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LASER DOPPLER VIBROMETRY

Analisi non invasive per la caratterizzazione degli affreschi nella Reception Room del Senato degli Stati Uniti d'America

LASER DOPPLER VIBROMETRY

Non-invasive analysis for the characterization of Fresco in the Senate Reception Room of the United States Capitol Building

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Durante gli anni hanno avuto notevole sviluppo le tecniche per la caratterizzazione degli affreschi che permettono di determinare lo stato di conservazione dei beni artistici. In questa analisi si esaminano le tecniche non-invasive per la caratterizzazione di essi, in particolare della tecnica usata per analizzare le pareti affrescate della Reception Room del Senato degli Stati Uniti d'America.

Il focus è incentrato sulla Laser Doppler Technology che utilizza un Vibrometro Laser Doppler capace di rilevare la velocità di vibrazione degli elementi esaminati senza prenderne contatto e di un sistema di eccitazione strutturale per fa vibrare la struttura sottostante. Questo principio è basato sul fatto che un'area in cui vi è presente un difetto vibra "a una velocità maggiore" rispetto ad un'altra che non presenta difetti. La restituzione dei dati avviene tramite immagini e mappe a colori che vanno dal blu/verde per aree non/poco danneggiate fino al rosso per aree fortemente danneggiate che nella maggior parte dei casi presentano un distaccamento della sottostruttura dell'affresco stesso.

Questo metodo presenta caratteristiche distintive quali non intrusività, alta sensibilità alle vibrazioni, portabilità e restituzione dei dati molto semplice ed intuitiva.

È una tecnica molto versatile utilizzata per esaminare una vasta gamma di strutture, da quelle più piccole come ad esempio le icone fino a quelle di notevole entità come ad esempio grandi edifici. Inoltre, rappresenta una tecnica di indagine ben consolidate nel settore dei beni culturali.

A tal proposito si è scelto di utilizzare questa tecnica per valutare lo stato di conservazione degli affreschi nella Reception Room del Senato degli Stati Uniti d'America.

In questa analisi sono presenti approssimativamente 60 scansioni che interessano i quattro muri della stanza e il soffitto che classificano le aree in: intatte, anomale e quelle che hanno bisogno di ulteriori analisi. In particolare, sono state riscontrate numerose anomalie nel pannello centrale della cupola sud, in tutti i pannelli della cupola nord, nel pannello delle medaglie della parete est, nella lunetta meridionale sulla parete ovest e nella lunetta sulla parete nord. In ogni caso, essendo queste analisi preliminari, necessitano di ulteriori studi e indagini per individuare nello specifico le aree in cui bisogna intervenire.

Abstract

Through the years a lot has been said about the importance of the protection and knowing the state of conservation of the pieces of art, and it is still a fundamental theme which embraces different settings, from the engineering industry to the industry for the safety of the cultural asset. This analysis is focused on the state of conservation of the fresco and of the decorative plaster, particularly on some problematics about the detachment of the structure of the fresco which compromises its conservation through the time. The focus is on the non-invasive techniques and particularly on the Laser Doppler Vibrometry technique used to characterize and evaluate the state of conservation of the fresco and of the decorative plaster in the Senate Reception Room of the U.S. Capitol Building.

Contents

1 Introduction

The object of the analysis is a characterization of the fresco from a physical and chemical point of view and of all the problematics which damage it and of the techniques mainly used to evaluate them. About that non-invasive techniques are analysed which are as less invasive as possible so there are not noxious to the plaster. The focus is on the Laser Doppler Technology which uses the Laser Doppler Vibrometer that can detect the speed of the vibration of the analysed elements without any contact and an excitation system to excite and make the underlying structure vibrate. The principle is based on the prerequisite that an area where there is a flaw vibrates with a higher speed than an area without flaws. The return of the images happens thanks to coloured maps which hoes from blue/green for the non-damaged or the not so damaged areas and to the red for the damaged areas. This method has many peculiarities as for example the no remarkable intrusively, a high sensibility, portability, and remote measurements. Speaking of which this technique was chosen to evaluate the state of conservation of the frescoes in the Senate Reception Room (S213) of the U.S. Capitol. In this analysis there are approximately 60 scans of the four walls and of the ceiling of the room which classify the areas in: intact, anomalous, and in need or further analysis.

2 The United States Capitol

The United States Capitol, often called the Capital Building, is the headquarter of the United State of America Congress and of the legislative field of the federal government of the States. It is located in Washington DC, capital of the United States, on top of capitol hill, on the eastern side of National Mall, a monumental boulevard.

