AGH University of Science and Technology

Optimisation of the X-ray fluorescence imaging system for mapping of pigments in historical paintings

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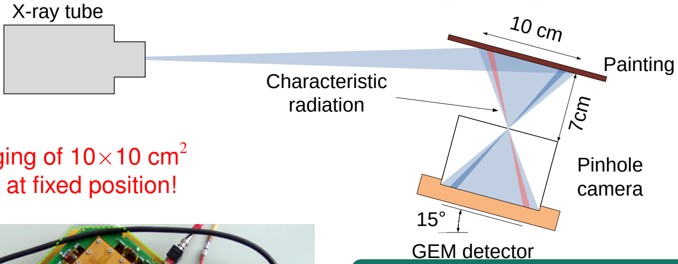
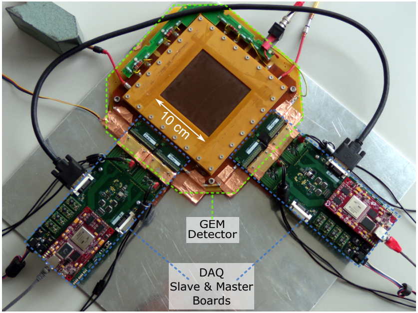
Outline

1. Introduction
   - Brief description of the motivation of our work
2. Detection system
   - Short overview of the Gas Electron Multiplier (GEM) based imaging system
3. Pigment specific imaging results
   - Presentation of the results obtained during scanning of painting phantom
4. Position resolution of the system
   - Information about the position resolution of the system in a few configurations
5. Conclusions
   - Remarks on results and a few words about future plans

Introduction



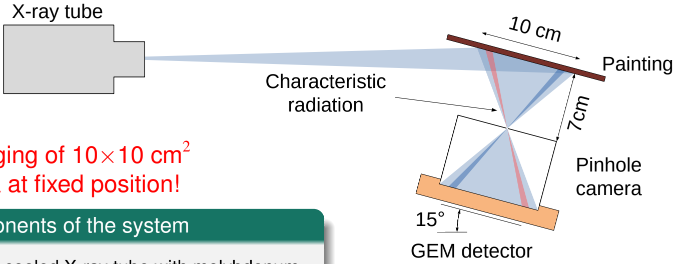
Imaging of 10×10 cm^2 area at fixed position!



The main advantages of the presented system are as follows

- Imaging of large areas of paintings in a fixed detector position (safety of the investigated objects)
- Relatively fast measurement (hours)
- Infinite depth of field (of camera obscura)
- Affordable costs

The principle of the method has already been proven.



Imaging of 10×10 cm^2 area at fixed position!

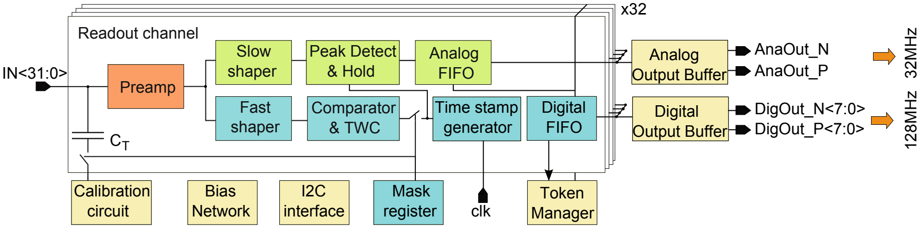
Key components of the system

- Water-cooled X-ray tube with molybdenum or copper anode working at 20-30 kV
- Beam cross-section area $4 \times 10\,\mathrm{cm}^2$ which allow to illuminate the painting area of about $10 \times 10\,\mathrm{cm}^2$
- Cadmium pinhole camera 0.5,1 and 2 mm in diameter with adjustable height
- Magnification factor ∼0.5-2×
- Position sensitive GEM detector

