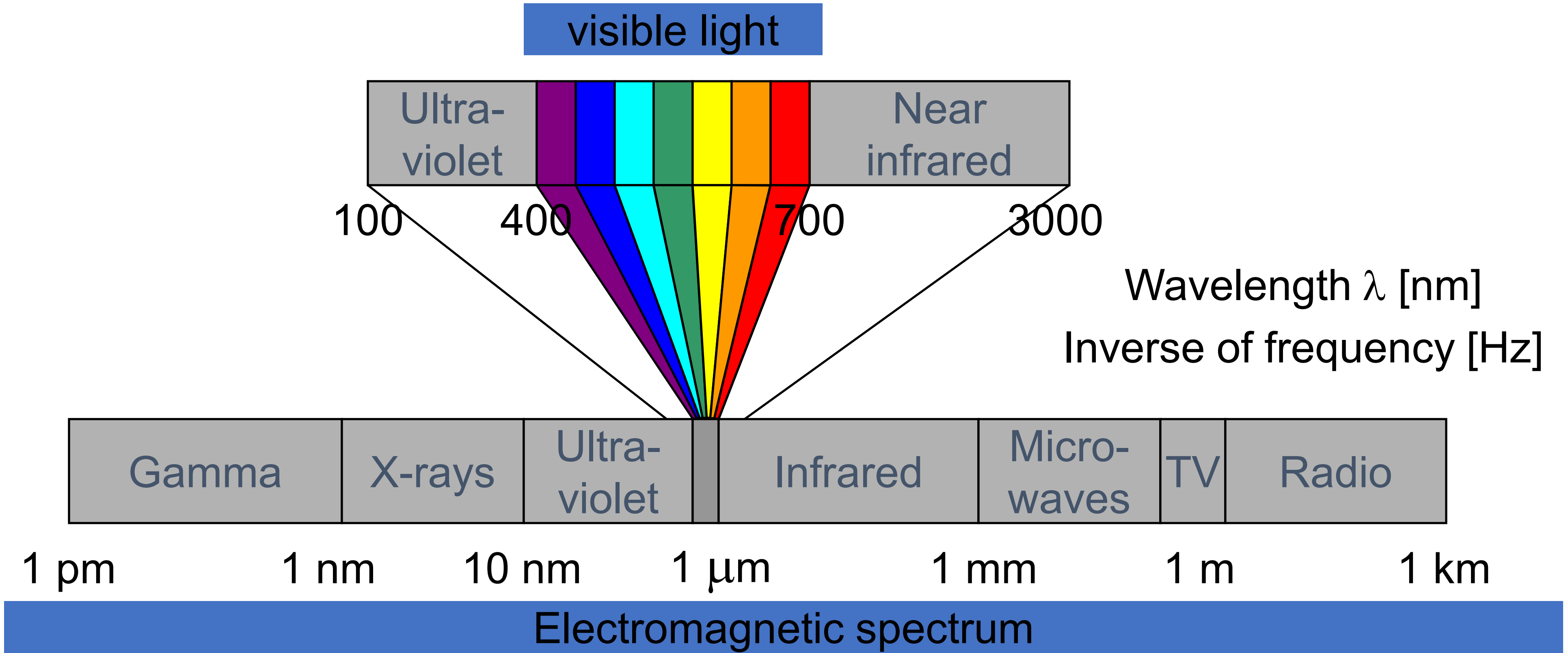
Multispectral imaging

- From 3 to K channels within (and beyond) the visible spectrum
- (Typically) aims to measure spectral reflectance
- Mitigates metamerism
- The ultimate RAW
  - Capture the physics of the scene now – make the pleasing picture later
- Fundamental imaging principle with many variations:



Multispectral and hyperspectral imaging

- Many labels and definition exist
  - Multispectral imaging (MSI), Multispectral colour imaging, Multi-visible-spectral imaging, Visible spectrum imaging, Multi-channel visible spectrum imaging (MVSI), Hyperspectral imaging (HSI), reflectance imaging spectroscopy (RIS), Spectral imaging…
- Multi: tens of channels, Hyper: hundreds of channels?



How many channels do we need?

CGIV 2002

On the spectral dimensionality of object colours

Jon Y. H
Gjøvik University Co
SINTEF Electronics and Cyb

Abstract

How many components are needed to represent the spectral reflectance of a surface? What is the dimension of a spectral reflectance? How many image channels are needed for the acquisition of a multispectral colour image? Such and similar questions have been discussed extensively in the literature. We have done a survey of the literature concerning this topic, and have seen that there is a large variation in the answers. We propose a method to quantify the effective dimension of a set of spectral reflectances. The method is based on a Principal Component Analysis, and in particular on specific requirements for the accumulated energy of the principal components. We apply the analysis to five different databases of spectral reflectances, and conclude that they have very different statistical properties. The effective dimension of a set of Munsell colour spectra is found to be 18, that of a set of natural object reflectances 23, while the effective dimension of a set of reflectances of pigments used in oil painting was only 13.

JIST 2006

Journal of Imaging Science and Technology® 50(1): 45–52, 2006.

Multispectral Imaging: How Many Sensors Do We Need?

David Connah†, Ali Alsam and Jon Y. Hardeberg▲
Gjøvik University College, P.O. Box 191, N-2802 Gjøvik, Norway
E-mail: dc@cmp.uea.ac.uk, ali.alsam@hig.no, jon.hardeberg@hig.no

Abstract. *The surface reflectance functions of natural and man-made surfaces are invariably smooth. It is desirable to exploit this smoothness in a multispectral imaging system by using as few sensors as possible to capture and reconstruct the data. In this paper we investigate the minimum number of sensors to use, while also minimizing reconstruction error. We do this by deriving different numbers of optimized sensors, constructed by transforming the characteristic vectors of the data, and simulating reflectance recovery with these sensors in the presence of noise. We find an upper limit to the number of optimized sensors one should use, above which the noise prevents decreases in error. For a set of Munsell reflectances, captured under educated levels of noise, we find that this limit occurs at approximately nine sensors. We also demonstrate that this level is both noise and dataset dependent, by providing results for different magnitudes of noise and different reflectance datasets. © 2006 Society for Imaging Science and Technology.* [DOI: 10.2352/J.ImagingSci.Technol.(2006)50:1(45)]

LIM 2024

10:15

Is Multispectral Enough? An Evaluation on the Performance of Multispectral Images in Pigment Unmixing Task

Mitra Amiri and Giorgio Trumpy, Norwegian University of Science and Technology (Norway)

Abstract: Multispectral imaging in contrast with hyperspectral imaging is a cheaper and more accessible method with a feasibly mobile setup. However, the restrained spectral resolution of multispectral images is a limitation that influences the applicability of this method in different fields. In this study, we tried to answer the question of whether multispectral images are suitable enough to be used in the spectral unmixing task. For this specific application, we explore spectral unmixing of an oil painting to obtain pigment maps. We observe that the performance of the multispectral imaging system in the pigment unmixing task is significantly influenced by two key factors: the number of bands in the multispectral imaging system and the spectral range covered by these bands in relation to the spectral features of the pigments present in the spectral library.

10:30 – 11:00

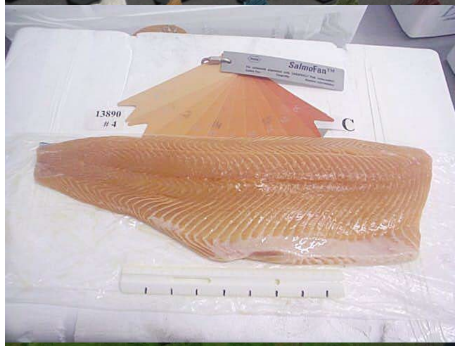
COFFEE BREAK

LATE BREAKING POSTERS

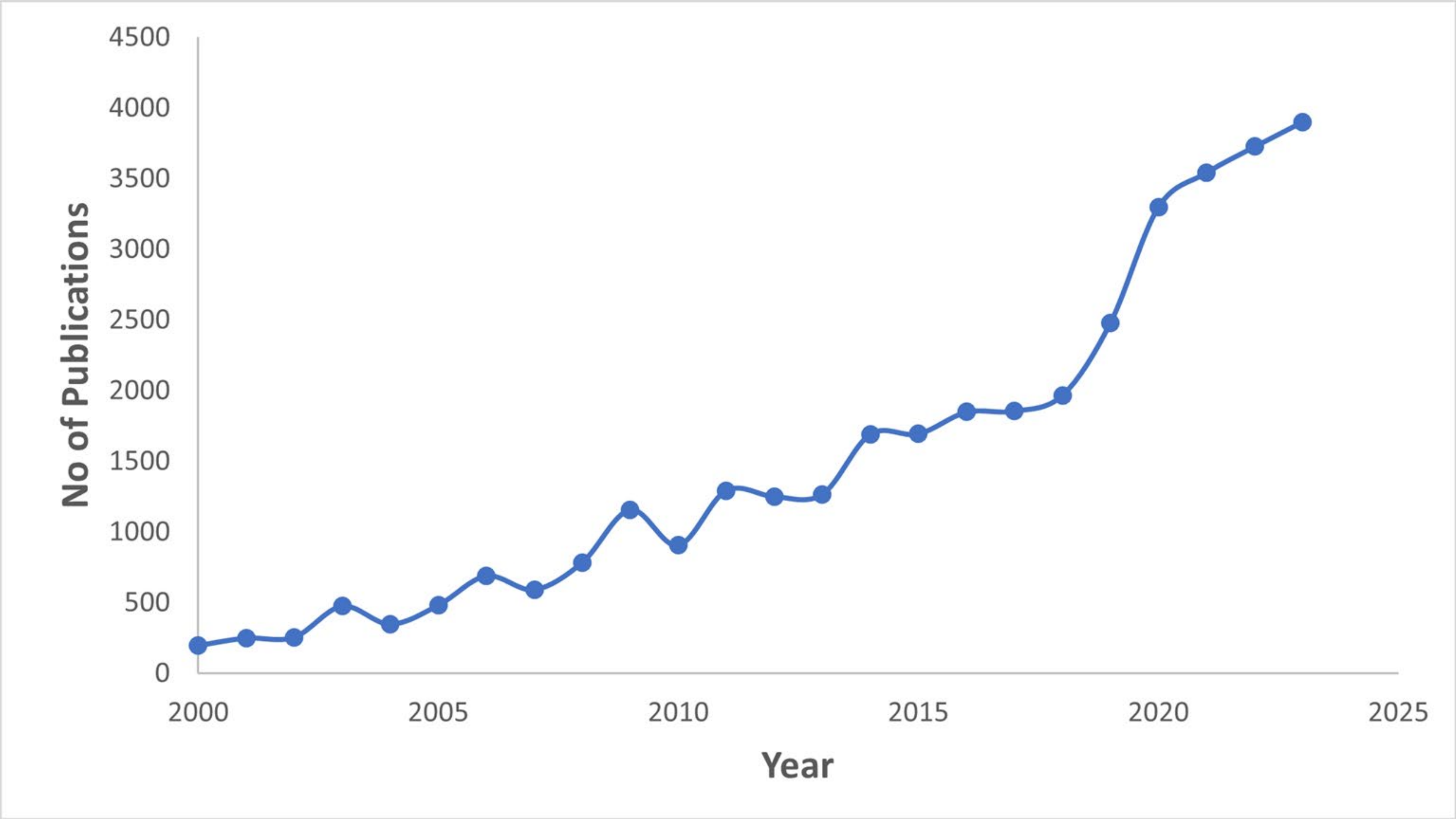
Applications areas for spectral imaging

- **Cultural heritage** (Maître et al. 1996, Cotte&Dupouy 2003, Shrestha et al. 2012, George et al, 2014, Hardeberg et al, 2015, …)
- **Remote sensing** (Clevers et al. 1994, Herold et al. 2004, Hatfield et al. 2008, …)
- **Medical imaging** (Farina et al. 2000, Huang 2012, Torretta et al. 2013, Delpueyo et al. 2015, Minami et al. 2015, …)
- **Biometrics** (Rowe et al. 2007, Ngo et al. 2009, Zhou&Kumar 2011, …)
- **Surveillance** (Ambinder 2011, …)
- **Military** (Richter, 2005, …)
- **Industrial inspection and quality control:** e.g. paper (Shrestha et al 2015), textiles (Herzog&Hill 2003)
- **Precision agriculture and food** (Polder et al. 2003, Gowen et al. 2007, Deng et al 2018, …)
- **Document Forensics** (Morgan 1995, …)
- **Computer Graphics** (Devlin et al. 2002, Bergner et al. 2009, …)
- **Printing and Displays** (Urban&Grigat, 2006, Gerhardt&Hardeberg 2008, Berns et al. 2008, Yamaguchi et al. 2002, …)
- **Computer Vision:** e.g. autonomous vehicles, object recognition, ...
- **Consumer imaging?**
- **AR/VR?**