The original building was completed in 1800, but it was considered unusable from 1814, because of a fire caused by the British army during the war in 1812, and it was later fully restored within 5 years. The building was then modified, with the add of a massive dome and with the expansion of the two side wings for the bicameral legislature.

The United States Capitol is an example of the neoclassical style, and the final result was achieved thanks to the work on many architects. It is characterized by the massive central dome ad the two side wings, where the two fields of the Congress are located. The northern wing is occupied by the senate, the southern wing by the chamber of representatives. *[1.]*

2.1 The Senate Reception Room (S 213)

The Senate Reception Room, situated in the northern wing of the United States Capitol, and next to the Senate Chamber, is one of the room with most history and decorations. The room was initially designed by Thomas U. Walter[1] in 1853, and then decorated and frescoed by Costantino Brumidi[2] with the supervision of Montgomery C. Meigs[3]. It was designed as a point of meeting between the members of the US Capitol and the senators, it is still used as a space for meetings.

Thomas U. Walter designed the room and divided it in two parts. The southern part is crowned by a shallow coffered dome, while the northern part by a Roman style-style vault. The two parts are divided by a monumental arch.

The Senate Reception Room in being used since 1859, when the Senate moved to its new chamber. Since then, it was redecorated and various upgrades were added to its system and its adornment.

During the 19th century the room was unofficially known as the "Ladies Reception Room" or the "Ladies Parlor", because, during the American civil war (1861-1865), it was used as a point of meeting for women who became widows because of the

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[1] Thomas Ustick Walter was an American architect, he was the fourth architect of the capitol and responsible for adding the two wings.

[2] Costantino Brumidi was a Greek-Italian-American historical painter, considered one of the best American artist of his era.

[3] Montgomery Cunningham Meigs was a career United States Army officier and civil engineer, who served the U.S. Army during and after the American Civil War.

war. They reunited to put pression on the senators in order to receive compensations for the war.

At the end of the 19th century, as the time passed and the decorative style changed, the room was enriched with additional interior decoration, included the elaborate gilded cornices that crown both the windows and the mirror.

In 1893, with the add of a telephone switchboard and a telephone booth, the role of the room completely changed. It became a point of communication between the inside and the outside of the building. In fact, the senators, staff and visitors, not only could communicate with each other inside of the building, but even outside. For this reason, in the same period, the room was known as the “Public Reception Room”.

During the 20th century the room was used as a space for the meetings between the Senators and their voters. In 1958 the Senate brought some relevant changes and decided to completely fill the blank areas of the walls with portraits of eminent Senators. Those decisions gave to the room a symbolic role, as senatorial portrait gallery or “hall of fame”.

Nowadays the room, even if the use is changed, still preserves the role it was originally designed for. *[2.]*

(Figure 2-1) Panoramic of the S213: The east wall on the left; The south wall on the right; The south dome on the top

(Figure 2-2) Panoramic of the S213: The north dome

2.1.1 Frescos and Decorative Plasters in S213

The Senate Reception Room is one the most highly ornamented rooms in the Capitol. A relevant part of the ornaments was realized by Brumidi with the use of different techniques to decorate the walls and the ceiling. He used the fresco technique, which consisted in applying watercolor paints directly onto wet plaster. Other decorations were realized with oil paints on dry plaster.

Brumidi presented a first sketch in a written form for the allegorical subjects on the ceiling in 1855, and then added mural to the room, which were never completed, for the impressive and rich decorated space. In 1858 he painted the cherubs in the center of the ceiling's dome and then completed the allegorical figures of the four cardinal virtues: Prudence, Justice, Fortitude and Temperance.

(Figure 2-3) The south dome: The Cherubs

Once the widening of the two side wings was completed, Brumidi couldn't be paid with construction funds any longer, and was removed from the payroll. He was then hired again in 1869 to paint the scenes of Liberty, Peace, Plenty and War in the groin vaults on the northern end.

(Figure 2-4) The north dome: the scenes of Liberty, Peace, Plenty and War

Between 1870 and 1871 Brumidi designed and painted trompe l'oeil figures of maidens and cherubs to resemble marble sculpture in the lunettes. Finally, in 1972, he was paid to fill one of the blank areas on the southern lunette with a scene of the President Washington, Thomas Jefferson and Alexander Hamilton.

(Figure 2-5) The south wall: President Washington with Jefferson and Hamilton.