In current work we are studying in more detailed way the features of our system

- A pinhole camera properties
- Position resolution of the overall system (mainly a pinhole camera diameter and hight)
- Pigments recognition enhancement by using Cu anode for the X-ray tube

Readout electronics (designed at AGH)



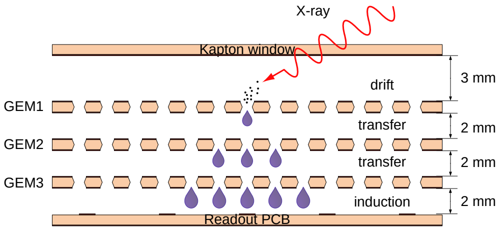
Main parameters of the GEMROC ASIC

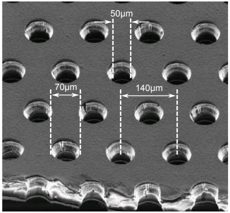
- 32 channels, each split into energy and timing sub-channel
- Self triggering mode
- Data derandomization and zero suppression
- Equipped with testability functions
- Deliver energy, position and time informations

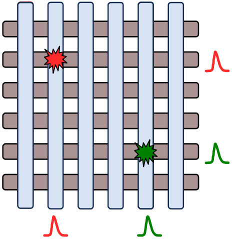
Gas Electron Multiplier (GEM) detector

GEM detector parameters

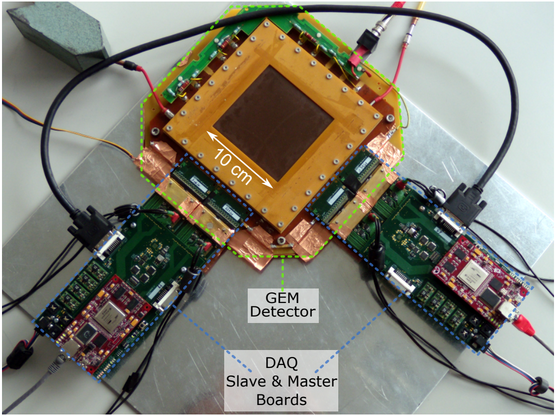
- Position sensitive detector with active area $10 \times 10\,\mathrm{cm}^2$
- 128×128 orthogonal readout strips
- Charge collected on several readout strips
- Position reconstruction
  - Matching time stamps of signals of X and Y strips
  - Fine position reconstruction using signals amplitudes (Centre of Gravity method)
- Ar/CO_2 active gas mixture
  - Low cost
  - Moderate detection efficiency







Detection system (GEM & front-end & DAQ)



Parameters of the system

- Dedicated readout electronics
  - Simultaneous measurement of time and amplitude
  - Finding coincidences of X and Y signals (reconstruction of 2D position)
- Energy resolution of about 20 $\%$ FWHM for 5.9 keV
- Position resolution of about $100\ \mu\mathrm{m}$ rms. (without pinhole camera)
- High count rate capability up to 5×10^6 cps

Test phantom with stripes

Photograph of the whole phantom

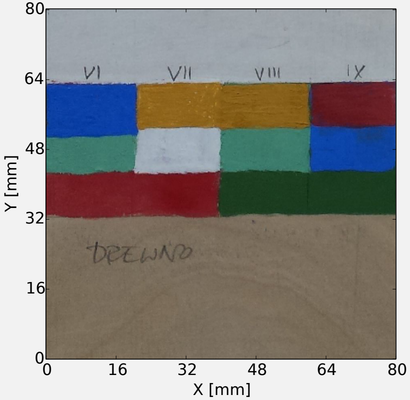
Phantom prepared by National Museum in Krakow

Test phantom with stripes – detailed view

Prepared phantom

- A pattern of stripes painted with inorganic pigments on a wooden panel
- The phantom was prepared according to the XV century painting techniques and using paints based on historical pigments by Kremer Pigmente GmbH & Co. KG.
- Different pigments are overlapping each other and are painted on top of three different bottom layers (wood, lead-white and chalk)

