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Application of Reflectance Transformation Imaging for visualizing early signs of corrosion in historical glass corrosion

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Abstract

Reflectance Transformation Imaging (RTI) is a multi-light imaging technique using a camera on a fixed position and orthogonal to the studied surface, while varying the light position for each image captured. This allows for the reconstruction of a surface's visual appearance and the characterization of the surface by providing additional information on surface deformations and local micro-geometry. RTI was applied on historical model glass corroded in the presence of volatile organic compounds (VOCs) to visualize early stages of corrosion. RTI was used to create relighting visualizations and generate maps based on statistical descriptors derived from the local reflectance distribution of the pixels. Selected maps were able to assist in the quantification of corrosion signs i.e., fine cracks and salt neocrystallizations (SN), on a more global scale as compared to digital microscopy (DM). Therefore, RTI could provide an imaging solution for the characterization of corrosion signs on transparent colourless glass surfaces, which could not be visualized using simple RGB photography neither with transmitted nor reflected light.

Motivation: The project under MSCA-ITN CHANGE aims to explore imaging techniques that can provide high-definition documentation and monitoring of transparent glass objects to detect any signs of corrosion. The goal is to develop a protocol that can identify glass corrosion in the presence of volatile organic compounds (VOCs) at an early stage, allowing for timely preventive interventions.

Problem: The project was hosted at the collection centre of Swiss National Museum (SNM) in Affoltern am Albis, where various degradation signs were detected on historical glass objects belonging to 17^{th}-20^{th} century. These objects were stored in mobile chipwood shelves with uncontrolled relative humidity and temperature for around 32 years and later moved to better storage with metal shelves in 2000 [1]. Chipwood is known to emit VOCs, especially formaldehyde, formic acid, and acetic acid [2]. Transparent colourless glass poses a challenge for monitoring its degradation and therefore needs regular assessments to detect early signs of degradation. The research presented here is aimed at better understanding, documenting, and monitoring the degradation of historical glass in the presence of VOCs, which has not been studied extensively, until date.

Approach: The methodology for studying corrosion or degradation of historical objects was developed using artificially corroded model glass prepared using traditional glass blowing techniques to replicate the composition and surface finish of actual historical objects from the SNM collections. Curved rectangular model glass of approximately 5cm x 3cm size were manufactured which underwent artificial aging to simulate an indoor environment with a high concentration of VOCs (acetic acid and formic acid) and fixed relative humidity of 50% [3]. Five batches of aged model glass were withdrawn at 3-5 months intervals and subjected to various imaging and chemical analytical techniques. Reflectance transformation imaging (RTI) results are discussed here and compared with digital microscopy (DM) results.

RTI is a computational photographic technique that captures the reflectance response of a subject under different lighting conditions and combines them to produce an interactive representation of the subject that can be manipulated by the viewer. Different techniques can be employed to analyse the RTI data, including Polynomial Texture Mapping (PTM), Hemispherical Harmonics (HSH), and Discrete Modal Decomposition (DMD) [4]. PTM is the most commonly used method and was originally developed by Tom Malzbender [5]. One of the key benefits of RTI data is the ability to generate a relightable file, enabling interactive visualization of the object under varying lighting conditions. However, acquiring RTI data for transparent surfaces is challenging due to the complex interactions between the surface and its light environment [6]. Nonetheless, some previous works have explored relighting visualizations of glass objects [7][8][9]. In addition to relighting visualizations, RTI data can be utilized to create normal maps based on local geometry and statistical maps based on local reflectance [10]. These maps are generated by computing local descriptors from local angular reflectance and characterize different features (i.e., various degradation patterns) present on corroded glass surfaces. This is feasible because light interacts differently with isotropic or anisotropic features on the surface. The reflectance response of an isotropic surface is uniform and does not change with the angle of incident light, while for an anisotropic surface, it varies depending on whether the angle of incident light is parallel (low response) or perpendicular (high response), leading to significant variation.

