

## 3D SURFACE ACQUISITION: COMPARISON OF TWO MICROTOPOGRAPHIC EQUIPMENTS WHEN MEASURING MATERIALS OF CULTURAL HERITAGE

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### Abstract

Surfaces of materials from cultural heritage are exceptionally varied as patina, varnish, wear or scratches are added intentionally or with time to the base material, whether it is wood, marble, stucco, or brass. Measuring their texture provides a lot of information to curators but it constitutes a challenging task for the engineer. The present study focuses on the question of texture acquisition by means of two optical micro-topographic instruments. As those instruments deeply differ in their working principle, it is necessary to check if results are comparable in terms of roughness. Moreover, in order to define the space of materials they are able to record, the study highlighted how the global appearance of an object interferes with the measurement of its surface relief, because of the design of the utilized instruments.

*Keywords:* Optical metrology, 3D, Appearance, Roughness, Cultural heritage, Scientific techniques in conservation and restoration.

### 1 Introduction

Materials of cultural heritage are abundant and diverse. Marble, paper, bronze, photographs, oil, wood, in good condition or damaged, restored, antique or new, raw or worked... the list is infinite. Curators, archaeologists and restorers are interested in the study of their surface as it gives information on material, details, tools used, degradations caused by time, and so on. For this purpose, metrological devices dedicated to surface analysis can record the aspect of an object, at a considered scale. The resulting 3D model constitutes an exact reproduction, at a specific time, of the considered piece. Different kinds of measurements can later be performed on the 3D model: size of elements, depths and heights of furrows or statistical measurements such as roughness, which opens new perspectives for cultural heritage studies.

#### 1.1 State of the art

Micro-topographic measurements, even if they are not very common in the cultural heritage field, have found some applications. For example (Mélard, 2010) uses a light profilometer for topographic investigations: some small prehistorical stones are recorded to distinguish the lines and reconstitute the engraving process. Roughness parameters are also computed and compared to determine the geographical origin of the stones. (Van den Berg, 2008) compares the utility of different 3D surface devices to study the cleaning of paintings. Roughness profiles acquired before and after cleaning are examined, and technologies (light microscope, confocal white light profilometer and scanning electron microscope) are compared. (Béland and Bennett, 2000) performed topographical measurements on paper surfaces with a laser confocal method and related the micro-roughness to the observed gloss.

#### 1.2 Issue

The Centre de Recherche et de Restauration des Musées de France (C2RMF) owns two metrological devices (a Stil™ micro-topographical instrument and an Hirox™ digital microscope) able to record the texture of an object. Those instruments are both contactless, offering the possibility to study fragile art pieces. They both allow surfaces topographies recording and roughness computation.

The working principle of those devices is fundamentally different, and none of them is conceived for the specific study of cultural heritage materials. In the laboratory, they are mainly used for qualitative studies of the aspect of surfaces or quantitative measurements of lengths and depths, as we can see on Fig. 1. This paper aims to extend quantitative and statistical measurements at a micro-scale, especially roughness, and for this purpose needs to answer two main questions. First, are roughness results from these two devices comparable? Second, is it possible to establish a range of measurable cultural heritage materials?



**Figure 1 – Examples of surface analysis. (a) Automatic diameter computation, Rhodian goldsmithery (Fifth century BC, Louvre collection). (b) Lengths measurements on a metallographic cross-section. Hirox™ images © D. Robcis.**

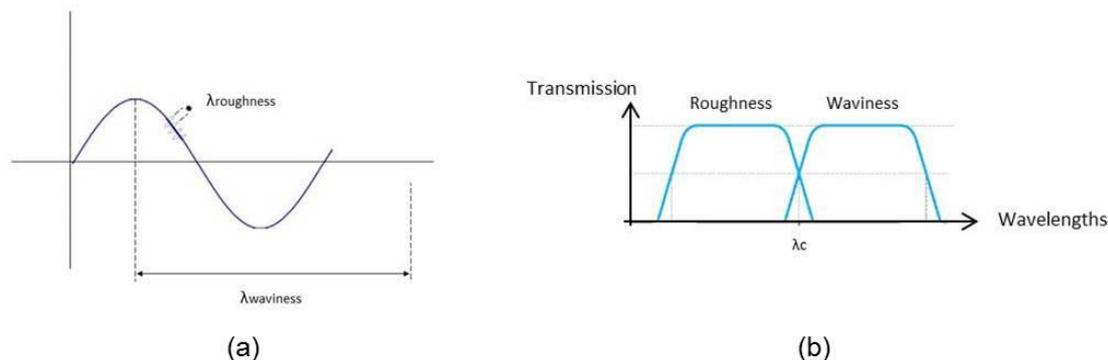
The following paper develops those points and presents our results. First, instruments will be introduced, before coming to the metrological comparison section. Then, we will present the materials of interest. Finally, some perspectives will be discussed.

