

# A Novel method for Non-Destructive Stratigraphy Determination of Artworks using Acoustic Microscopy and UV/VIS/nIR spectroscopy

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## Introduction and content

A main challenge for the documentation of artworks is to reveal the information that stems from the internal paint layers of artworks (stratigraphy) non-destructively. This information is mainly acquired through analytical spectroscopic methods which require a micro-sampling operation. Most of the times, the objects under study are extremely valuable and therefore may not be subjected to any intervention. This fact renders the micro sampling a prohibitive procedure. The core target of this work is to develop a non-destructive testing system, which will permit the stratigraphy reconstruction of the paint layers of artworks, at any point or at a region of interest of the painted surface. In this paper we propose the combined use of two modalities towards this effort: Acoustic microscopy and UV/VIS/nIR spectroscopy. The acoustic microscopy is used for the determination of the profile of the stratigraphy (number of layers and possibly their thickness) and the UV/VIS/nIR spectroscopy is used for the estimation of the material of each paint layer. Combining these two modalities, a macroscopic approach is applied in order to determine the material of each paint layer using signal processing and systems theory [1]. The proposed algorithm has been tested using painted stratigraphies existing in Byzantine artworks. The measured spectra and the reconstructed ones calculated by the proposed algorithm are in good accordance.

## Description of the system

The general description of the overall system is shown in figure 1. The artwork is modelled as a sequence of successive layers. Each layer is treated as an independent sub-system (figure 2). Using acoustic microscopy we may obtain the number of the layers of the stratigraphy. Using the UV/VIS/nIR spectroscopy an estimation of the materials existing in each paint layers is achieved. Monochromatic light for each wavelength in the region between 200nm and 2400nm penetrates sequentially into the artwork from the spectrophotometer. The light passes through all the individual sub-systems, backscatters from each consecutive transition, and is received by the external probe of the device providing the diffuse reflectance spectra. Each sub-system (paint-layer) is assumed to have a forward transfer function  $H_{if}$  and a backward transfer function  $H_{ib}$ . Therefore, as light travels through each layer, two light components are produced: The forward, or incident component  $i_{if}$ ;  $i_{if}=i_o * h_{if}$  or in the frequency domain  $I_{if}=I_o H_{if}$  and the backward, or reflected component  $i_{ib}$ ;  $i_{ib}=i_o * h_{ib}$  or in the frequency domain  $I_{ib}=I_o H_{ib}$ , where \* represents the convolution of the signals,  $i_o$  the incident light and  $I_o$  its corresponding spectrum. In general, we assume that we have an n-th layered stratigraphy that we may represent as a sequence of successive sub-systems (figure 2). If we have an incident radiation  $i_o(\lambda)$  then the forward and backward output after the first sub-system will be  $i_{1f}=i_o * h_{1f}$  and  $i_{1b}=i_o * h_{1b}$  respectively. The radiation input for the second sub-system is  $i_{1f}$ . Similarly, the forward and backward radiation outputs of the second sub-system are  $i_{2f}=i_{1f} * h_{2f}$  and  $i_{2b}=i_{1f} * h_{2b}$ , respectively. The backward radiation of the second sub-system traverses also the first sub-system. Therefore, the total radiation output from the first and second sub-layers will be:  $R= I_o$

$H_{1b}+I_{1f}$   $H_{2b}=I_0$   $H_{1b}+I_0$   $I_{1f}$   $H_{2b}$   $H_{1f}$ . The total response from a n-th layered system can therefore expressed as:

$$R_{n-th} = I_0 H_{1b} + I_0 H_{1f}^2 H_{2b} + I_0 H_{1f}^2 H_{2f}^2 H_{3b} + \dots + I_0 H_{1f}^2 H_{2f}^2 H_{3f}^2 \dots H_{(n-1)f}^2 H_{nb} \quad (1)$$

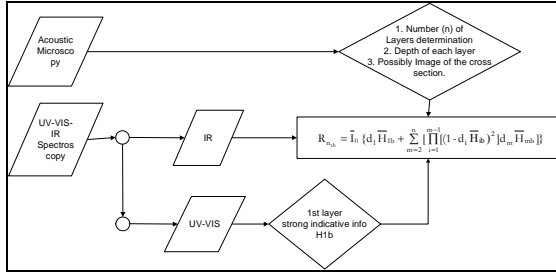


Figure 1: General description of the system.

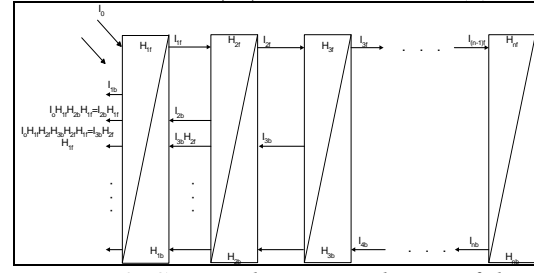


Figure 2: System theory simulation of the UV/VIS/nIR backscattered light from artworks

Provided that the thickness of the paint layers is between 2-100 $\mu$ m and that the horizontally scattered power of the enclosed grains is negligible, we may assume that photon energy is

practically conserved. Therefore, for each layer we may accept that  $\bar{H}_{ir} = (1 - \bar{H}_{ib})$ . Thus, the total response of a stratigraphy containing n layers,  $R_{nth}$ , is a polynomial with coefficients only the backward transfer functions of the consecutive sub-systems:

$$R_{nth} = \bar{I}_0 \{d_1 \bar{H}_{1b} + \sum_{m=2}^n [\prod_{i=1}^{m-1} [(1-d_i \bar{H}_{ib})^2] d_m \bar{H}_{mb}]\} \quad (2)$$

where  $\bar{I}_0$  is the spectrum of the incident radiation,  $\bar{H}_{1b}, \bar{H}_{mb}$  are vectors and  $d_i$  represents the thickness of each sub-layer. The simulated spectra are calculated using Eq. 2, the transfer functions obtained from the spectral responses of the reference panels, the number of the successive paint layers and their thickness values.