Phantom with stripes (zoomed)



- Investigated area of the phantom

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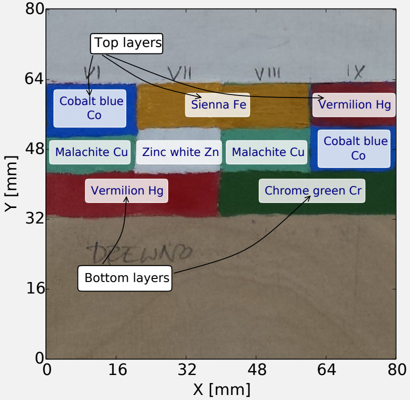

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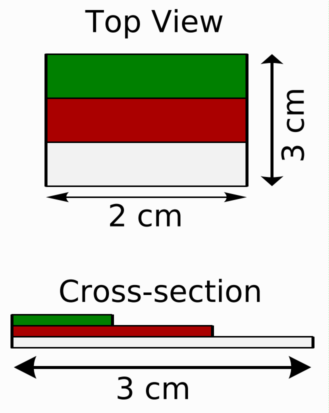
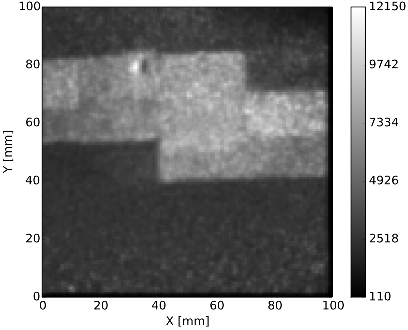


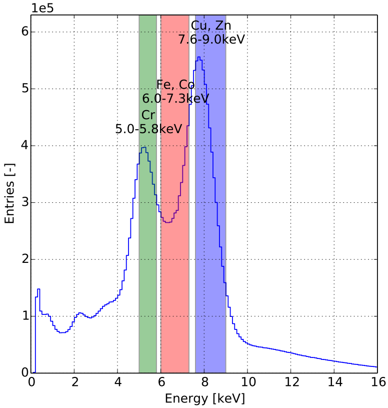
- Schematic view of painting layers

XRF imaging results (fragment of phantom with stripes)

Total intensity map



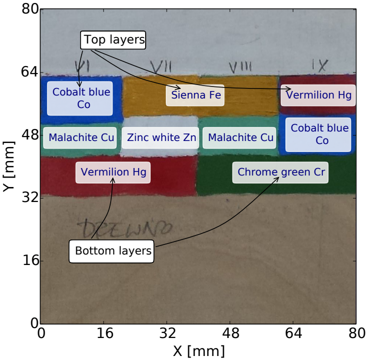
Cumulative energy spectrum

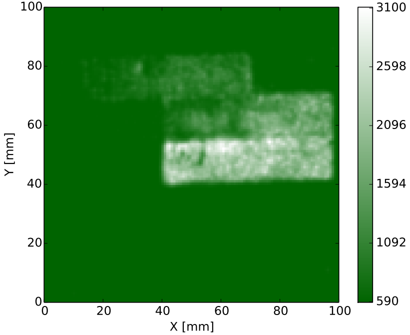


XRF imaging results (fragment of phantom with stripes)

Cr window: 5.0-5.8 keV

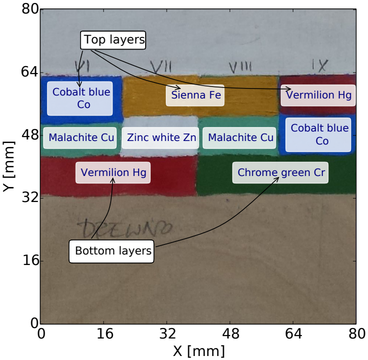
- Visible chrome green bottom layer
- Attenuation by Vermilion Hg pigment clearly seen (top-right corner)