In 1876 he presented a petition to fill the remaining areas of the room with portraits of the presidents, but his idea didn't succeed. A century later the Senate decided to realize Brumidi's idea. The portraits were installed in 1959. Three of the rondels left by Brumidi were filled between 2004 and 2006 with portraits of senators from the 20th century. *[3.]*

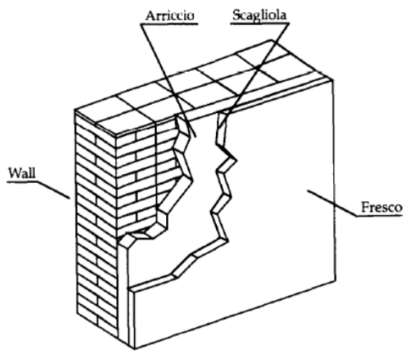
(Figure 2-6) The west wall: the portrait panel on the left and the pilaster on the center.

3 The Fresco

The fresco is a type of painting executed on the fresh plaster of a wall, it is also the technique of painting most used on wall. This technique did not suffer any variation and it's still the same today. One of the main characteristics of fresco is that it has an high resistance of the pictorial surface, which doesn't need any kind of protective paint. In fact, this technique provides for a complete integration of the color in the supporting structure where it is applied. *[4.]*

3.1 Physico – Chemical Characteristics

The structure is generally the same any time, composed by two or more coats of painting applied on the wall, and some little variatons are possible based on the artist who creates it. *(Figure 3-1)*



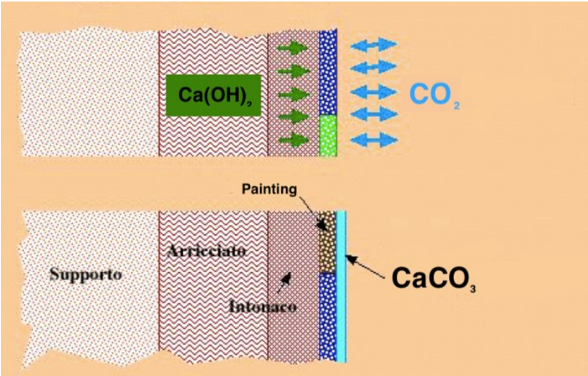
(Figure 3-1) The layered structure of the fresco. [5.]

The first step of the process consist in the drafting, on a smooth wall, of a thick layer of a rough dough composed by sand and lime, called “arriccio”, which has the role to prepare the surface and to make it as uniform as possible. On top of that the most important element of the structure is coated: a thin dough of coat composed by sand and lime, called “scagliola”. Finally, on top of this dough, when it is still damp, the color is coated. Thanks to this peculiarity the color is chemically incorporated and preserved for an illimited time. The lime is prepared with a traditional method which consists on fragments of stone (calcium carbonate), cooked in a charcoal oven (quicklime), mixed with water and left to rest for at least six months, which then becomes calcium hydroxide (slaked lime). The lime, coated on the “arriccio” and covered by color, thanks to the carbon dioxide of the air, turns again into calcium carbonate, which, as said before, is a stable and resistant mineral composite. *[5.]*

3.1.1 Carbonation

The quicklime [$Ca(OH)_2$] is combined with carbon dioxide [CO_2] to form the calcium carbonate [$CaCO_3$], based on the chemical reaction. *(Figure 3-2)*

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ *[6.]*



(Figure 3-2) Formation of the calcium carbonate. [6.]

3.2 Damages of the Frescos

The frescos are wall paintings and for that reason they suffer from environmental factors and pollutants. The most common factors which affect the state of conservation are: the humidity, the vibrations, the temperature changes and the biological agents. The water (H2O), acid gases (mainly SO_X[4]), carbon dioxide and heavy hydrocarbon are particulary harmful for the fresco. Those factors can cause two kind of damages: superficial (erosion, discoloration or fouling), or interior, which, in certain case can also be invisible to naked eyes. Object of the study are the interior damages, among which the most relevant are the delamination and/or the detachment of the lower layers, which are initially located but, as the time

[4] SOx, that stands for, Sulphur Oxide, refers to many types of sulphur and oxygen containing compounds such as SO, SO_2, SO_3, S_7O_2 etc. that have an acid ph.

passes, they cause a not perfect contact between the layers. As the time passes, because of the humidity trapped on the cavity caused by the detachment, the delaminated area propagates. The fresco can suffer huge damages, until the real physical detachment of a layer from another one, or from parts of it. Even if there isn't a detachment, the delamination can damage the aesthetics of the fresco itself, so the loss of a work of art. Some example of frescos are reported in the following figures where the detachment of the layers can be seen.

(Figure 3-3) Hades Abducting Persephone in the Small Royal Tomb at Vergina, Macedonia Greece.