## 2 Definitions and techniques

### 2.1 About roughness

#### 2.1.1 Filtering process and definitions

Roughness is a mathematical parameter that describes the texture of a material. It gives an estimation of the irregularities and defaults of the surface, which can be classified as follows: shape and position defaults (1<sup>st</sup> order), periodical waviness (2<sup>nd</sup> order), periodical roughness (grooves and ridges, 3<sup>rd</sup> order) and a-periodical roughness (splints and stings, 4<sup>th</sup> order). Long wavelengths of a surface are waviness, and short ones roughness: roughness defines the defects which have a small spatial period compared to the characteristic length of the surface (see Fig. 2. (a)).



**Figure 2 – (a) Roughness and waviness. (b) Filtering.  $\lambda_c$  is the cut-off value.**

Roughness and waviness are separated during filtering process. The cut-off wavelength  $\lambda_c$  is the relevant value chosen in order to distinguish them (see Fig. 2. (b)). High-pass filtering gives the roughness profile and low-pass filtering the waviness profile.

## 2.1.2 Roughness parameters

Some of the roughness parameters are statistic estimations and others simple heights measurements on a roughness profile. Most frequent are (in agreement with the ISO 4287 norm):

- $Ra$  the arithmetic average:

$$Ra = \frac{1}{lr} \int_0^{lr} |Z(x)| dx \quad (1)$$

where  $lr$  is the considered length of the profile  $Z(x)$ ,

- $Rq$  the root mean squared roughness:

$$Rq = \sqrt{\frac{1}{lr} \int_0^{lr} (Z(x))^2 dx} \quad (2)$$

- $Rz$  the maximal height:

$$Rz = Rp + Rv \text{ with } Rp = \max(Z(x)) \text{ and } Rv = \min(Z(x)) \quad (3)$$

## 2.2 Apparatus

### 2.2.1 The micro-topographic station

The Stil™ CHR 150N micro-topographic station is a confocal microscope with chromatic coding. The instrument combines the confocal principle, excluding the light that doesn't come from the focus point, with a chromatic lens, thereby having the information in height without any shifting along the Z axis.

Practically speaking, a white light source (halogen lamp) is coupled with a sensor, a spectrometer and a computer. The chromatic lens of the sensor breaks down the wavelengths of the incident white light and each of them strikes at a different height, known by calibration (see Fig. 3). Then, analysing the returned reflected wavelength, the system gives the exact height of every reached point. As the object is put on an X/Y motorised platform, we get a map of the considered surface in (X, Y, Z).

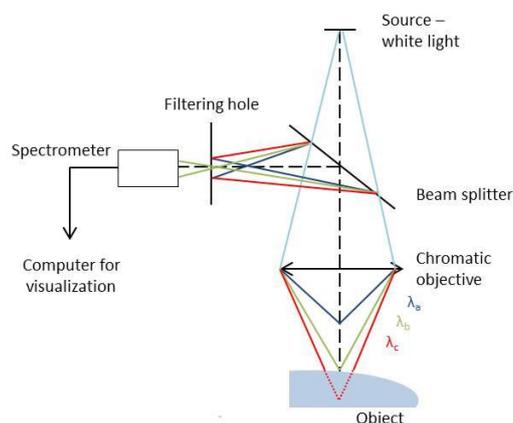


Figure 3 – Micro-topographical principle

Such a system couples the advantages of the confocal microscopy (high lateral resolution and high signal to noise ratio) with easily achievable information in Z. The sensor used in this study reaches the 0-300  $\mu\text{m}$  distance range (numerical aperture 0.43). Resolution in height is around 10 nanometres and 156 nm is the smallest step in (X, Y).

### 2.2.2 The digital microscope

The digital microscope Hirox™ KH-8700 (MXG-2500 REZ lens) combines high qualities of classical microscopy with the 3D reconstruction function of objects. In its 3D mode, the microscope takes multiple photographs at different heights between two points defined by the

user, before merging the captures of the considered surface in order to create a digital image of deeper depth of field, i.e. of deeper volume (ideally, each of those images has a shallow depth of field). This final image gives us the information about texture.