Multispectral Take-off



Source : Dimensions.ai

Spectral imaging companies

SPEKTRALION

specim
A Konica Minolta Company

HySpex by neo

SALVO COATINGS
a Division of Salvo Technologies

SpectroCam™

spectricity

LUMIERE TECHNOLOGY

PHASEONE

TOC Transformative Optics™

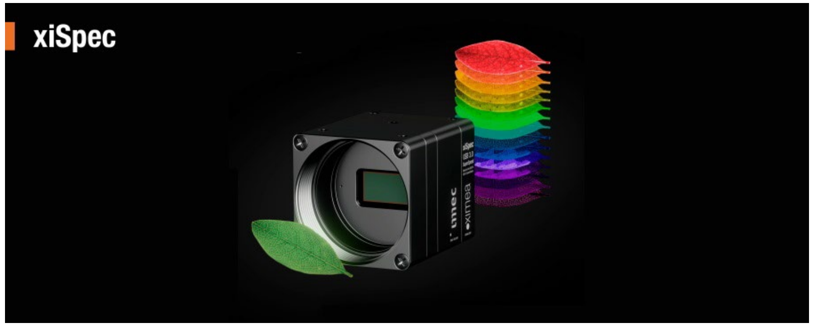
Headwall

XPECAM®

spectral instruments imaging
A BRUKER COMPANY

HUAWEI

chromodynamics



SILIOS TECHNOLOGIES

ASI APPLIED SPECTRAL IMAGING

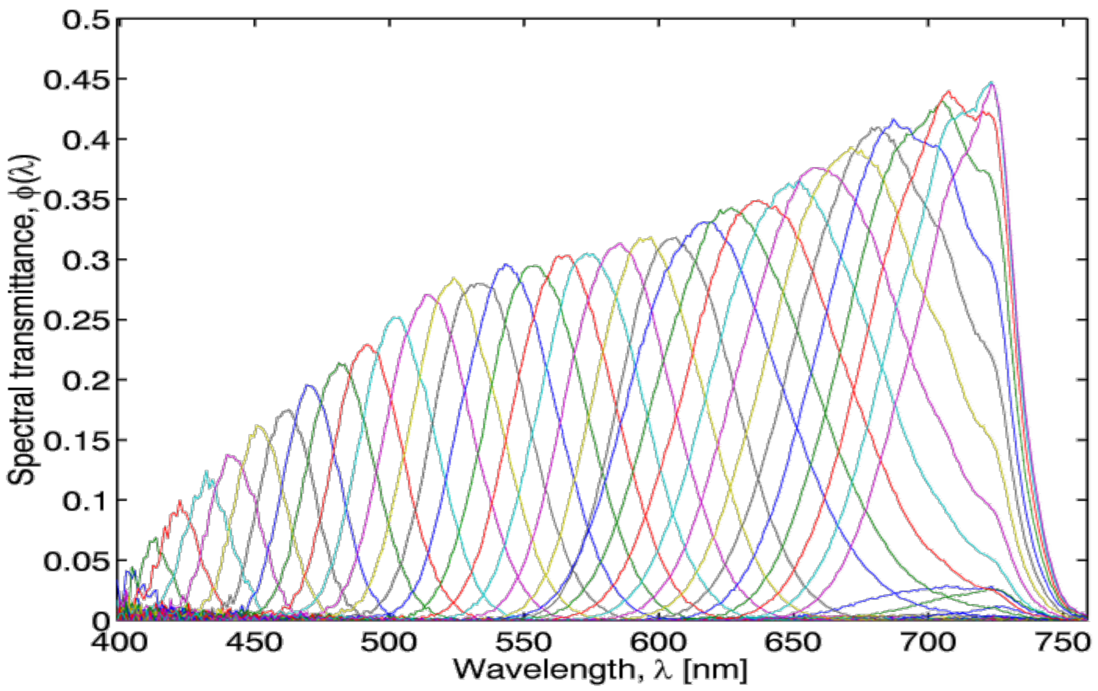
VOYAGE 81

DT HERITAGE

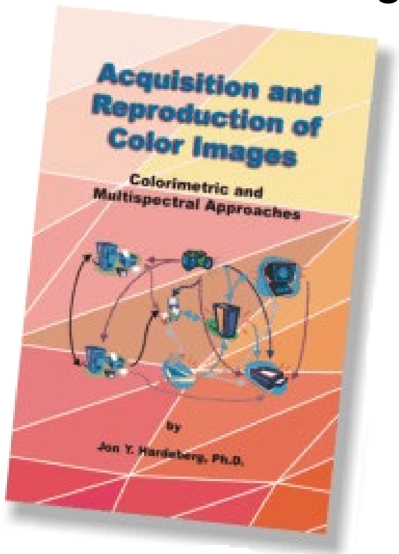
SONY

Videometer

Multispectral imaging: Examples



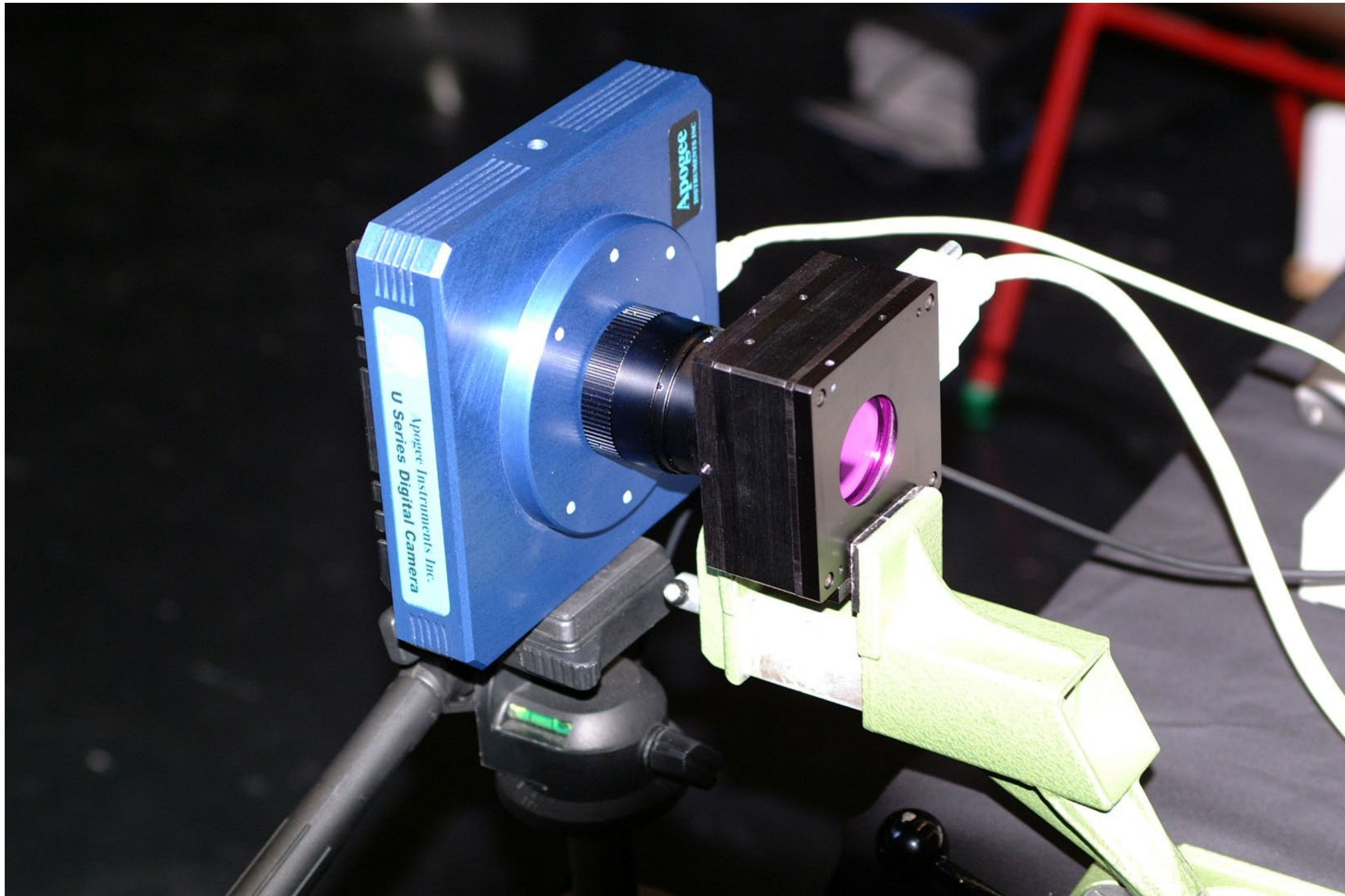
- Ecole Nationale Supérieure des Télécommunications (Paris, France)
  - My PhD 1996-1999
  - Monochrome CCD camera
  - LCTF tunable filter CRI Varispec VIS2
    - Several layers of Lyot-type birefringent filters