(Figure 3-4) Fresco in the terrace houses in Ephesus at Selcuk, Turkey.

The conservation, with the most of the work of arts, is obtained with the control of the environmental conditions, for example in museums. This, for obvious logistical reasons, is not possible for the frescos, which can't be removed and, in the most cases, it isn't possible to control the environmental conditions. An important consideration is that the frescos are usually located in hard to reach places, like the domes, or walls of a huge size. Furthermore, as they are generally located in places of religious importance and often crowded, the monitoring can't obstruct the normal use of the building. For this reason, it is fundamental to use methods less invasive as possible. Because of that optical instrument are very suitable. *[7.]*

4 Non-Invasive Techniques for the Diagnostics of the Frescos

The non-invasive techniques and analysis allow to know the structural characteristics, the conservation and the problems about materials under investigation without affecting the integrity. They also allow to diagnose and to know in advance the causes of the detriment of the human's works of art. there are various techniques, and each of them has its strenghts and its weaknesses. *[8.]*

4.1 Visible Test

One of the methods uses the electromagnetic waves in the visible band. It is the frequency range where the human eye is sensitive and can see. It corresponds to all the colors of the rainbow. This method is useful to detect superficial anomalies or to perform dimensional inspections. In regarding the applications, we can find the ones about oxidation, corrosion, erosion of interior sufraces or superficial ones. This test only works on a superficial level so it is limited. *[8.]*

4.2 Radiography

Another method works thanks to x-ray and y-ray (electromagnetic waves with an high energy). It can be used on works of art of a limited size. When the electromagnetic waves go through an object, they are absorbed as a function of thickness and the density of the crossed matter. When there's an anomaly or a gap of density inside the analyzed object, it is stressed by a softening of those radiations. This method can underline the volumetric flaws. It has a wide field of application because, by choosing the appropriate energy delivered, itis possible to inspect almost all materials. At the same time, it has some limits because it can be used only for small sized pieces and the work of art needs to be removed from the place where it's usually located. *[8.]*

4.3 Ultrasound

This method is based on the phenomenons of reflection and refraction which an acoustic wave suffers when it is travelling inside a material and it meets an obstacle during its propagation. It allows to detect even deep volumetric flaws (bubbles) and planar flaws (delamination). Almost all kind of material can be examined as long as they are compact and fine-grained, those are its limits of application. *[8.]*

4.4 Holographic Interferometry

The method is based on the phenomenon of the optical interference which occurs when two images of an illuminated object by a monochromatic source (laser) are overlapped, and the surface deform itself in the direction of the observation, when a stress is imposed. It can detect structural and function anomalies of the materials and of its components. It also has some limits in the use because of the particular optical configuration required and because of the low spacial resolution of the sensors. *[8.] [10.]*

4.5 Ground-Penetrating Radar

The geophysic survey methodology can be applied on every mean which is dense and has a low conductivity, which allows to obtain information about the interior structure of the analyzed mean. A two-way radar is used because it can enact and receive electromagnetic impulses and can detect the reflected signals from the discontinuity surfaces of materials with a different dielectric property found inside the analyzed mean (stratification of the materials, fractures, cavities and delaminations. It is generally used for the evaluation of the underground, artefacts and wall structures. His main characteristics are that it has a fast execution, an high resolution and accuracy of localization. *[8.]*

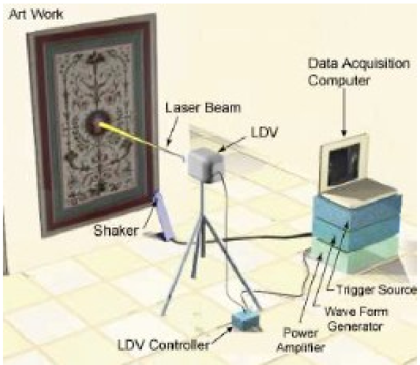
4.6 Thermography

The method is based on the acquisition of images in the infrared emitted by bodies in operation of their temperature. It is based on the measure of the superficial distribution of the temperature of a material followed by a thermal stress. Any anomalies found in this distribution are indicative of a possible flaw. It can detect structural anomalies and flaws in the materials of simple and complex structures. It can be used on any type of material even if it can find some difficulties with material which are good heat conductors.