RTI was performed using a fully automated custom-built dome-based system. The system includes a single light source mounted on a motorized arc, which allows for the light to be positioned at any angle within the 0° to 360° azimuth and 0° to 75° elevation range of the dome with a radius of 220 mm. It also features a 12.4-megapixel monochrome camera with motorized zoom and focus. A white LED light was employed as the light source (Figure 1). Due to the interaction between the motorized hardware and custom control software, the system guarantees extremely accurate and consistent RTI data acquisition [4].

Different lighting patterns, both homogeneous (light positions are equally spaced in the azimuth elevation space) and non-homogeneous, at low dynamic range (LDR) with fixed exposure level or high dynamic range (HDR) with varying exposure levels. The methodology of coupling the HDR and the RTI was developed to be able to measure surfaces with a high dynamic and to avoid exposure time configuration that can't be well configured for the whole acquisition when two light angles can give completely different angular reflectance response from the surface. While LDR is the classical acquisition HD-RTI allows for a better characterization of the surface. The data given by the actual HD-RTI acquisitions can be considered like the full response of the surface without the limitation of the sensor [11].

The greatest challenge faced was eliminating background noise. To address this issue, a dome-shaped double-walled light trap was designed, and 3D printed using matte black plastic. With the holes in the inner wall, more light can be trapped within the space and the oval rectangular opening on the top provides a defined area for data acquisition.

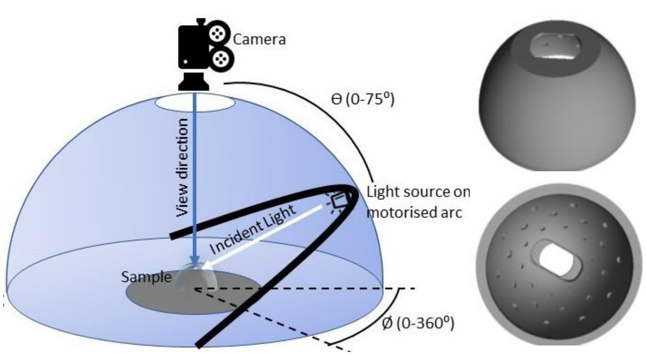


Figure 1. Schematic diagram of the RTI dome setup with matte black plastic background designed for reducing noise.

The final data was acquired by placing the model glass on the designed light trap and using 500 homogenous light positions in LDR configuration (Figure 2 a) and 250 homogenous light positions around a single ring at 0° elevation angle (ϴ = 0) in HDR configuration (Figure 2 b) for each model glass. Due to the transparent material and curvature of the model glass, some angular positions of lighting gave a high response while the others did not. When characterizing the surface, only a few high responses could create "artifacts". Thus, the more the light positions used, the fewer the artifacts. Thus, the number of light positions were chosen to provide a compromise between covering the maximum number of positions while keeping the acquisition time to a minimum possible.

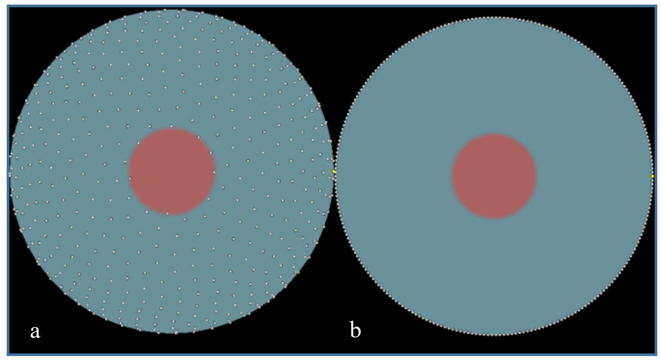


Fig. 2: Light positions for a) LDR acquisitions b) HDR acquisitions

Digital microscopy (DM) was performed using Keyence VHX 6000 with automatic focus and stitching at 100x in reflected light. The microscope was manipulated using software provided by the manufacturer. DM was performed on five model glass samples from each aging period (total 25 model glass) for visualizing corrosion features especially wet salt neocrystallizations (SN) and fine cracks (investigated area is ≈600 mm^2/aging period).