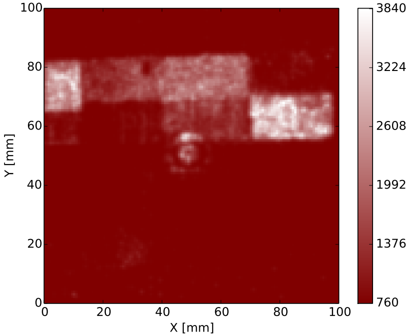




Co and Fe window: 6.0-7.3 keV

- Visible cobalt blue and sienna layers

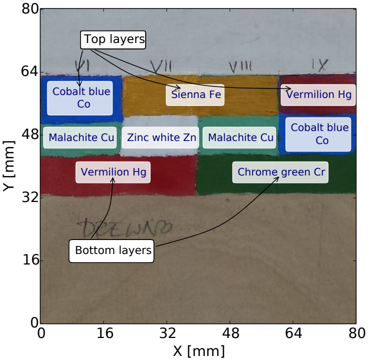


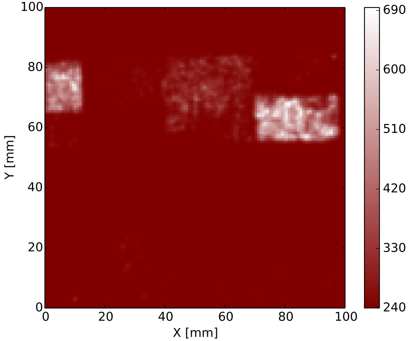


XRF imaging results (fragment of phantom with stripes)

Co window: 6.8-7.0 keV

- Visible cobalt blue

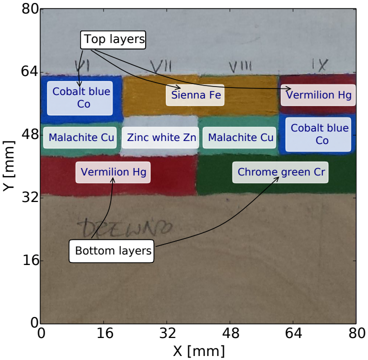


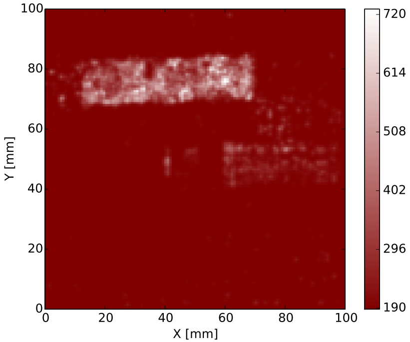


XRF imaging results (fragment of phantom with stripes)

Fe window: 6.3-6.5 keV

- Obtained by subtraction (Co&Fe window – Co window)
- Visible sienna layer

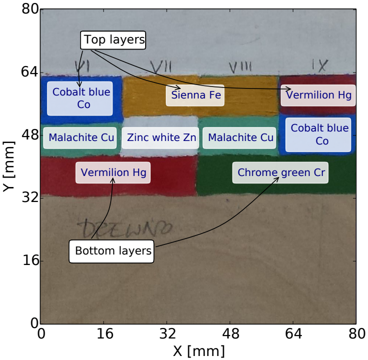


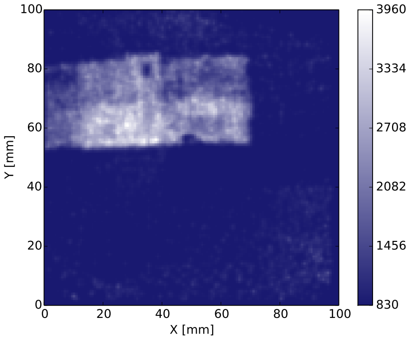


XRF imaging results (fragment of phantom with stripes)