The digitally enhanced depth of field is eventually completed by an enhanced visual field thanks to the mapping mode of the device. The MXG-2500 REZ lens gives access to a broad spectrum of magnifications (from x35 to x2500). The visual field ranges from 8 to 0.12 mm, depending on the chosen magnification, and the lighting system allows the user to select the best lighting for the considered object (from coaxial to side-lighting). Resolution in height is around 50 nanometres (minimal distance between cross-sections), according to the constructor.

### 2.2.3 Software and norms

Micro-topographic Stil™ profiles or surfaces contain only topographical information and are extracted in .pro or .sur formats respectively, opened on Mountains Map 6.2 or 7.2 (Digital Surf™). Hirox™ KH-8700 gives .tdr files that are the combination of topographical information and surface photographs. They can be exploited on the Hirox™ viewer or with the Mountains Map 7.2 Premium version.

On Mountains Map, it is possible to compute many roughness parameters in accordance with different normalisation systems (by default the ISO 4287 and ISO 25178 norms). On the contrary, on the Hirox™ viewer, only Ra, Rz and Rzjis (Japanese JIS norm) are computable. As this is tedious for the user to treat all Hirox™ data with Mountains Map, it is necessary to know if roughness values from Hirox™ are directly comparable to roughness values from Stil™ micro-topographical device.

Note that the considered devices can record surfaces or profiles, but for time measurement reasons, we restricted to profiles only.

## 3 Metrological comparison

### 3.1 Protocol

The study is decomposed in three steps which are summed up on Fig. 4:

- First, the analysis of metrological performances of both devices in order to quantify the accuracy and precision of each of them.
- Second, the determination of the internal computing process of Hirox™ for roughness and filtering, by comparing roughness Hirox™ values with corresponding Mountains Map ones.
- Finally, the exploitation of multiple measurements made with both devices on Mountains Map 7.2 to conclude on their potential similarity.

To answer those issues, rigorous calibrated surfaces were used. Those surfaces have to present a known roughness and be acceptable for both devices (not too flat, not too high). Two kinds of adequate standards are at our disposal. The first one is a Mahr™ standard (PGN-3, n°6820420; see Fig. 5.), which presents a triangular profile formed by very thin metallic lines on a transparent glass surface. Two roughness parameters are defined for the cut-off value  $\lambda_c = 0.8$  mm:  $R_z = 3.3$   $\mu\text{m}$  and  $R_a = 0.90$   $\mu\text{m}$ . The second pattern is a set of Flexbar™ standards constituted of 30 surfaces in nickel and of diverse roughness. This set was made for tactile control of roughness in the mechanical industry, so cut-off values are not specified, but  $R_a$  values are still indicated.

As the Mahr™ standard is not easy to measure with the optical Hirox™ microscope, due to its glass configuration, measurements were mostly performed with Flexbar™ standards – even if they are not conceived for this purpose.

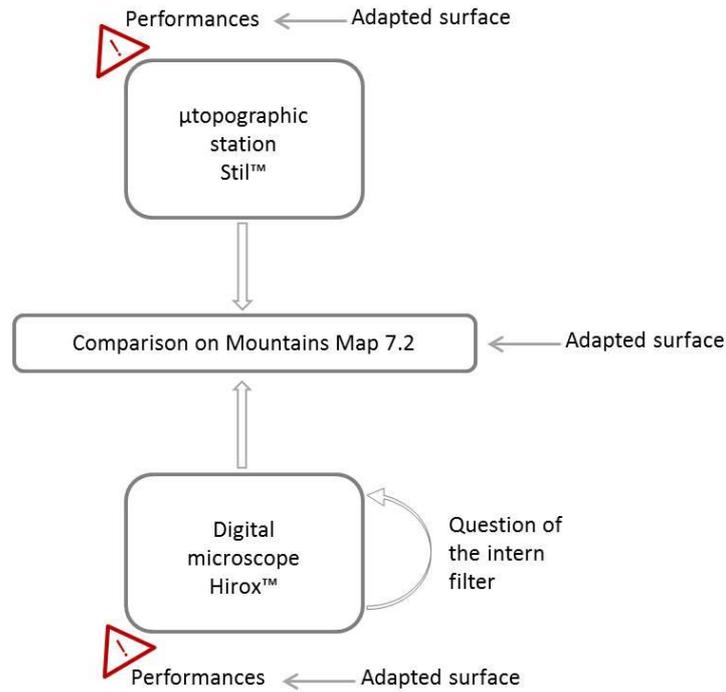


Figure 4 – Protocol of the study.