RTI data was gathered from two model glass from each aging period (total 10 model glass). Out of the two model glass, since the presence of liquid SN on the model glass surface obscured the fine cracks underneath, one model glass was wiped in the centre (with soft paper tissue dipped in 1000mL water + 5 drops ethanol mixture) and one was left unwiped for visualizing fine cracks and SN, respectively (investigated area is ≈480 mm^2/aging period).

Matlab was employed to process the RTI data and generate maps of geometrical descriptors (such as slopes and curvature) and statistical descriptors (such as mean, median, kurtosis or skewness). Image processing was done using Fiji distribution of ImageJ [12] for quantification of the length of cracks as well as the total area covered by the SN.

Results: Model glass presented wet SN which were clearly visible with naked eyes, but whose visualisation was impossible using visible light photography both in reflected light (Figure 3a), and in transmitted and cross-polarized light (Figure 3b). To the contrary, wet SN could be easily captured in DM images (Fig. 3c). Given the curved rectangular shape of the model glass, DM images could be acquired from three narrow rectangular regions on every model glass (Figure 3c). Due to differently sized model glass, the rectangle area varied between 28±2 mm x 5±2 mm. RTI relighting visualizations and maps were generated for a specific region in the centre (≈24x21 mm^2). Wet SN (grey circular features inside white circle) and fine cracks (example inside blue rectangle) were fully visualized using the relighting video (Figure 3d).