https://www.amazon.com/dp/1581121350/

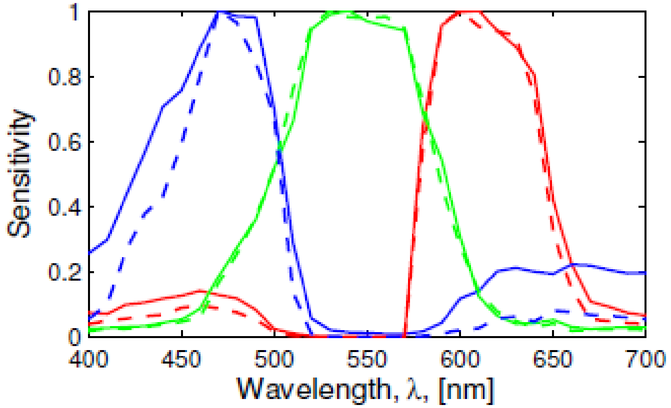
Multispectral imaging: Examples

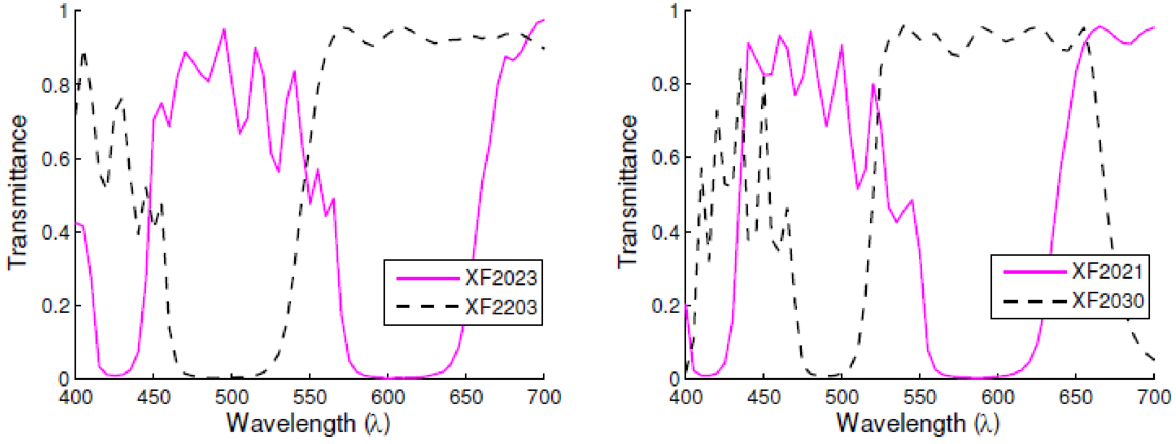
- NTNU Colourlab
  - Monochrome CCD and LCTF



Multispectral through stereo

R Shrestha; JY Hardeberg & A Mansouri. **One-Shot Multispectral Color Imaging with a Stereo Camera**. SPIE Proc. 7876, Electronic Imaging Symposium, 2011.

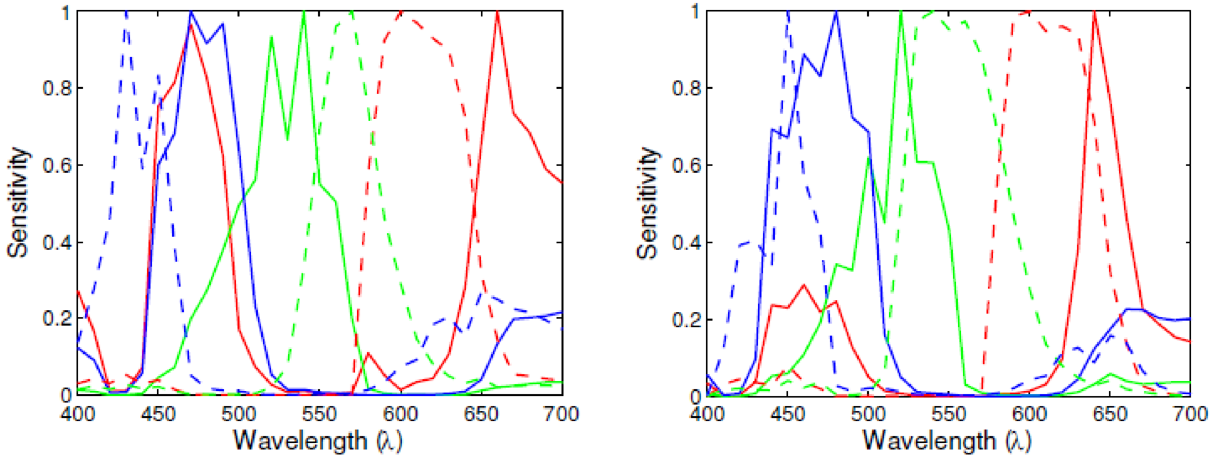




(a) For Minimum RMSE

(b) For Minimum ΔE^*_{ab}

Figure 7. Transmittances of the filters selected (Fujifilm3D)



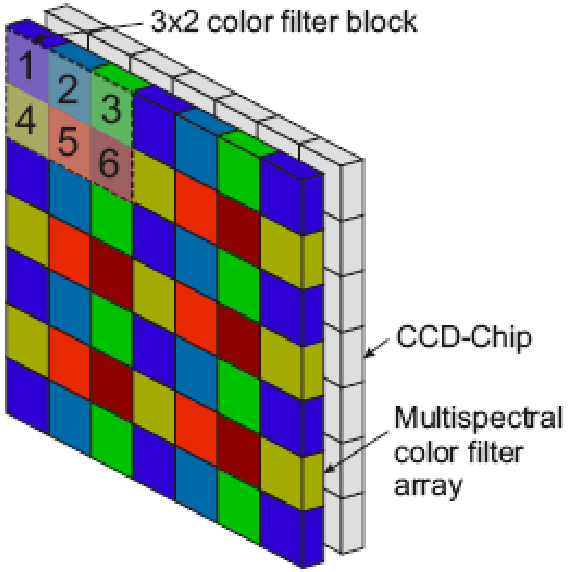
(a) For Minimum RMSE

(b) For Minimum ΔE^*_{ab}

Figure 8. Multispectral 6-channel normalized sensitivities (Fujifilm3D)

Spectral Filter Array (SFA) approach

- Building on well proven colour filter array (CFA) concept which is in practically all colour cameras
- Simply extended to more than 3 channels to achieve single shot multispectral imaging
- Trade-off between spatial and spectral resolution

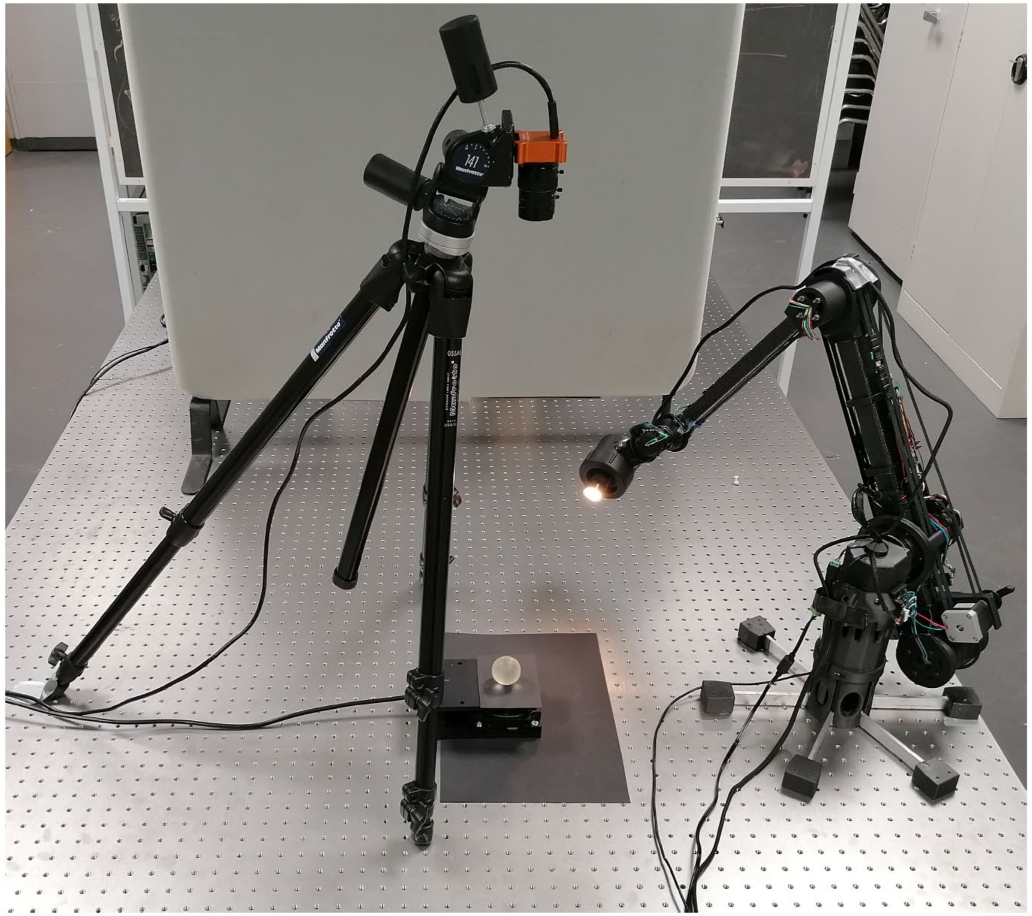


(a) Color filter array

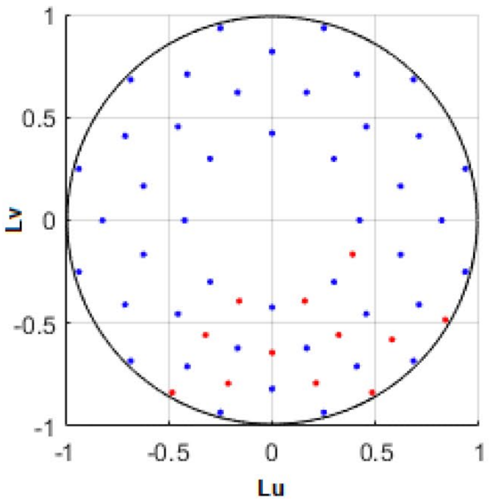
Multispectral RTI (Reflection Transformation Imaging)

RTI Setup:

- 5-joints robotic arm
- 9-channels multispectral camera (440-700 nm)
- Turntable



Light-source positions during captre:



ApPEARS ESR1 - Measurement system for appearance measurement

ApPEARS
APPEARANCE PRINTING
European Advanced Research School

Majid Ansari-Asl

Host Institution: NTNU
PhD Enrollment: NTNU

Main Supervisor(s)

- Jon Yngve Hardeberg (NTNU)

Co-Supervisor(s)

- Gael Obein (CNAM)
- Markus Barbieri (Barbieri Electronics)
- Knut Wold (NTNU)

Objectives

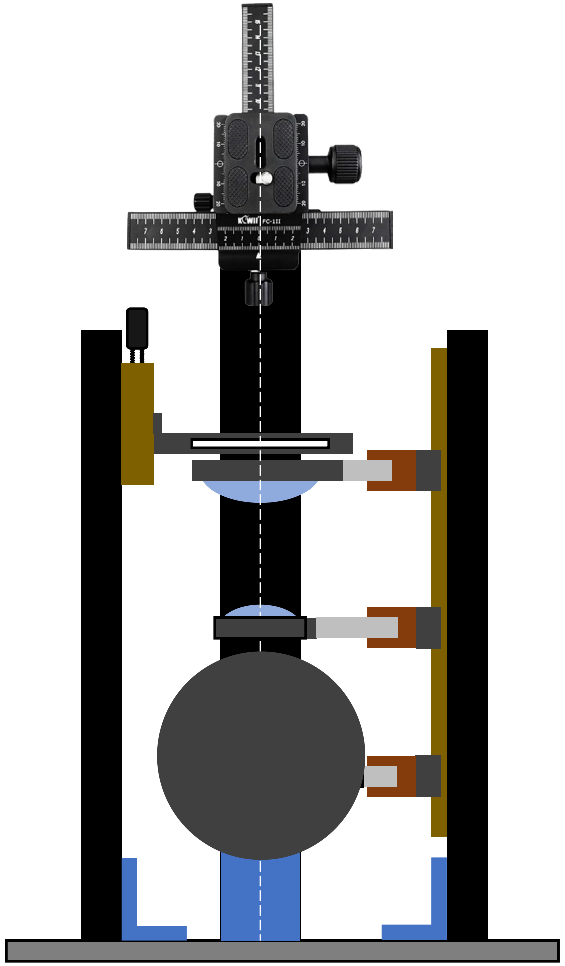
Develop an efficient measurement method(s) to measure material appearance properties for objects printed using 2.5D/3D print techniques.