Figure 5 – (a) The Mahr™ standard and (b) the Flexbar™ standards.

### 3.2 Results

#### 3.2.1 Metrological performances

45 independent measurements were performed on one of the Flexbar™ surface of roughness  $R_a = 1.6 \mu\text{m} (\pm 10\%)$ . Repeatability tests show that for the Stil™ instrument, 60% of the measurements were correct, i.e. between the limits fixed by the Flexbar™ set constructor (see Fig. 6). Uncertainties of the entire roughness acquisition chain were also quantified for different cut-off values. For example, for a cut-off value of 0.8 mm, we obtain an uncertainty on  $R_a$  of  $0.03 \mu\text{m}$  (this corresponds to the computation process of measurements presented Fig. 6).

On the Hirox™, 30 independent measurements were also performed on the same Flexbar™ pattern.  $R_a$  values were computed directly on Hirox™. Repeatability tests indicate that only 30% of the acquisitions range between the Flexbar™ limits (see Fig. 7). Uncertainties of the entire roughness acquisition chain were quantified for different cut-off values. For example, for a cut-off value of 0.8 mm, we obtain an uncertainty on  $R_a$  of  $0.04 \mu\text{m}$  (this still corresponds to the computation process of measurements presented Fig. 7). Uncertainty is low but also precision of the Hirox™ computing system, so results on performances have to be nuanced.

In fact, they greatly depend on the user's ability to determine bottom and top limits for the 3D reconstruction, which makes the measure difficult.



Figure 6 – Ra values for the Stil™ acquisitions. Treatment on Mountains Map 6.2.

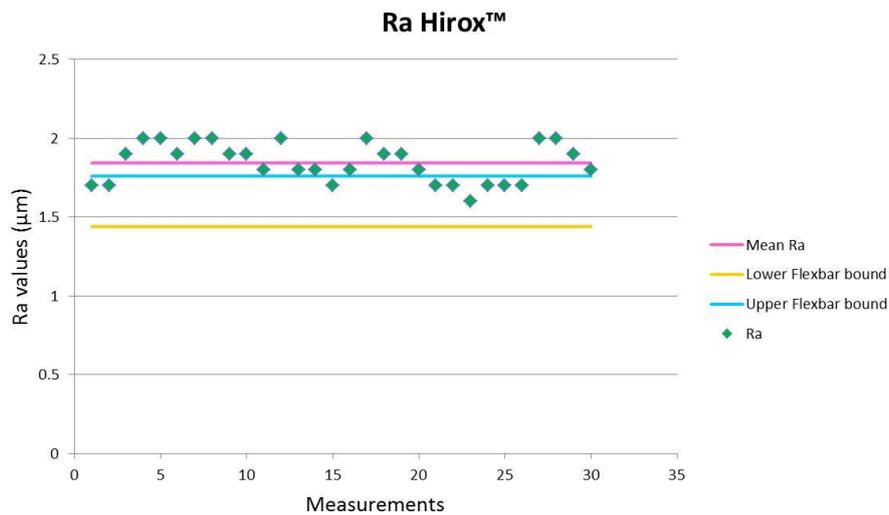


Figure 7 – Ra values for the Hirox™ acquisitions. Treatment on Hirox™.

### 3.2.2 Hirox™ data processing

The measurements previously performed and analysed with Hirox™ were also analysed with Mountains Map 7.2. Hirox™ filter were compared to different Mountains Map filters (Gaussian, RC, RC-PC, double Gaussian, spline and robust Gaussian) for different cut-off values, graphically by the visual analysis of roughness and waviness curves, and numerically by the compared analysis of Ra and Rz values. We conclude on the similarity of Hirox™ filtering process with the Mountains Map 7.2 Gaussian filter (ISO 11562; ISO 16610-21 or 16610-61).