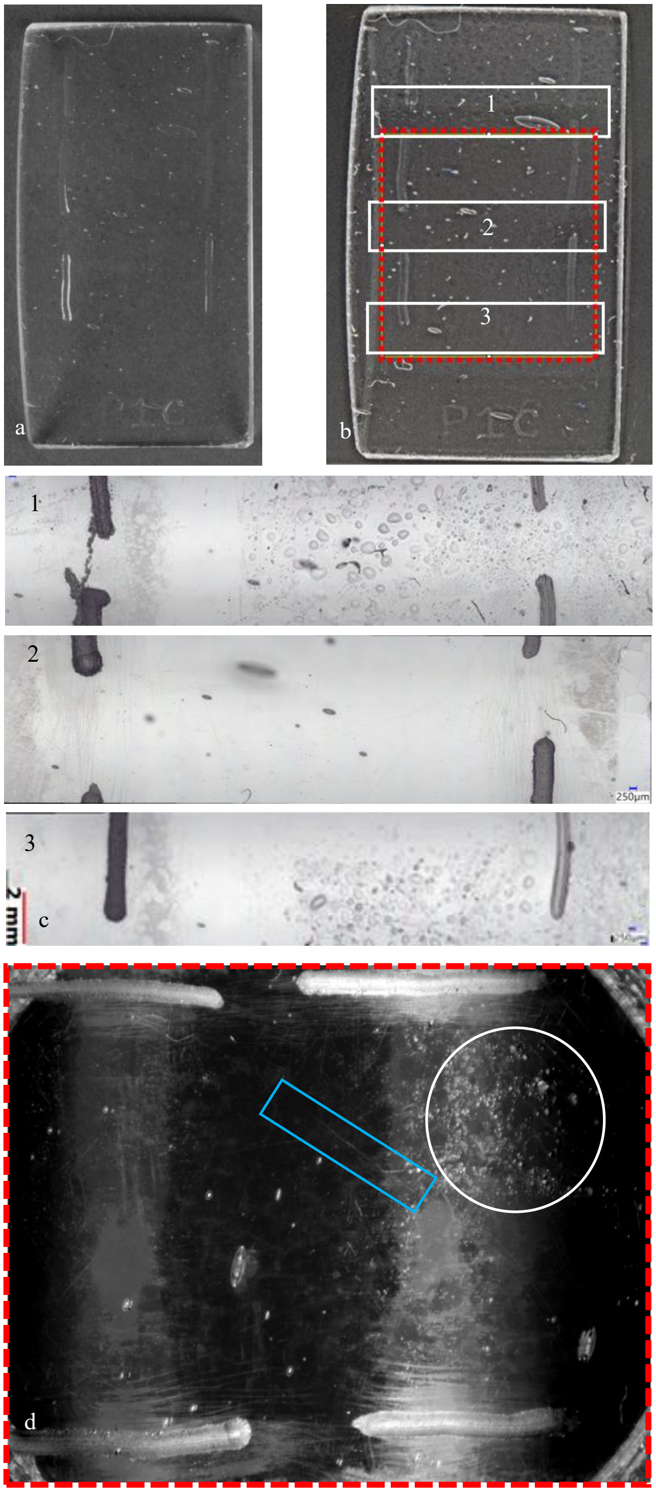
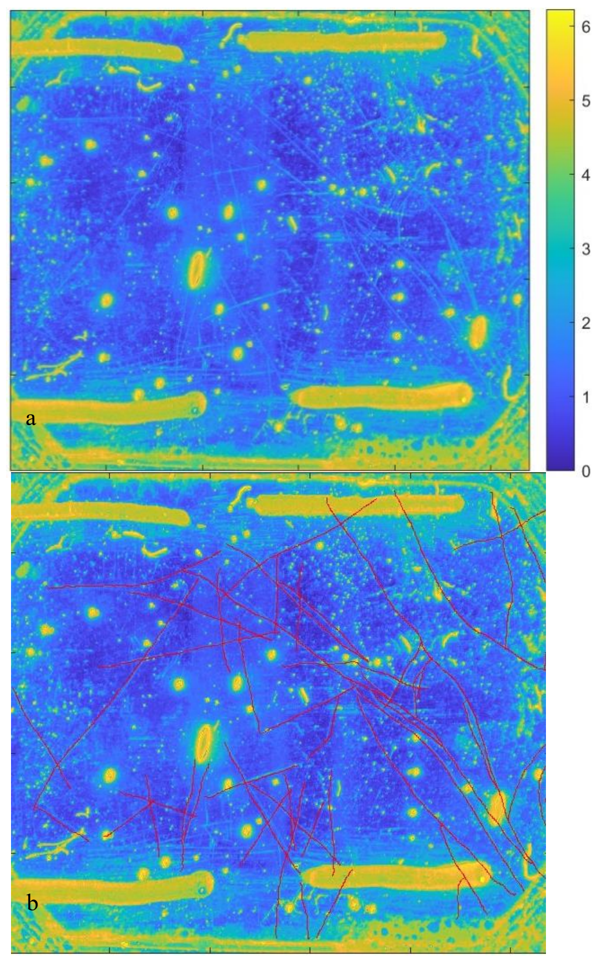


***Figure 3**. Visible light RGB photograph of model glass (≈50x30 mm^2) aged for 9 months and wiped in the centre a) in diffused reflected light on black background b) in transmitted and cross-polarized light, showing the three DM narrow bands of acquisition (inside white rectangles) and one RTI acquisition region (inside dotted red rectangle) c) three narrow bands of model glass acquired using DM (≈28x5 ±4 mm^2 each); d) Screenshot from interactive RTI relighting visualization video (≈24x21 mm^2)*

In case of DM, both the features can be visualized within the same acquisition (Figure 4c). A review of all the statistical descriptor RTI maps– based on LDR and HDR configurations showed that fine cracks were best visualized with (Shannon) entropy maps (that measure the level of 'uncertainty' or 'chaos' in a pixel reflectance distribution) (Figure 4a) using the HDR configuration while SN were best visualized with standard deviation maps (that describe the dispersion of the distribution) (Figure 5a) using the LDR configuration.