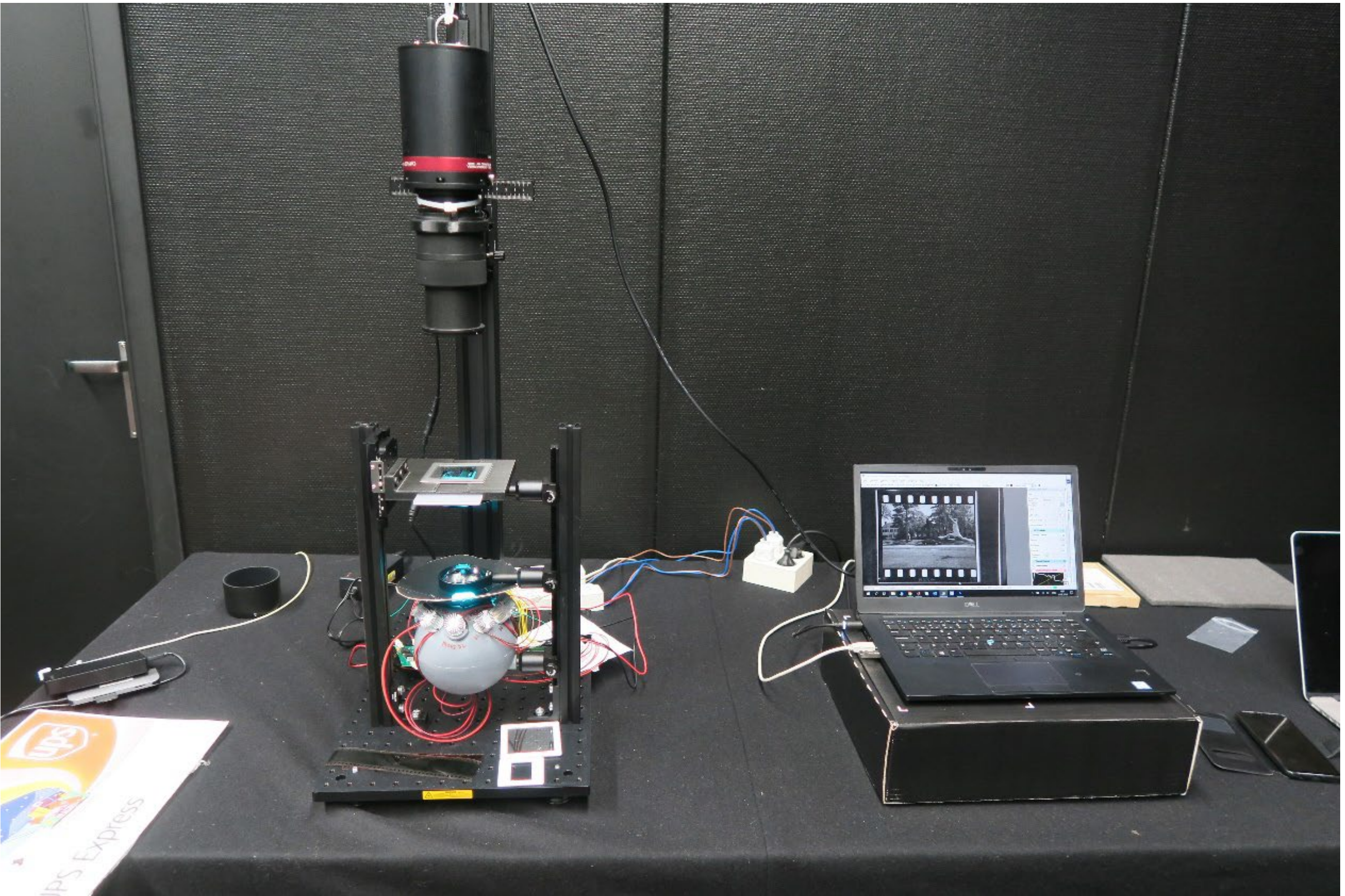
1. Define measurement-architectures for colour, gloss and texture measurements.
2. Define innovative translucency measurement and find simplified description parameter.
3. Define test charts for the different attributes.
4. Evaluate and specify the accuracy of the measurement values

Expected Results

1. The system will help to evaluate a reproduction against an original and help predict the appearance characteristics of specific materials/inks/varnish.
2. Define and measure new attributes to describe and predict the visual appearance of 3D surfaces.
3. Propose and describe the file format to describe the appearance characteristics.