### 3.2.3 Instruments comparison

Six of the 30 Flexbar™ surfaces were used to perform a global comparison between Hirox™ and Stil™ instrumentations. On the Hirox™ measurements, we compute Ra and Rz directly with the Hirox™ viewer and also on Mountains Map 7.2 (Gaussian filter). On the Stil™ measurements, we compute Ra and Rz roughness values on Mountains Map 7.2 (Gaussian filter). An example of results is given Table 1.

**Table 1 – Example of results (cut-off value  $\lambda_c = 2.5 \text{ mm}$ ) on the Flexbar™ surface  $R_a = 6.3 \text{ }\mu\text{m} \pm 10\%$ .**

	Ra ( $\mu\text{m}$ )			Rz ( $\mu\text{m}$ )		
	Hirox™ Hirox™	Hirox™ Mountains Map	Stil™ Mountains Map	Hirox™ Hirox™	Hirox™ Mountains Map	Stil™ Mountains Map
Profile 1	6.9	6.65	6.21	27.8	26.5	24.5
Profile 2	6.8	6.60	6.27	25.2	24.9	24.3
Profile 3	6.6	6.49	6.22	24.8	26.7	24.6
Average	6.77	6.58	6.23	25.93	26.03	24.47

A few points can be noticed. First, all  $R_a$  values belong to the interval indicated by Flexbar™, which is comforting on the instruments performances. Second, difference between values obtained via Hirox™ and values obtained via Stil™ are really minor, of the order of a few tenths of  $\mu\text{m}$ . This allows us to say that results from both devices can be compared.

#### 4 Materials study

The second part of our study deals with the capacity of our instruments to record different kinds of materials. Indeed, cultural heritage materials present a wide range of colours and gloss, are randomly misshapen, heterogeneous and anisotropic. We sorted materials depending on their appearance properties: colour, gloss, translucence, texture. As we have seen, the instrumentation used allows the acquisition of surface geometry, i.e. texture. Nevertheless, Hirox™ microscope gives a visualisation of the texture that depends on gloss, colour and translucence. On the other hand, the micro-topographical Stil™ instrument, which takes its signal from the reflexion on the material, will not give the same quality of texture reconstruction depending also on the colour, gloss and translucence of the analysed material. Therefore, the goal of this part is to understand the limits of our instrumentation, knowing that the global appearance of an object will interfere with the measurement of surface relief and to determine a range of measurable materials for each instrumentation process.

##### 4.1 Protocol

During our study, we had the possibility to work on a very diverse set of materials, representative of different artistic applications. They are presented on Fig. 8. We limited the study to old papers, wood, brass, lacquer, aluminium and varnish.



**Figure 8 – Materials of interest.**

All those materials have diverse appearance properties: dark and pale colours, rough and flat textures, glossy and non-glossy reflections, translucent or opaque media (see Tab. 2).

We selected zones on around 35 materials samples that we scanned with both instruments. When the acquisition and the roughness measurement were possible, quantitative results were carefully examined and compared on Mountains Map 7.2 and/or the Hirox™ viewer.

**Table 2 – Appearance properties of the considered materials.**

	Color	Texture	Gloss	Translucency
Paper	pale	rough and diffuse	no	no
Wood	pale	rough	no	no
Brass	golden	flat with scratches	yes	no
Aluminium	silvery	flat with scratches	yes	no
Lacquer	black	smooth	yes	no
Varnish	no	smooth	yes	yes

## 4.2 Results

Considering the large amount of data and images collected and processed, the results have simply been summarized here material by material.

### 4.2.1 Paper

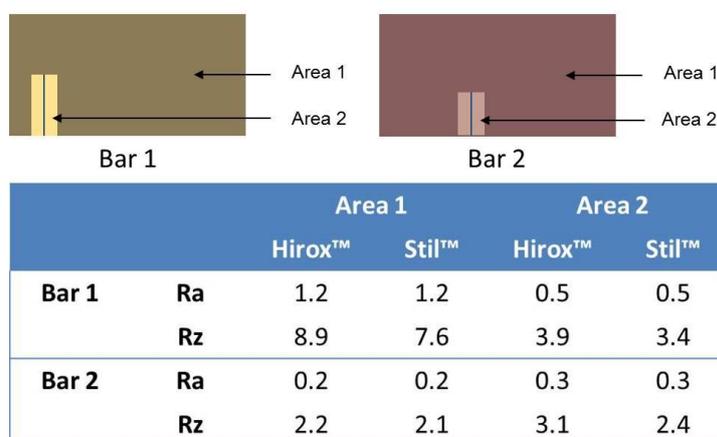
The diffusing structure of paper makes measurements with Stil™ micro-topography difficult: profiles present too many non-measured points for roughness computation to be possible. With Hirox™, 3D reconstructions are possible but artefacts appear as soon as magnification becomes too high: then the limited scale doesn't allow roughness calculation.