In case of RTI, the automatic detection of cracks using 'colour thresholding' was not successful due to the lack of enough contrast in the colour of the cracks (blue green in figure 4a) against the background colour (blue in figure 4a) while the engravings and air bubbles within the same map presented much higher contrast (bright yellow in figure 4a). Similarly, in case of DM, greyscale thresholding could not isolate the cracks from the wet SNs which obscure the fine cracks under them (figure 4c). Consequently, cracks were quantified by manual tracing over the RTI and DM images (red lines in figure 4b and black lines in figure 4d). Crack density was defined as the total length of fine cracks divided by the total area analysed for cracks, therefore the unit is in mm^{-1}. The comparison of crack density calculated from both the modalities showed comparable results (Figure 4c).



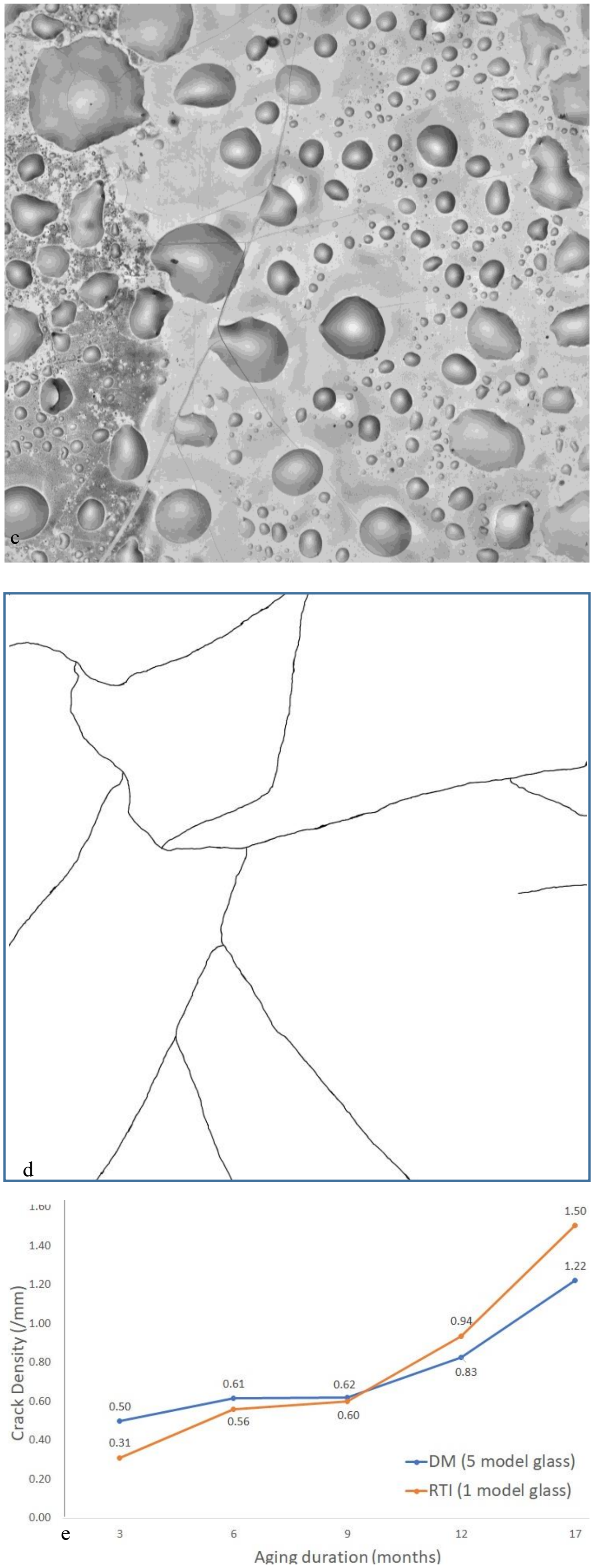
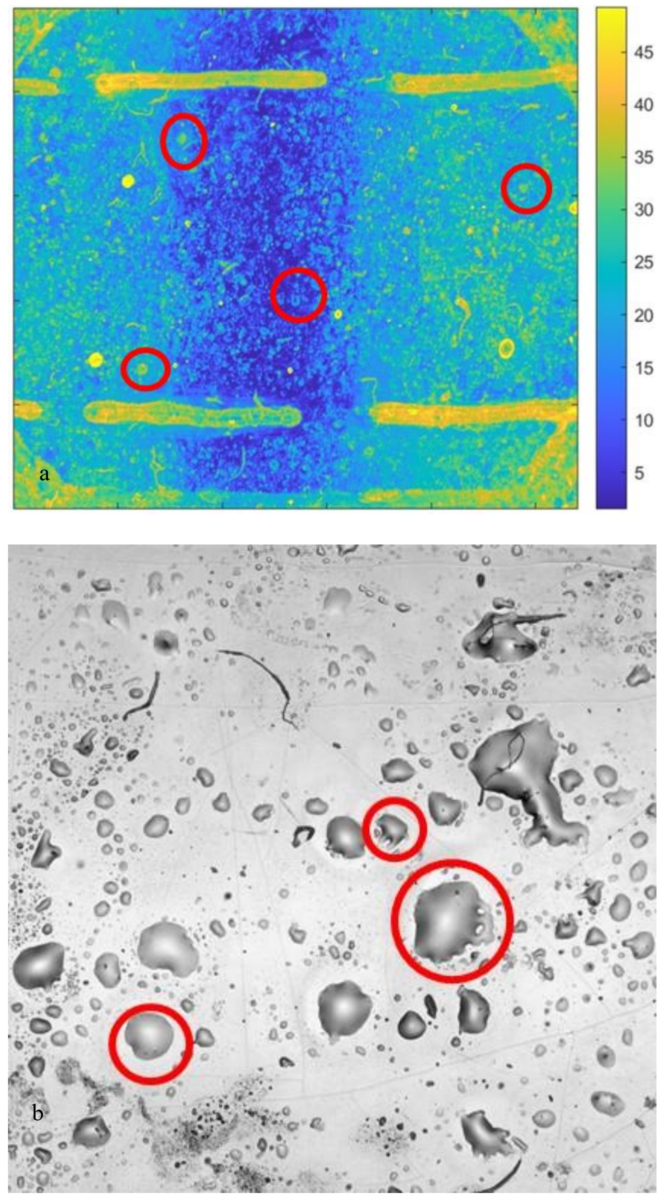