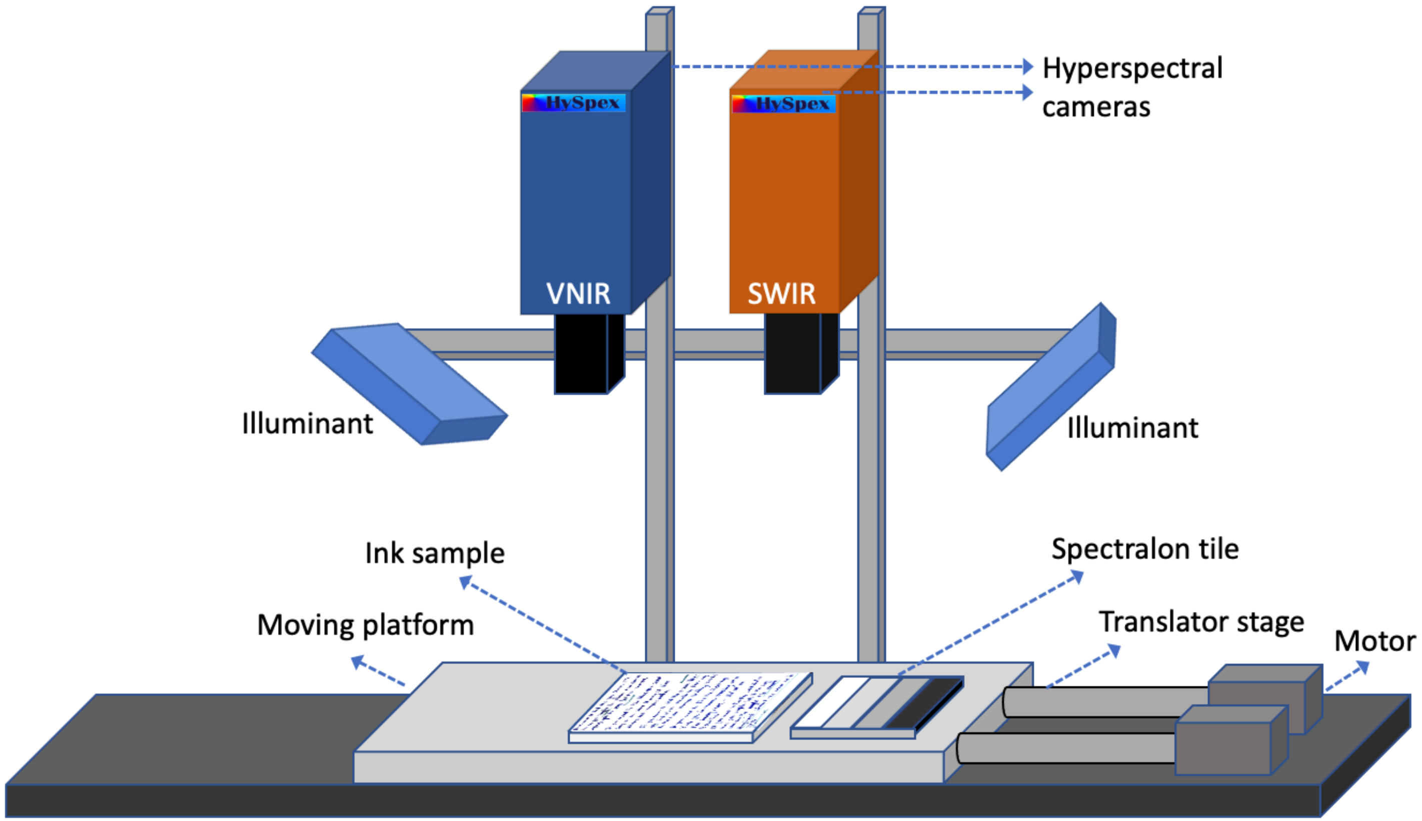
Multispectral film scanning using LEDs

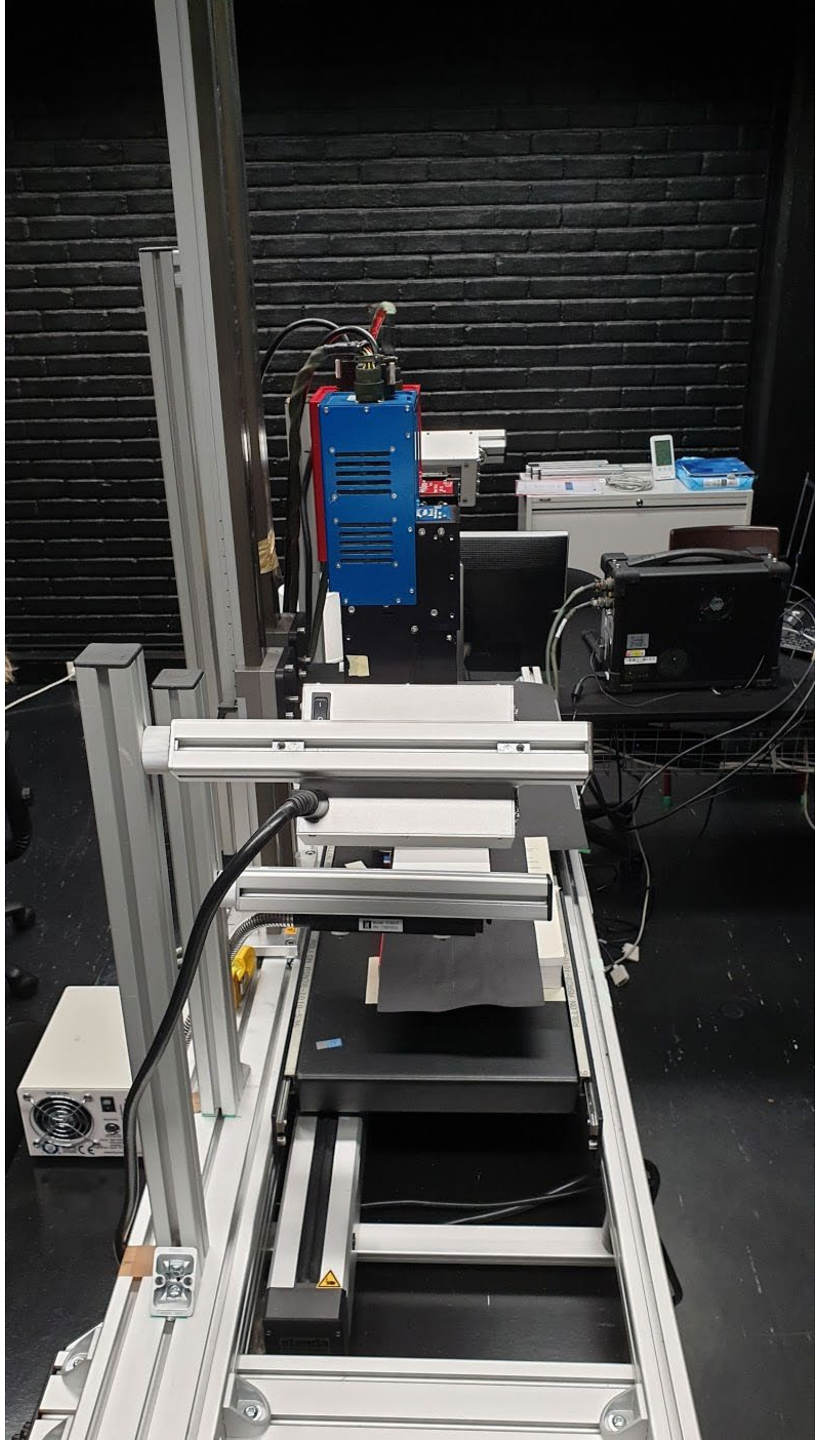




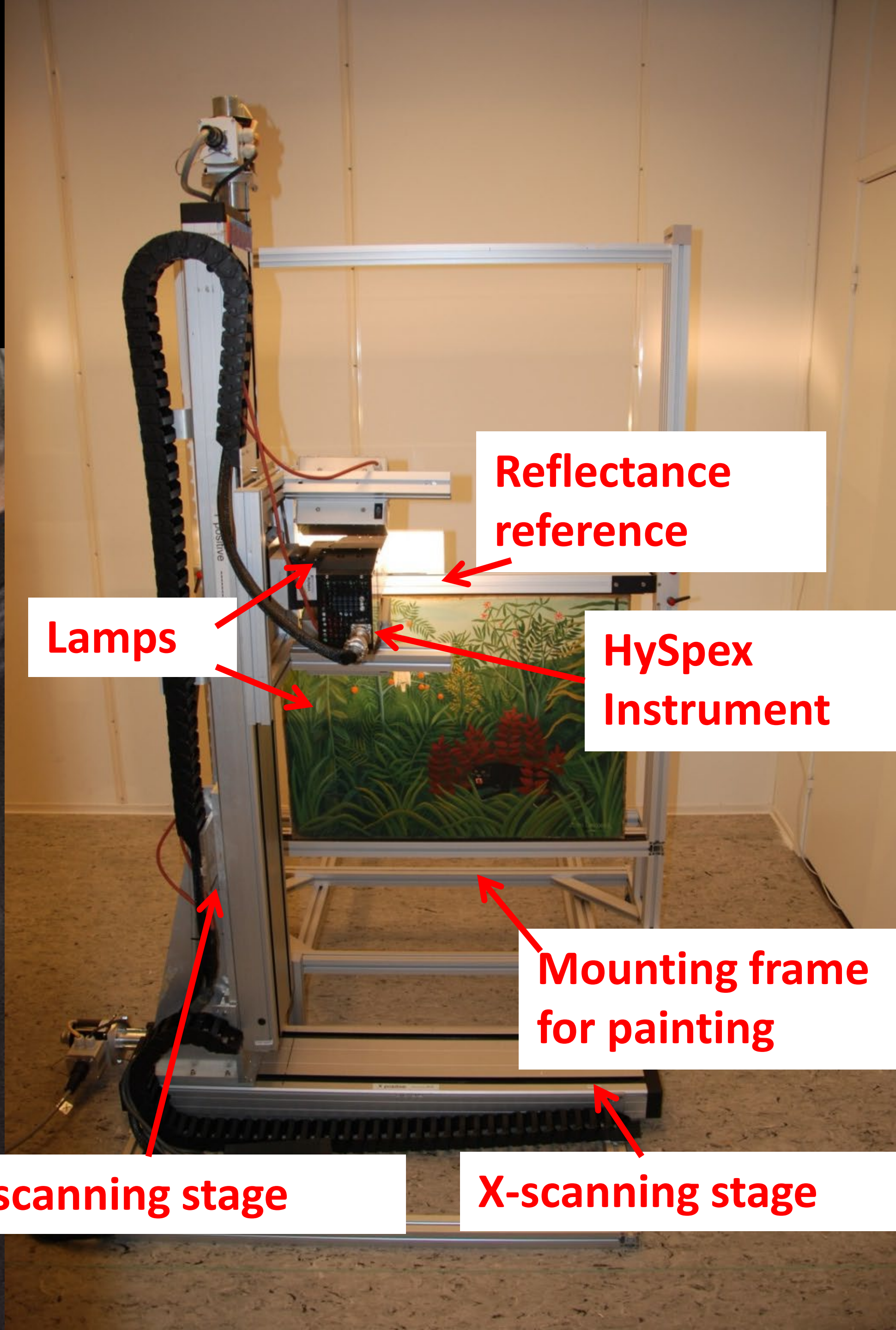
Giorgio Trumpy, J. Y. Hardeberg, S. George, and B. Flueckiger. “A Multispectral Design for a New Generation of Film Scanners.” In Proc. SPIE 11784, Optics for Arts, Architecture, and Archaeology VIII, 2021.

Hyperspectral scanning – pushbroom principle



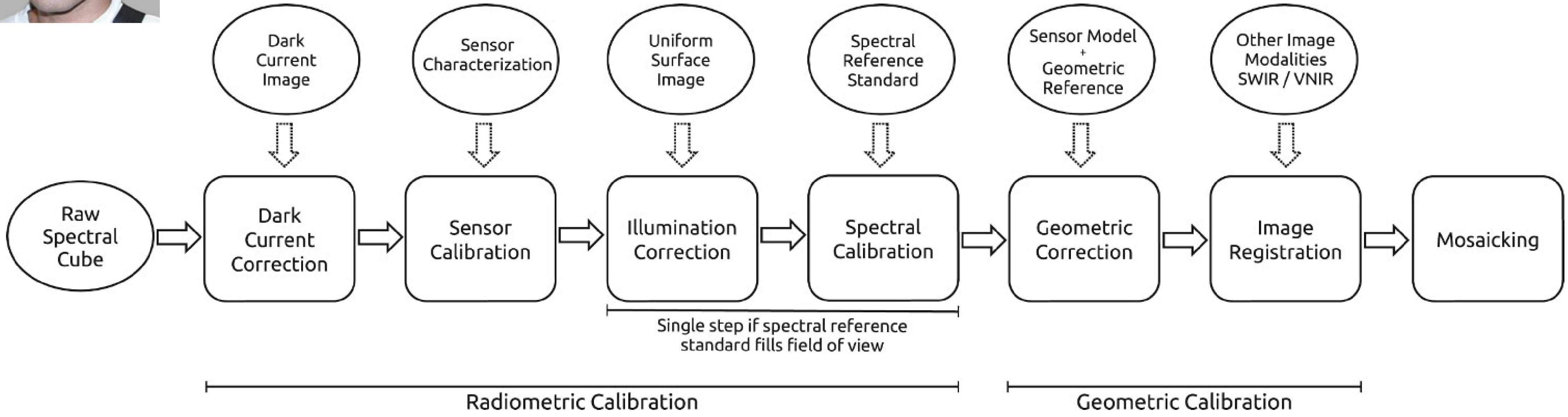


2013 Hyperspectral Scanning of The Scream (1893) at the National Museum of Norway by NTNU Colourlab and Norsk Elektro Optikk AS



Hyperspectral imaging workflow

- Increasing use of hyperspectral imaging in the analysis of works of art
- The calibration of data that is both spectrally and spatially accurate is an essential step in order to obtain useful and relevant results from hyperspectral imaging
- Data that is too noisy or inaccurate will produce sub-optimal results



R. Pillay, J.Y. Hardeberg, S. George. 2019. Hyperspectral imaging of art: Acquisition and callibration workflows. *Journal of American Institute for Conservation*.

NTNU

CHANGE
CULTURAL HERITAGE ANALYSIS
FOR NEW GENERATIONS

- **Funding Body** EU
- **Funding programme**
  Marie Skłodowska-Curie Actions
- **Project duration**
  May 2019 – April 2023
- **Project Coordinator**
  Jon Yngve Hardeberg, NTNU

- **Deputy Coordinator**
  Sony George, NTNU

- **Project Manager**
  Anneli T. Østlien, NTNU

CHANGE is funded by the European Union's
Horizon 2020 programme under the Marie
Skłodowska-Curie grant agreement No 813789

https://www.change-itn.eu

Agnese Babini

NTNU
Kunnskap for en bedre verden
ESR1
Hyperspectral imaging of stained glass windows

Dipendra Mandal

NTNU
Kunnskap for en bedre verden
ESR2
Quality Evaluation in CH Digitization

Evdokia Saiti

NTNU
Kunnskap for en bedre verden
ESR3
Registration techniques for differential and multi-modal data

Saha Sunita

ESR4
Analysis and visualization of multi modal image data in CH surfaces monitoring

Athanasia Papanikolaou

ESR5
Portable multi modal device(s) for surface measurement/monitoring

Jizhen Cai

CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE
ESR6
Development of multi modal image data fusion methods for change monitoring

Yoko Arteaga

CENTRE DE RECHERCHE ET DE RESTAURATION DES MUSÉES DE FRANCE
ESR7
Microscopic 3D imaging and conservation

David Lewis

UBFC
UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ
ESR8
Capture and characterization of change in the appearance of CH objects surface

Ramamoorthy Luxman

UBFC
UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ
ESR9
Appearance change assessment: Link between local geometry and global appearance descriptors

Jan Cutajar

ESR10
Imaging-based documentation and analysis for change monitoring of novel dry-cleaning restoration/conservation methods for unvarnished paintings

Silvia Russo

Hes·so
ESR11
Analysis and assessment of degradation of polychrome artworks

Alessandra Marrocchesi

UNIVERSITEIT VAN AMSTERDAM
ESR13
Low-budget portable device for technical imaging of CH artifacts

Deepshikha Sharma

SCHWEIZERISCHES NATIONALMUSEUM. MUSÉE NATIONAL SUISSE. MUSEO NAZIONALE SVIZZERO. MUSEUM NAZIUNAL SVIZZER.
ESR12
Analysis and monitoring of degradation of ancient glasses

Cyprus University of Technology
ESR14
Enrichment of 3D volumetric data with metadata and semantics

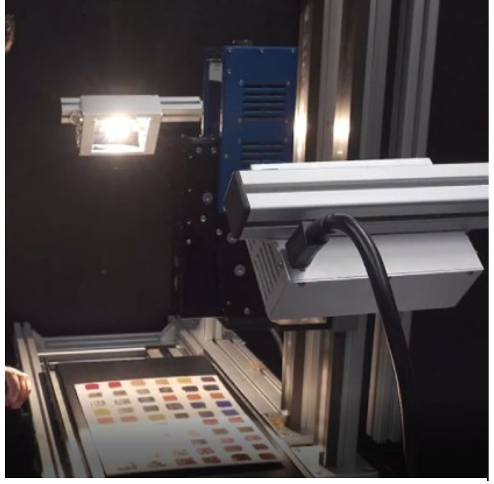
Amalia Siatou

Hes·so
ESR15
Use of imaging techniques to characterize and monitor the surface of historical oxidized, patinated and varnished metals

Quality evaluation in cultural heritage digitization

- Identification of critical parameters for digitizing microfiche.
- Introduction of alternative imaging devices for microfiche digitization.
- Determination of important acquisition parameters for paintings using hyperspectral imaging.
- Development of various algorithms for pigment classification using hyperspectral imaging.