### Application of the system on painted stratigraphies

In order to determine the response and the transfer function of each subsystem of a given stratigraphy using the proposed algorithm, the backward transfer functions  $H_{ib}$  of each pigment must be known. For that purpose, special reference samples were fabricated from pure pigments or mixtures of them [1], corresponding to well known stratigraphies. The reference panels are made in a way to facilitate the measurement of the backscattered response from each sub-layer or from combinations of them comprising three successive sub-layers. The proposed algorithm was tested using these reference panels. We present a few typical cases of the measurements acquired from the stratigraphies using acoustic microscopy [2] in figures 3-5 and UV/VIS/nIR diffuse reflectance spectroscopy in figures 6-9. The simulated UV/VIS/nIR spectra are labelled in red and the corresponding measured ones labelled in blue.

### Results and forthcoming work

The measured spectra and the reconstructed ones (figures 7, 9) using the proposed algorithm are satisfactorily similar. In order to optimise the paint layers identification procedure, we divided the detected spectrum into sub-spectral areas between 200nm-400nm, 400nm-1500nm and 1500nm-2400nm. In these sub-spectral areas, the transfer functions of the pigments appear to have considerable uniqueness. We simulated all the possible stratigraphies-combinations using the transfer functions for each layer from the reference panels. Each of these simulated spectra was then compared with the measured spectra of the experimental painted stratigraphies. The maximum correlation coefficient between the measured spectra and the simulated ones was obtained in the case where the corresponding layers of the stratigraphies were of the same material. More work must be done in the interpretation of the nIR information using signal processing techniques. For the time, the successful matching is around 90% for the first layer

determination, 66% for the second layer determination and very low for the third layer. The next issue is the identification of each paint layer of the stratigraphy. Towards this target, acoustic microscopy was used for the first time in the non destructive stratigraphy determination of artworks [2],[3] according to the best of our knowledge. The results of the acoustic microscopy are very promising for the determination of the number of the paint layers in the algorithm. The time of flight of the received echoes is in accordance with the measured velocity of the material under study. Even higher frequency acoustic signals must be used and examined as well in the future, after devising an optimum way of coupling the transducer with the artwork without damaging it. Finally, the combination of the acoustic microscopy method with the nIR spectroscopy method is also applied for the first time in this field.

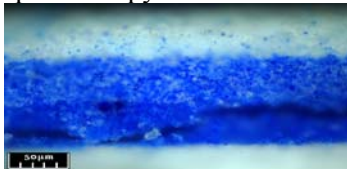


Figure 3: Stratigraphy No 90  
1<sup>st</sup> (layer): Ultramarine, 2<sup>nd</sup>:  
Ultramarine+Lead white, 3<sup>rd</sup>:  
Lead White

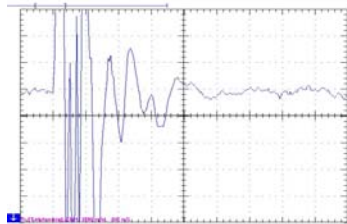


Figure 4: A-Scan from 1<sup>st</sup> & 2<sup>nd</sup>  
layer of stratigraphy No 90

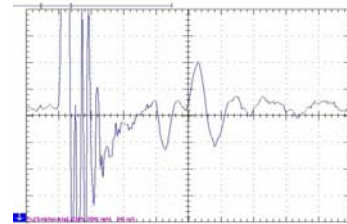


Figure 5: A-Scan from all  
layers of stratigraphy No 90

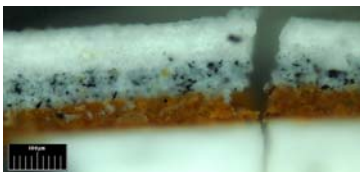


Figure 6: Stratigraphy No 104  
1<sup>st</sup> (layer): Warm Ochre, 2<sup>nd</sup>:  
Lead white+Carbon Black,  
3<sup>rd</sup>: Lead White

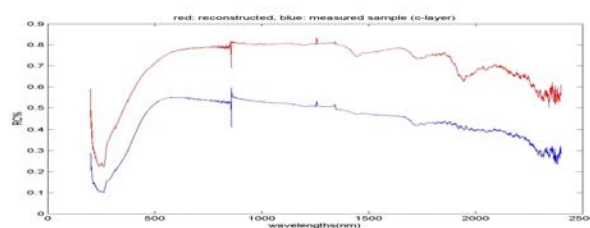


Figure 7: Simulated spectra of the stratigraphy No 104 and the  
measured one

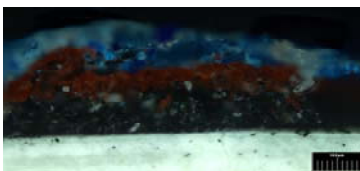


Figure 8: Stratigraphy No 122  
1<sup>st</sup> (layer): Carbon Black, 2<sup>nd</sup>:  
Caput Mortuum, 3<sup>rd</sup>: Azurite

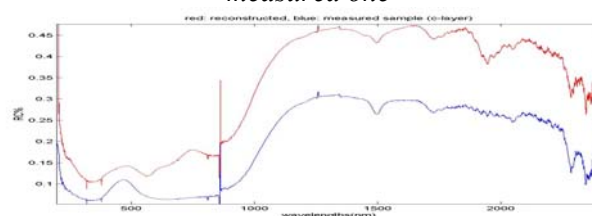


Figure 9: Simulated spectra of the stratigraphy No 122 and the  
measured one

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## References

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