Figure 4. *a) (Shannon) entropy map of model glass aged for 9 months along with the b) manual tracing of cracks (≈24x21 mm^2) c) Photomicrograph extracted from DM image of model glass aged for 9 months (≈5x5 mm^2) along with d) manual tracing of cracks e) Graph showing temporal progression of crack density for model glass aged for different durations*

SN were quantified using colour and greyscale thresholding on RTI and DM images, respectively (Figure 5a and b). The percentage area covered by SN seemed to show similar trends for RTI and DM between 6 and 9 months as well as between 12 and 17 months but no similarities in the intermediate aging period of 9 to 12 months (Figure 5c), since noise from air bubbles and corresponding shadows was manually removed in case of DM images but not from the RTI maps affecting the accuracy of quantification in this latter case. In both the cases, a significant reduction was observed in the percentage of area covered by SN after 17 months of aging possibly due to the surface run-off of large enough wet SN from the vertically standing model glass.



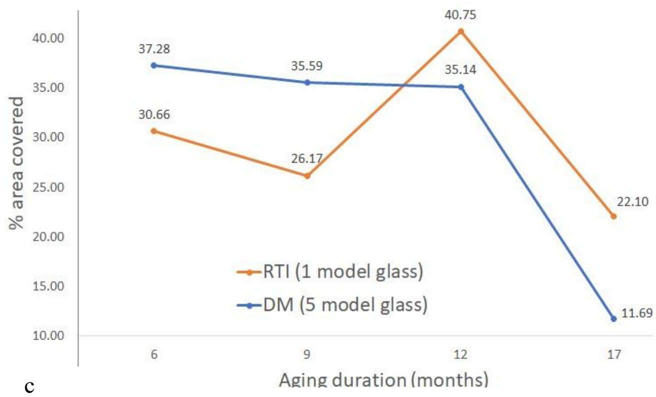


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Figure 5. a) Standard deviation map of model glass aged for 9 months highlighting SN in yellowish-green colour (≈24x21 mm²) (examples indicated as inside red circles) b) Photomicrograph extracted from DM image of model glass aged for 9 months (≈5x5 mm²) highlighting SN (examples inside red circles) c) Graph showing temporal progression of percentage area covered by SN for model glass aged for different durations