Cu and Zn window: 7.6-9.0 keV

- Visible malachite and zinc white layers

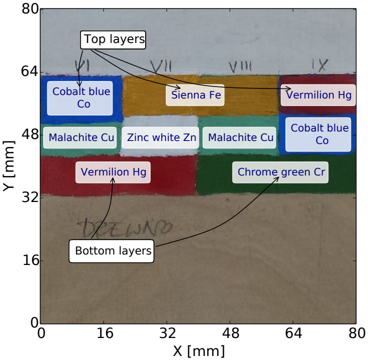


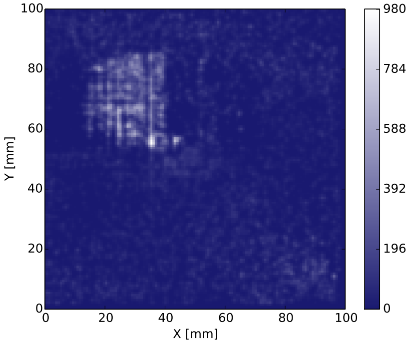


XRF imaging results (fragment of phantom with stripes)

Zn window: 8.55-8.75 keV

- Obtained by subtraction (Cu&Zn window – Cu window)
- Visible zinc white layer

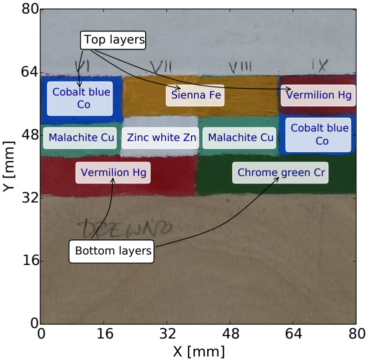


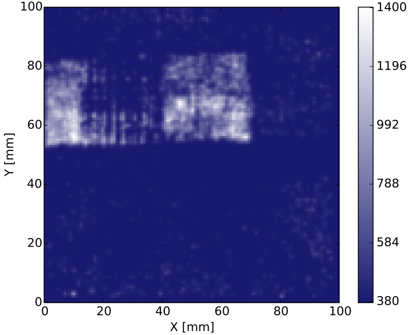


XRF imaging results (fragment of phantom with stripes)

Cu window: 7.9-8.1 keV

- Obtained by subtraction (Cu&Zn window − Zn window)
- Visible malachite layer





Pigment specific imaging results

Remarks

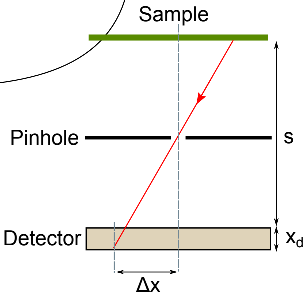
- The technique is suitable for qualitative pigment determination
- The limitations are mainly due to
  - Moderate intrinsic energy resolution of the GEM detector
  - The pigments chemical compositions can be similar (based on the same or slightly different in Z elements)
- X-ray tube with Cu anode provide better visualization of pigments based on lighter elements then Cu (no excitation of the detector inner components)
- X-ray tube with Mo anode is more suitable when pigments of higher-Z elements are dominating (not presented here)
- Future plans: new front-end electronics and Xe-based gas mixture surly will improve the results (to $\sim$15% FWHM of 5.9 keV)

Position resolution of the system – theoretical model

- Pinhole effective aperture: $d_{eff} = d\left[1 - \frac{\Delta x}{s}\left(1 + \frac{1}{M}\right)\right]$

$$\sigma^2 = \frac{{d_{eff}}^2}{8\ln(2)}\left(1 + \frac{1}{M}\right)^2 + \left(\frac{p}{\sqrt{12}M}\right)^2 + \frac{(x_d \Delta x/s)^2}{8\ln(2)M^2}\left(1 + \frac{1}{M}\right)^2$$

- Detector intrinsic position resolution
- Prallax error depending on the thickness of the drift gap in GEM