- These contributions provide valuable insights and techniques for preserving and analysing cultural heritage materials.



ESR 2: Dipendra Mandal

NTNU
Norwegian University of Science and Technology

Analysis and monitoring of degradation of historical glasses

Reflectance Transformation Imaging (RTI) and Hyperspectral Imaging (HSI) have been applied to detect early signs of corrosion in historical transparent glass.

- **RTI** visualizes early stages of corrosion and provides an imaging solution for corrosion signs not visible with simple RGB photography.
- **HSI** records high-resolution spectral information, identifying and quantifying corrosion, especially in the SWIR spectral region.
- These techniques were applied to model glasses subjected to accelerated aging, showing promising results for documenting volatile organic compounds (VOC) induced corrosion phenomena on glass surfaces.

Image: National Museum of Switzerland

ESR 12: Deepshikha Sharma

SCHWEIZERISCHES NATIONALMUSEUM. MUSÉE NATIONAL SUISSE. MUSEO NAZIONALE SVIZZERO. MUSEUM NAZIUNAL SVIZZER.

NTNU
Kunnskap for en bedre verden

ESR1 – Hyperspectral imaging of stained-glass windows

Agnese Babini

Host Institution: NTNU
PhD Enrollment: NTNU

Supervision team

- Sony George (NTNU)
- Jon Yngve Hardeberg (NTNU)
- Tiziana Lombardo (SNM)

Objectives

1. Development of imaging techniques for documentation of transparent/ translucent artifacts (focus on stained glass).
2. Develop a laboratory, in-situ setup for the HSI of stained glass panels.
3. Validation of the spectral data: comparison with UV-VIS-NIR spectroscopy of stained glass samples
4. Validation of identified chromophores: use of complementary analysis such as X-Ray Fluorescence spectroscopy (XRF) to characterize the elemental composition of the glass

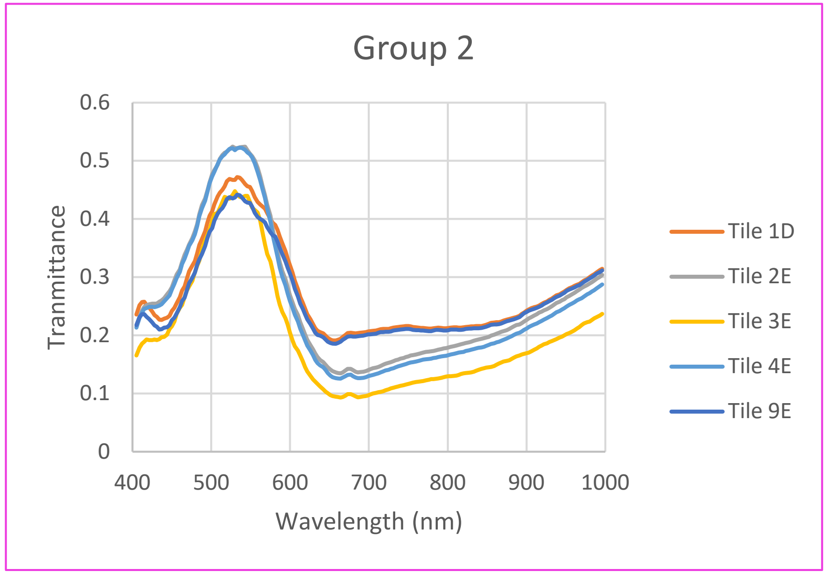
Results

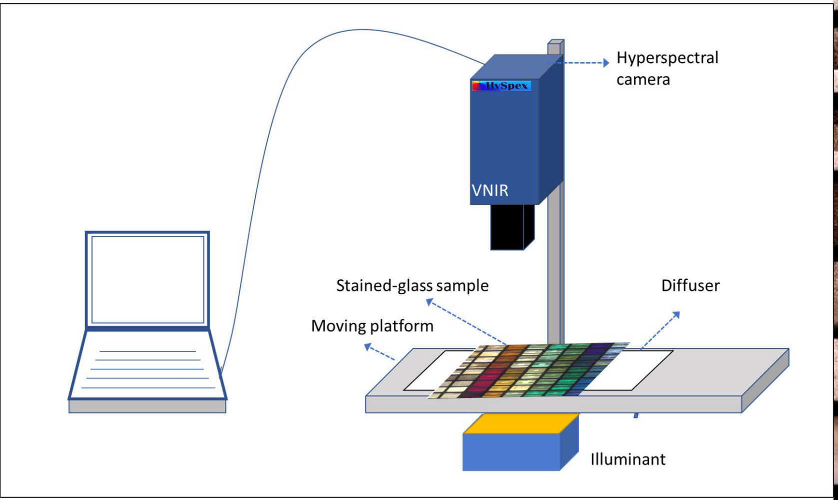
1. Prototype of imaging system for digitisation of optically complex CH artefacts
2. Change monitoring tools for challenging objects using multimodal imaging
3. Hardware and software tools for mass digitisation and processing of multimodal images.

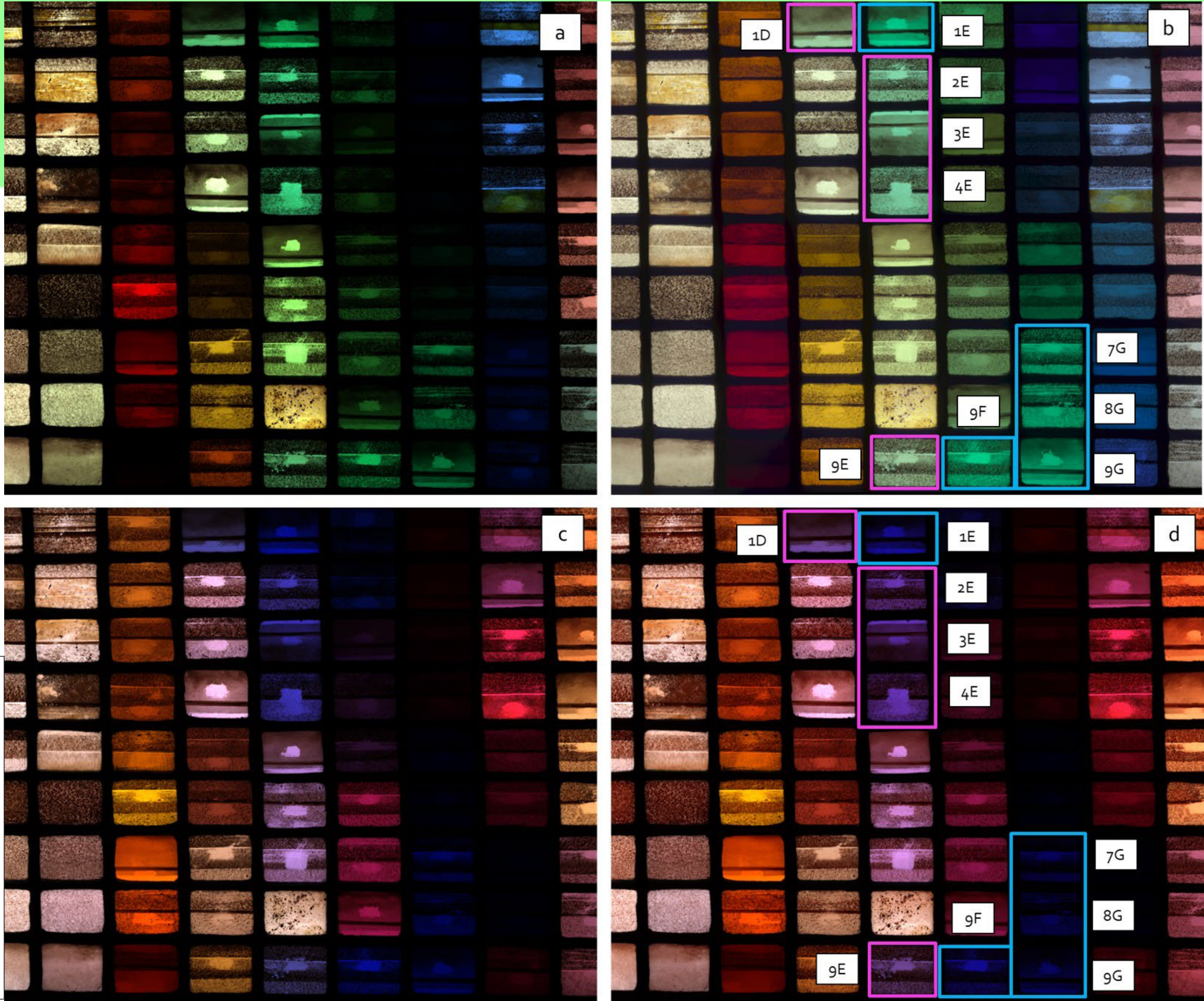
Secondments

1. CNRS - Digitization of films and photography materials
2. SNM - Modelling and monitoring of degradation of glass artefacts
3. UBFC - Methods for monitoring micro-macro changes in appearance using multimodal imaging

https://change-itn.eu/about/people/fellows/esr1-agnese-babini


Group 2
0.6
0.5
0.4
0.3
0.2
0.1
0
Tranmittance
400
500
600
700
800
900
1000
Wavelength (nm)
Tile 1D
Tile 2E
Tile 3E
Tile 4E
Tile 9E