Conclusions: RTI and DM were explored to assess and quantify early stages of corrosion on transparent glass, focussing on the detection of wet SN and cracks. Acquisition configurations and the statistical descriptor maps, which proved to be useful for characterizing corrosion features using RTI, were found. DM images could be used reliably for quantification of both features on the same acquisitions, however long acquisition times are needed to picture statistically representative areas and to process them for quantification. To the contrary, RTI could acquire data on larger areas in much shorter time than DM and two distinctive statistical descriptor maps (namely Shannon and standard deviation maps) can be successfully used for quantification. Nonetheless, the simultaneous acquisition by RTI of both wet SNs and fine cracks was not possible, as wiping of the surface was required to properly identify the cracks. Wiping the surface might not be acceptable for objects of historical value and therefore, selecting an area of fewer SN would be advantageous if museum objects need to be imaged. In addition, highly reflective features like air bubbles can be erroneously identified as wet SNs. Despite these inconveniences, RTI can be seen as a useful tool allowing detection of early signs of glass corrosion on transparent colourless glass. The results from RTI and DM acquisitions showed more similarity in crack quantification and to a lesser extent for SN quantification. Further research needs to be undertaken with more samples to gather more statistically sound results and make the quantification more robust and reliable.

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Author Biography

Deepshikha Sharma received her BTech in mechanical engineering from the GBPUAT, Pantnagar (2012), MA in archaeology from DCPGRI, Pune (2015) and MSc in Archaeological Materials Science from the University of Evora (2017). Currently pursuing her PhD in chemistry from University of Neuchâtel. She has worked on different research subjects ranging from public archaeology to archaeometallurgy and trace element analyses. Her current research under MSCA-ITN CHANGE focuses on studying glass corrosion and its documentation and characterization.

Marvin Nurit received his bachelor's and master's degree in computer science from the University of Bourgogne with a focus on imaging. He finished his doctoral thesis at the ImVia laboratory in 2022, working for the improvement of a device for the acquisition of local angular reflectance of complex surfaces i.e., the dome-based reflectance transformation imaging system at ImVia laboratory.

Ulrike Rothenhäusler received her diploma from the Academy of Fine Arts in Stuttgart, Germany. Since 2002 she has been working at the Collection Centre of the Swiss National Museum in the field of glass and ceramics. Since then, her work has included the detection of glass corrosion and the improvement of cleaning methods and storage conditions for glass.

Katharina Schmidt-Ott is head of conservation research at the Collection Centre of the Swiss National Museum. She has received her PhD in Conservation Sciences at the State Academy of Fine Arts in Stuttgart. Her research interests include corrosion of metal and glass and development of methods for conservation.

Edith Joseph received an MSc degree in materials chemistry and a PhD degree in chemistry on the application of FTIR microspectroscopy to cultural heritage materials. Currently she is an assistant professor, head of *the Laboratory for Heritage Materials Technology at the University of Neuchâtel. In parallel since 2012, she is employed as associate professor at the Haute Ecole Arc Conservation Restauration and developed her research activities on green technologies applied to cultural heritage involving both the institutions.*

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Tiziana Lombardo received her PhD in "Chemistry of Air Pollutants" from the University of Paris Est Créteil (UPEC), with a dissertation on glass deterioration. She worked at the UPEC as assistant professor and studied atmospheric corrosion of medieval and modern architectural glass. Since July 2013, she has been working as Senior Conservation Scientist at Collection Centre of the Swiss National Museum, where, among other tasks, she conducts research on corrosion of metal and glass artefacts.