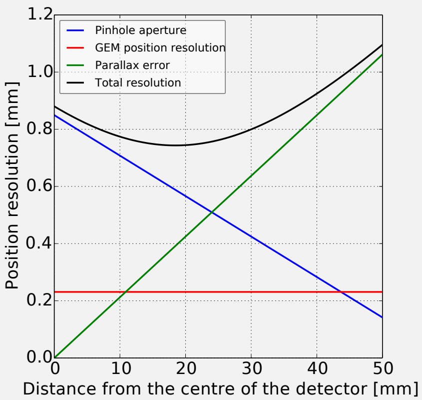


d – diameter of the pinhole
d_{eff} – effective diameter of the pinhole depending on the photon angle
M – magnification of the detection system
p – pitch of the GEM readout structure
x_d – thickness of the drift gap in GEM
s – object to detector window distance
Δx – distance from the centre of the detector to the photon registration position

Position resolution of the system – theoretical model

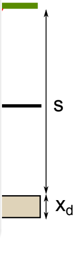
- Pinhole effective aperture: $d_{eff} = d\left[1 - \frac{\Delta x}{\ldots}\left(1 + \frac{1}{M}\right)\right]$

d = 1 mm and M = 1



$\sigma^2 = \ldots ^2$

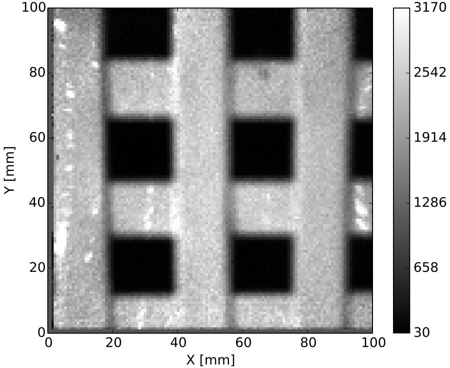
- D
- F
  c

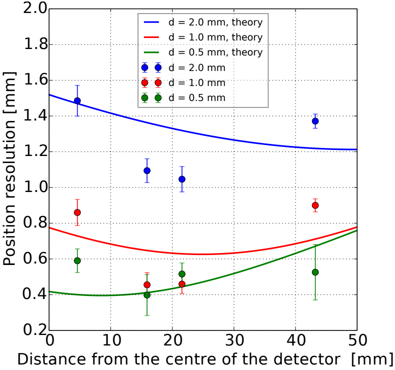


Δx – distance from the centre of the detector to the photon registration position