### 4.2.2 Wood

The lacunar structure of wood makes its measurement on Stil™ micro-topography particularly difficult. The shape and global texture can be recorded but there are too many non-measured points to compute roughness. On the other hand, with the digital Hirox™ microscope, the 3D reconstruction gives information on the structure. Roughness parameters are computable but results are non-verifiable as the micro-topographic Stil™ device gives no exploitable surfaces.

### 4.2.3 Aluminium and brass

On metal samples, the very flat structure of surfaces makes optical measurements a challenging task. Actually, Hirox™ 3D reconstructions are not precise enough and can present artefacts due to the large necessary magnification. With the micro-topographic Stil™ station, if gloss reflections are too intense on the metal surface, the sensor saturates and measurements are distorted. But most of the time, measurements are possible and roughness can be computed. For example, on brass samples, the comparison between roughness measurements on the micro-topographic Stil™ station and on Hirox™ gives very good results (see Fig. 9).



**Figure 9 – Examples of results on brass.**

#### 4.2.4 Lacquer

The very dark surface of lacquer prevents light reflection. Consequently, micro-topographic Stil™ measurements are impossible. On Hirox™, 2D photographs are exploitable as adjustable lighting can reveal some details of the surface, but 3D reconstruction presents optical aberrations.

#### 4.2.5 Varnish

The transparent structure of varnish makes the micro-topographical Stil™ sensor focalization impossible. Probably, an interferometer sensor would give more results but this is out of the present range of investigations. Hirox™ gives interesting 2D photographs of varnish layers, under an adequate illumination, but 3D reconstruction is aberrant.

#### 4.2.6 Summary

Capabilities of the considered instruments on the selected materials are summed up in Table 3.

**Table 3 – Conclusions.**

	Color	Texture	Gloss	Translucency	Stil™	Hirox™
Paper	pale	rough and diffuse	no	no	difficult	difficult
Wood	pale	rough	no	no	difficult	feasible
Brass	golden	flat with scratches	yes	no	feasible	feasible
Aluminium	silvery	flat with scratches	yes	no	feasible	feasible
Lacquer	black	smooth	yes	no	impossible	impossible
Varnish	no	smooth	yes	yes	impossible	difficult

It appears that lacunar structures such as those of paper and wood are quite difficult to measure. But this is a consequence of the arrangement of matter more than a consequence of their appearance properties. Very dark and glossy surfaces, such as transparent and glossy ones, are also impossible to measure. This is caused by their smooth texture (which makes focalization difficult) and their extreme colour and translucence properties. On the contrary, metal surfaces, which are yet very glossy and rough, are measurable by the considered devices.

### 5 Conclusion

On its first metrological part, the study concludes on the possibility of comparing results from both techniques. Metrological performances of the Stil™ machine are good and measurements are robust. With Hirox™, it is more difficult to obtain a good repeatability of results, mainly due to the difficult hand-adjustment of baseline focalizations, even for a regular user. Roughness results are comparable but the very limited set of roughness parameters proposed by Hirox™ promotes the use of the Mountains Map software, despite its constraints.

On the selected materials, we have verified that measurements were not always possible. Depending on the appearance properties of surfaces, instruments sometimes fail to reproduce a coherent texture map of objects. It has to be nuanced by the fact that we always looked at a very small scale, in order to compute roughness. For example paper could have been more easily recorded at a larger scale with another sensor than the 0-300µm used. But at the considered micro-scale, the range of measurable materials is quite limited as only metals seem to give comparable and satisfying recordings with both techniques.

### 6 Perspectives

Two points can be considered for the moment. First, the presented results could open new applications of surface analysis for cultural heritage. For example, studying the effectiveness

of a restoration treatment could go through the quantitative analysis of surfaces and the comparison of roughness values before and after the application of the treatment.

At a second level, this preliminary study will allow us to further explore the relations between roughness and other appearance parameters. We chose to focus on gloss. Thanks to additional BRDF acquisitions and micro-facets models, it would be possible to evaluate an adequate roughness-gloss model for diverse cultural heritage materials.

### **Acknowledgements**

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