Hyperspectral camera
HySpex
VNIR
Stained-glass sample
Diffuser
Moving platform
Illuminant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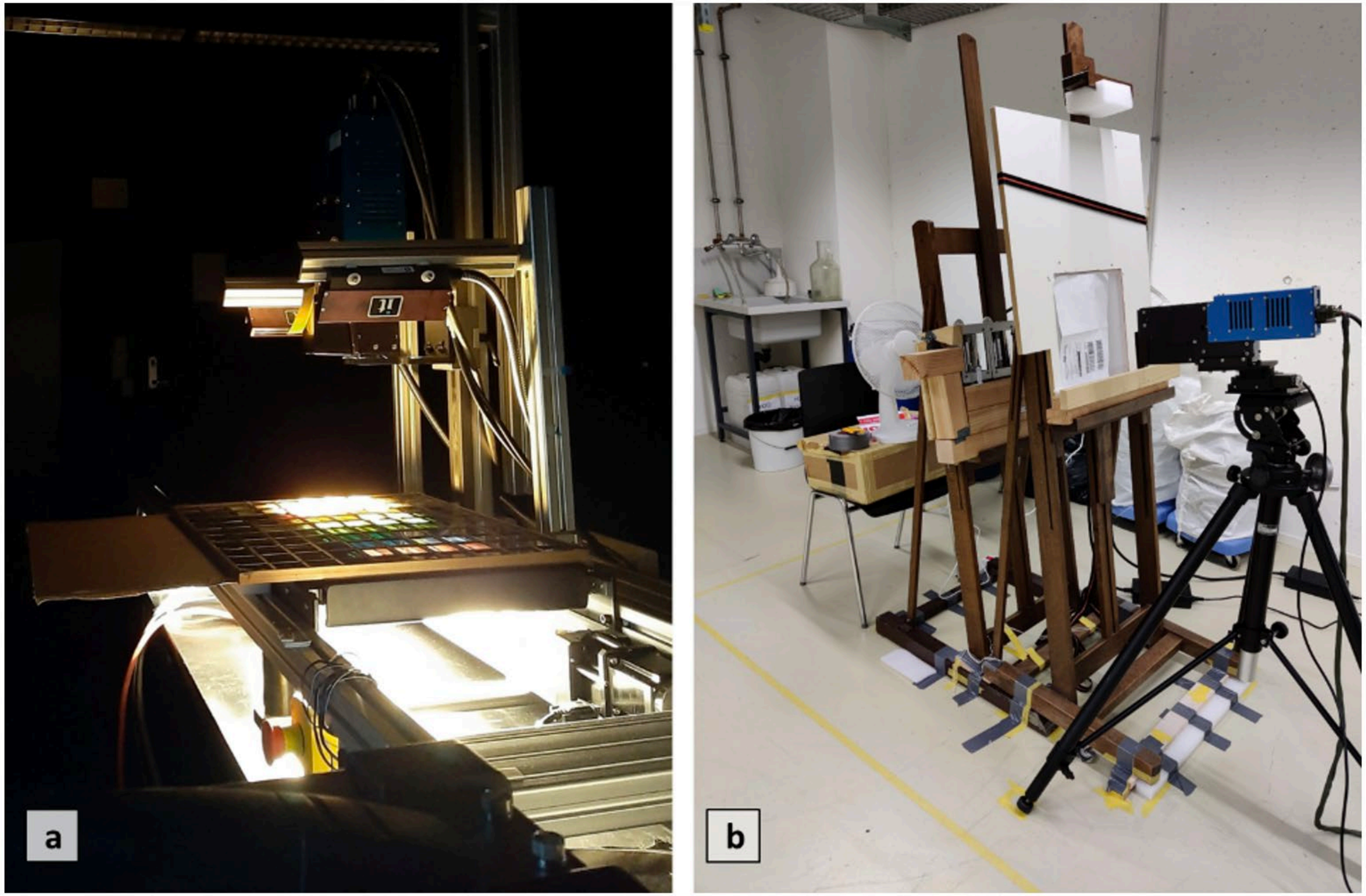
9E
9G

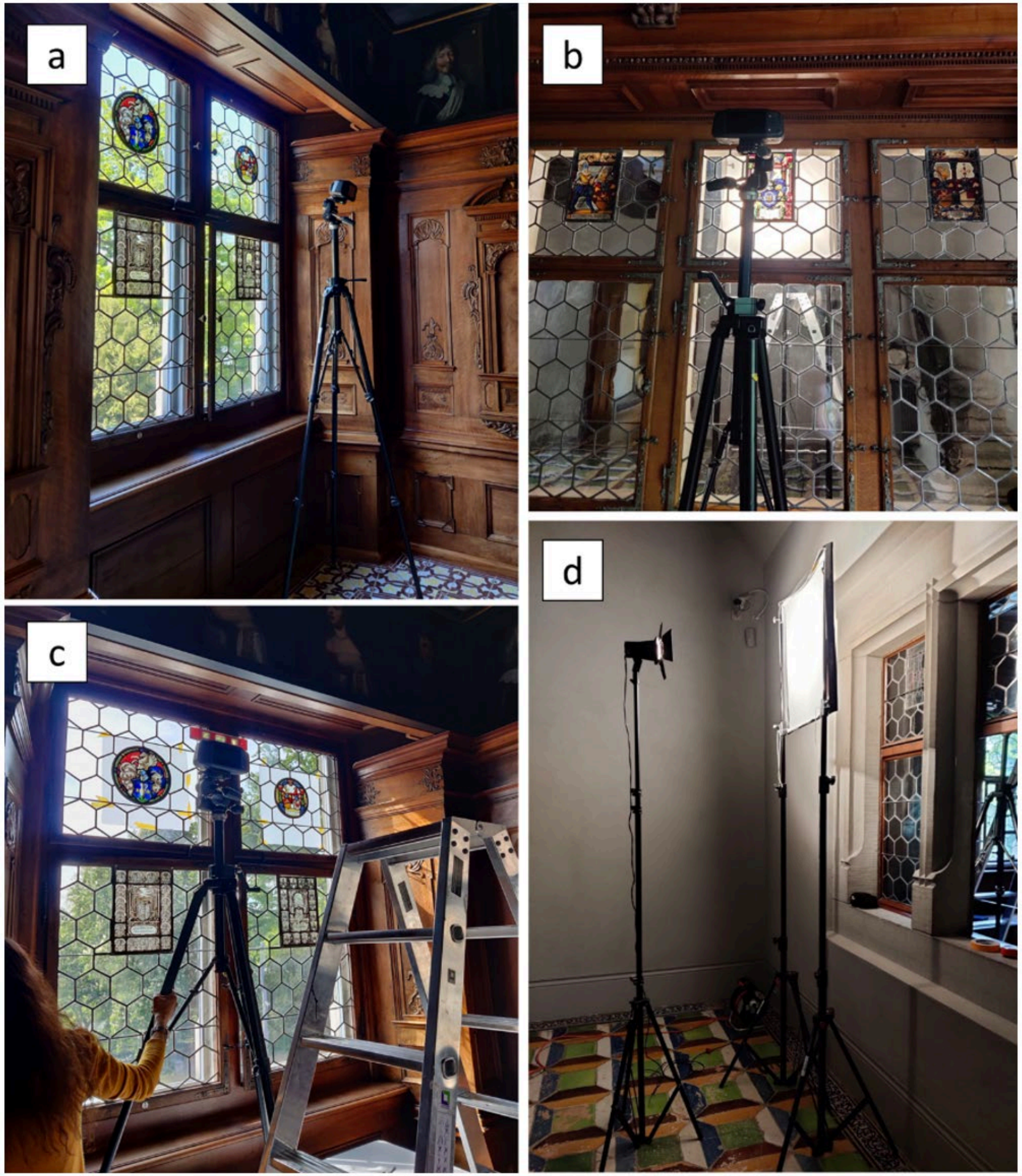
Laboratory and onsite experiments



HySpex VNIR-1800

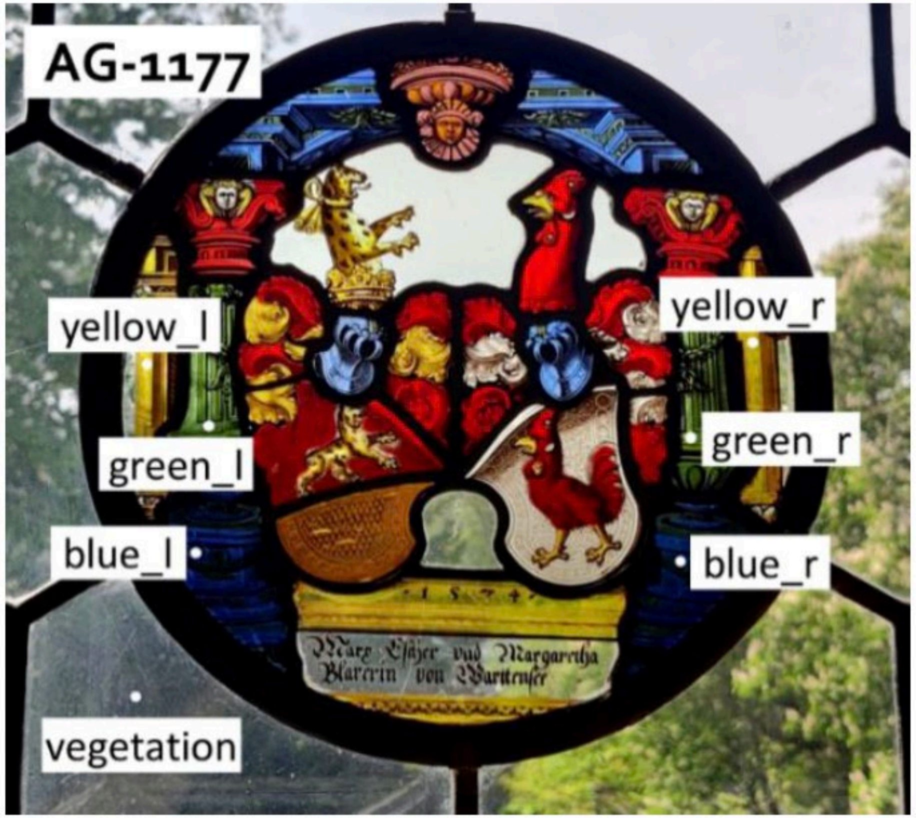
Spectral range	400 – 1000 nm
Spatial pixels	1800
Spectral channels	186

Hyperspectral Imaging @Swiss National Museum

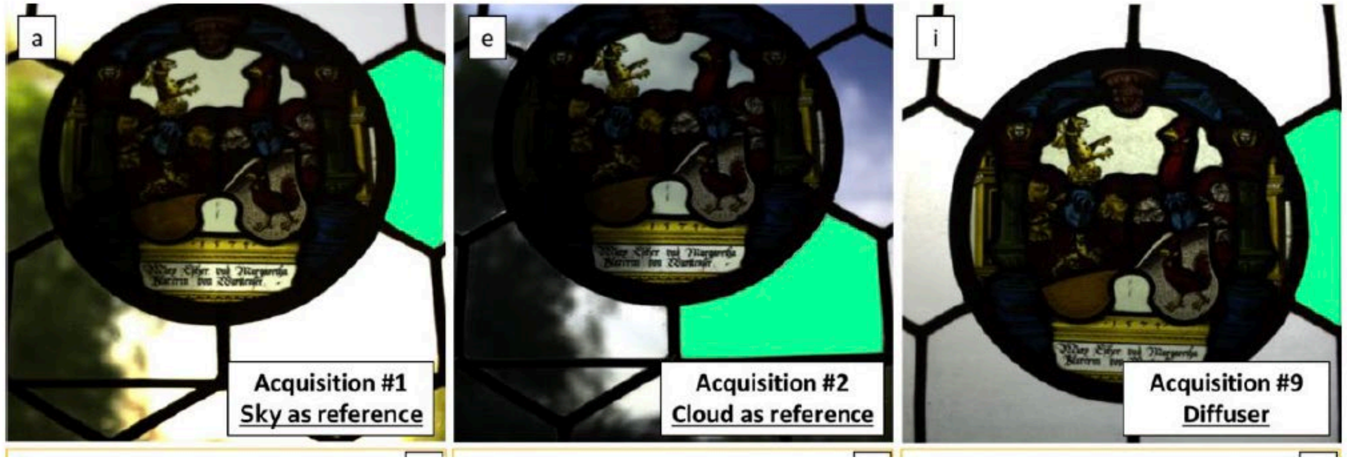


Specim IQ

Babini, Agnese, Tiziana Lombardo, Katharina Schmidt-Ott, K., Sony George, Jon Yngve Hardeberg. Acquisition strategies for in-situ hyperspectral imaging of stained-glass windows: case studies from the Swiss National Museum. *In Heritage Science (2023)*



Different backgrounds



Diffused and direct lighting conditions

Babini, Agnese, Tiziana Lombardo, Katharina Schmidt-Ott, K., Sony George, Jon Yngve Hardeberg. Acquisition strategies for in-situ hyperspectral imaging of stained-glass windows: case studies from the Swiss National Museum. *In Heritage Science (2023)*