Position resolution of the system – measurement results

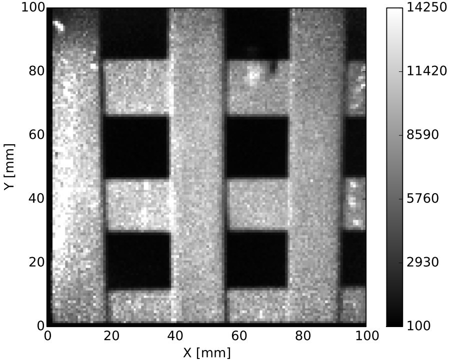
Pinhole diameter d=2 mm

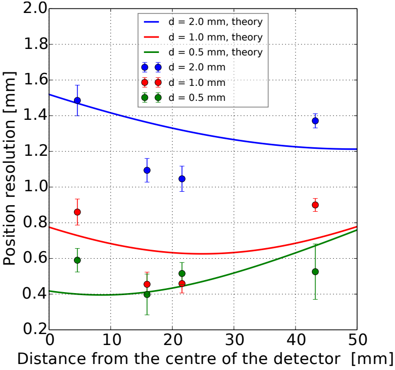




Position resolution of the system – measurement results

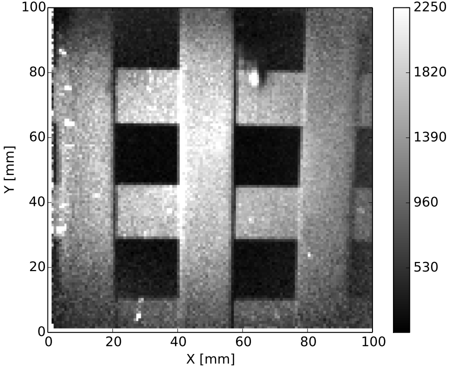
Pinhole diameter d=1 mm

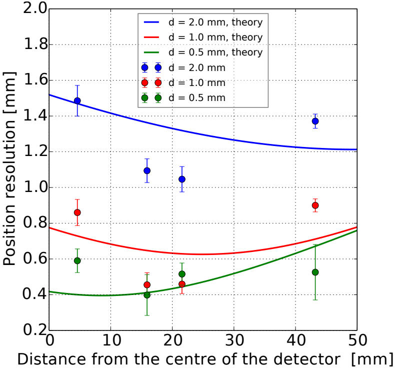




Position resolution of the system – measurement results

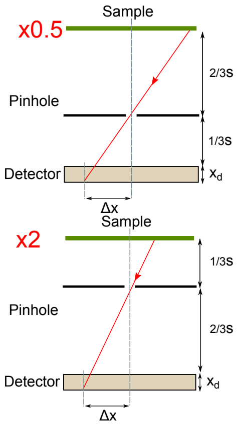
Pinhole diameter d=0.5 mm

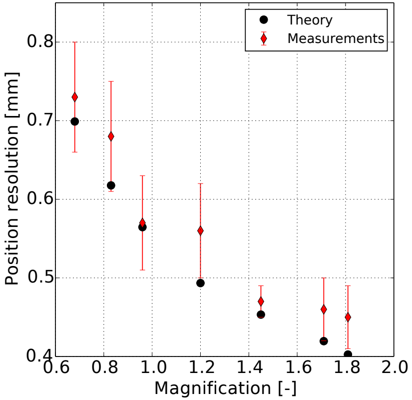




Position resolution of the system – measurement results

Results for different magnification factors $M = \frac{DP}{PS}$

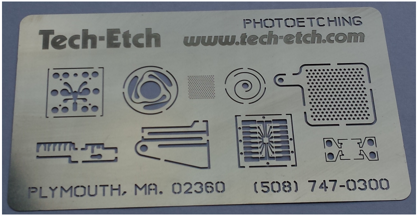


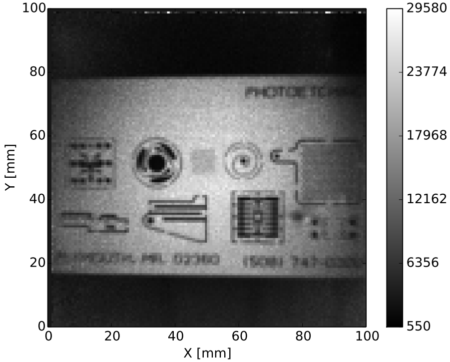


Position resolution of the system – measurement results

Stainless steel sheet

- Size of plate: 9×5 cm
- Pinhole d = 0.5 mm
- Magnification M $\sim$ 1.28
- Milled with patterns with different opening sizes





Conclusions

- The technique is suitable for fast course screening of large area paintings
- Due to limited energy resolution of the GEM detector it is not suitable for detailed elemental analysis
- The system is able to perform qualitative pigment determination
- Position resolution is at the level of 0.5 mm rms.
- Time of the measurement can be optimized at the expense of position resolution and vice versa
- The overall setup can be easily rearranged for traditional radiography imaging (not presented here)

Acknowledgements

- We thank the RD51 collaboration (especially L. Ropelewski) for its support and providing us with the GEM detector.
- Laboratory of Analysis and Non-Destructive Investigation of Heritage Objects, National Museum in Krakow (Ł. Bratasz)

Thank you for your attention!