Combined VNIR-SWIR hyperspectral imaging for CH artefacts

Federico Grillini

Host Institution: NTNU
PhD Enrollment: NTNU
2021 - 2023

Supervision team

- Jean Baptiste Thomas (NTNU, UB)
- Sony George (NTNU)

- *How to combine spectral and spatial information from VNIR and SWIR imaging systems*
- *How to detect and remove shadows in proximity imaging for the applications in CH domain*
- *Study polarisation spectral imaging*

Colourlab

Hyperspectral cameras

Name	VNIR1800	SWIR384
Detector	Si (CMOS)	MCT
Range	400-1000 nm	950-2500 nm
Bands	186	288
FWHM	3.26 nm	5.45 nm
Spatial lines	1800	384

Spectral Alignment

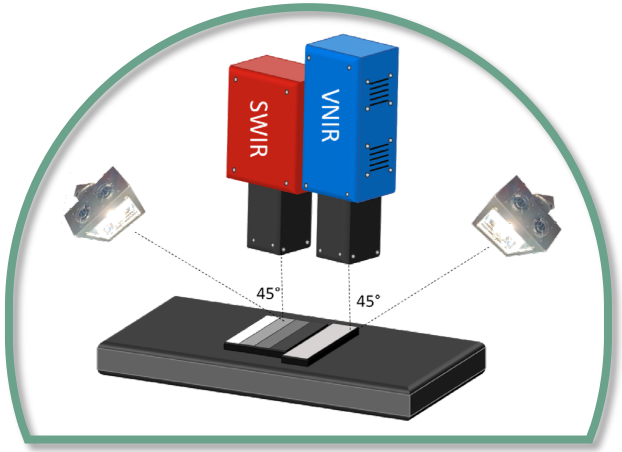
Spatial Alignment

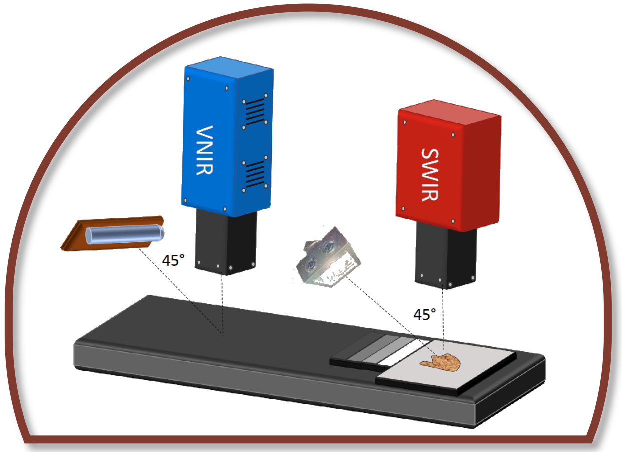
Federico Grillini, Jean-Baptiste Thomas, and Sony George. “Logistic splicing correction for VNIR SWIR reflectance imaging spectroscopy”. *In: Optics Letters 48.2, pp. 403–406. (Jan. 2023)*

Identify the optimal set-up

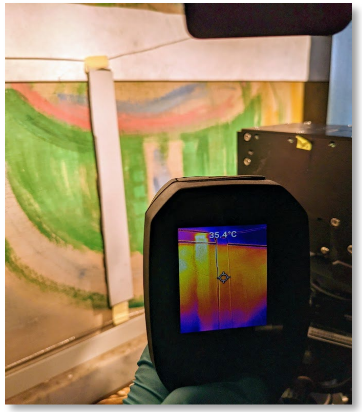
Colourlab

Choice of illumination: quantity, direction, and specific spectral characteristics



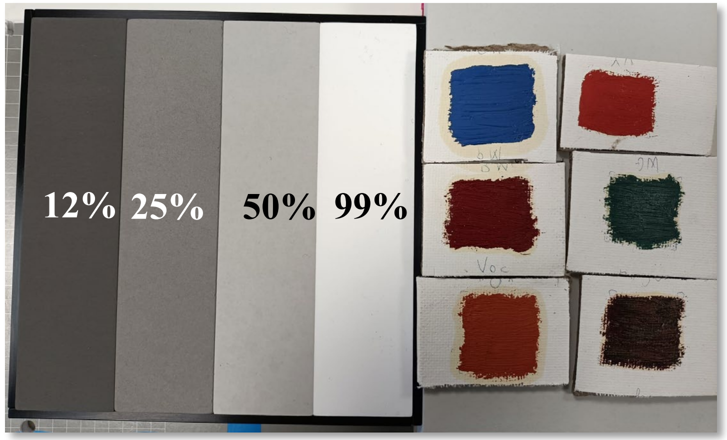


Temperature Monitoring



FLIR

Presence of standardized targets



NTNU

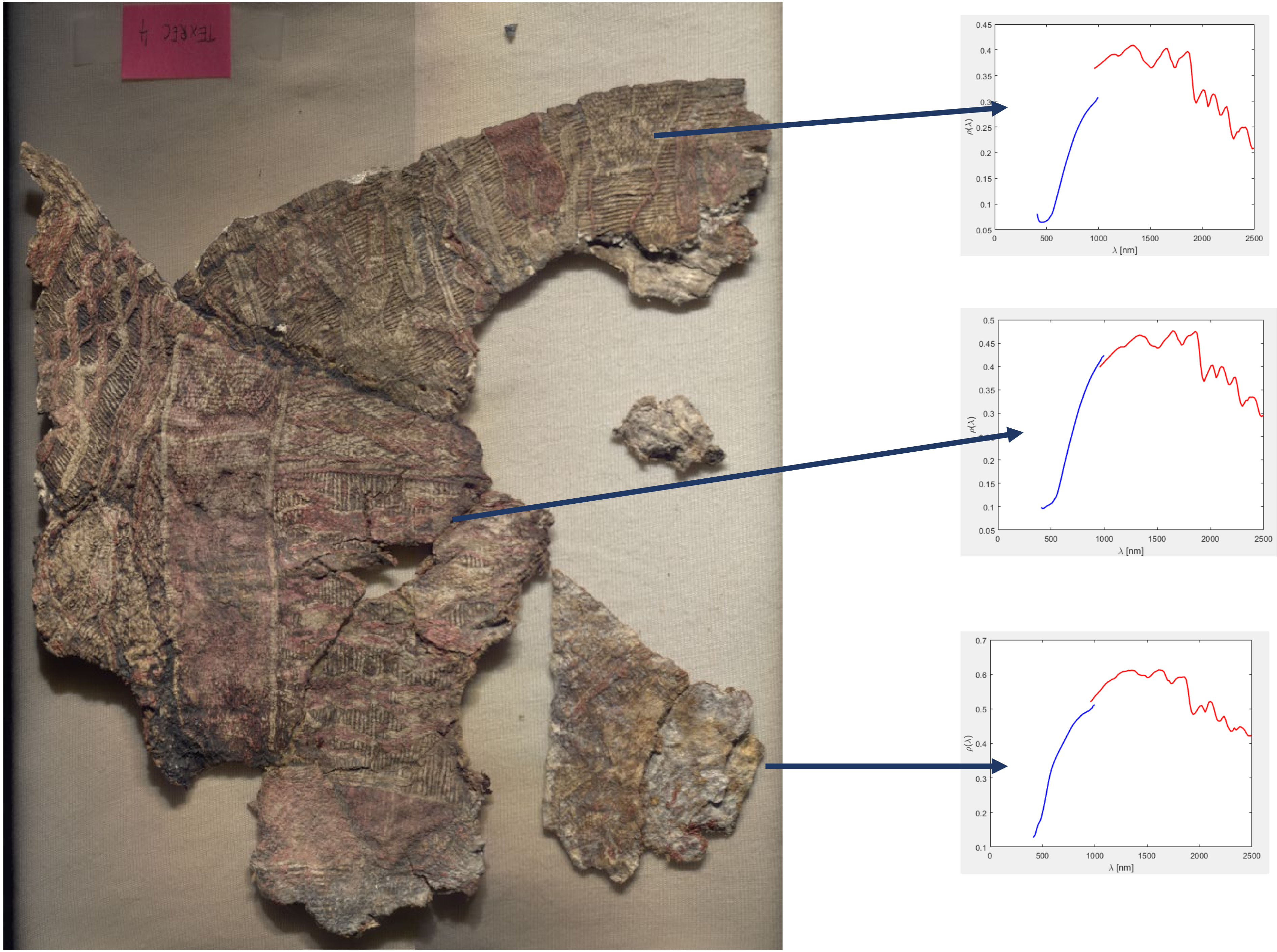
Spectral Analysis of Textile Fragments from the Oseberg Find

TexRec project

Virtual Reconstruction, Interpretation and Preservation of the Textile Artifacts from the Oseberg Find

Coordinated by the Museum of Cultural History, University of Oslo

Forskningsrådet


ρ(λ)
λ [nm]
0 500 1000 1500 2000 2500
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45
ρ(λ)
λ [nm]
0 500 1000 1500 2000 2500
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
ρ(λ)
λ [nm]
0 500 1000 1500 2000 2500
0.1 0.2 0.3 0.4 0.5 0.6 0.7

PhD project: «Multimodal Image Analysis and Visualisation for Painting Conservation»

- PhD student: Nina Eckertz
- Supervisors: Jon Y. Hardeberg and Hilda Deborah (NTNU), Irina Sandu (The Munch Museum)
- Duration: 2024-2027
- Work Packages and Objectives:
  - Multimodal Data Fusion and Visualisation
    - Advancing the analysis and visualisation of multimodal imaging data, by combining imaging techniques in a multimodal framework for an in-depth analysis of paintings
  - In-depth Characterisation and Multimodal Analysis of the Pigments and Paintings Techniques of a Selection of Paintings from MUNCH's Collection
    - Generate novel insights into Munch's artistic procedure by analysing the painting surface and painting techniques on a single painting and a selection of paintings from Munch's Warnemunde period (1907-1908)
  - Scientific Image Analysis and Visualisation Platform for Painting Conservation
    - Accelerate and enhance the painting conservation research process by providing a scientific image analysis and visualisation platform, specifically developed and tested with domain experts

PhD project: «Interactive Visualisation of Hyperspectral Images (HSI) in an Exhibition Setting»

- PhD student: Zealandia Sarah Nurul Fatma
- Supervisors: Hilda Deborah and Jon Y. Hardeberg (NTNU Colourlab), Eleftherios Papachristos (NTNU Department of Design)
- Duration: 2024-2027
- In collaboration with the National Library of Norway
- Scientific objectives
  - Advancing change detection, analysis, and modelling in cultural heritage by combining HSI, microfading, and chemistry analytical method.
  - Generate a novel image processing analysis and visualisation of semantic pigment mapping and pigment spatial correlation of old maps.
  - Develop a prototype of interactive exhibition experience based on HSI data by taking into account human computer design approach.

Wrap-up

- Multispectral imaging is a hot research topic
  - Lots of progress and current interest from companies
  - Also more academic research needed
- Multispectral imaging has been shown to be useful for many applications
  - Cultural heritage, material appearance, scene recocnition, illuminant estimation...
  - Still open search for the «killer app»
- Warm thanks: invitation, collaborators and students, audience
- Open for discussions and new collaborations
  - Student projects, EU projects, industrial PhDs, consulting, ...
  - jon.hardeberg@ntnu.no, http://www.colourlab.no
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