The contribution of heat is controlled in order to avoid to apply a too high temperature that can compromise the state of conservation of the analyzed object, and the heat flow is even. It allows to evaluate the presence of different materials and inhomogeneity such as the detachment of the coat, delaminations and presence and the spread of humidity. *[8.] [9.]*

5 Laser Doppler Vibrometry

The laser doppler vibrometry is an innovative technique which allows to detect the speed of the vibration of the analysed objects without losing any contact, evaluating the state of conservation and having a qualitative and quantitative characterization of the surface objects and of the wall structures. *[9.]*



(Figure 5-1) Scheme of an experiment with Laser Doppler vibrometry technology

5.1 The Laser Doppler Vibrometer

When we talk about measuring vibrations, a powerful instrument is the Laser Doppler Vibrometer (LDV), which can measure with accuracy the speed at any given moment thanks to interferometric techniques.

The basic idea is to measure and process information by replacing the senses of man. This instrument requires an association with another one, able to excite the structure using acoustic and mechanical system which make the surface vibrate. Usually those systems are controlled by a PC and allow to acquire and process data that can be transferred in other applications.

The LDV can study the vibrations and track 2D o 3D maps. *[11.]*

(Figure 5-2) Single and scanning LDV laser heads; SLDV system in the lab. [11.]

The principle says that an area where there is a defect vibrates with a higher speed than another surrounding area which doesn't have any defect. The technique allows to obtain quantitative information about the defect and about its temporal evolution.

Questo metodo presenta vari pregi:

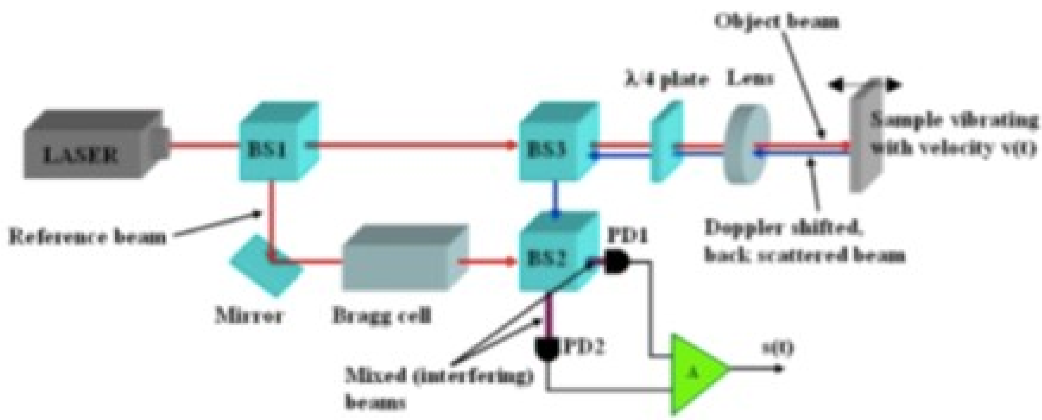
- No remarkable intrusiveness,
- Remote measurements,
- Ample frequency response
- High sensibility,
- Portability.

At the same time, it also has some flaws. The system must be completely isolated from the vibrations of the ground that can originate for different reasons such as the closeness of the building to a road. Those vibrations are sources of pollution of the results. *[11.]*

5.2 Basic Working Principles

This instrument uses the Doppler Effect or the Doppler Shift to acquire from a distance the speed of vibration. The doppler effect is caused by the relative motion of the source and of the observer: when the source of a wave and an observer are in a relative motion there is a difference between the frequency emitted by the source and the frequency received by the observer.

The surface vibrations induce the doppler frequency shift on the incident ray, this shift is linearly connected to the speed component which goes in the direction of the ray. A typical characterizing scheme is the March-Zander one:



(Figure 5-3) Scheme of LDV

One of the obstacles is that the Doppler shift in generally minor than the fundamental frequency of the laser, about the 0,92%. To solve this problem, we use the interferometry.

The laser light is divided in a “reference beam” and an “object (measurement) beam” by beam splitter BS1. The last one passes through beam splitter BS3 and is focused to a point on the vibrating object by the lens. The reflected ray comes back in BS3 which diverts it in BS2. In BS2 the reflected ray interferes with the "reference beam".

The intensity which results from the combination of two rays varies in a sinusoidal way with the difference of phase between the two rays that can be relevant or not depending on whether the object is still or moving at a v speed.

In the first case the difference is constant and defined by the optical path L travelled by the light between the surface and the BS2. If the surface is moving, as in the second case, it is possible to express the phase as the product of a variable pulse in the time (instant frequency) for the time itself; the value of this frequency is equal to the value of the frequency shift (doppler effect) caused by a v.

The wave reflected by a moving surface is subjected to a shift doppler (f_d) of its frequency proportional to the speed of the surface (v) and to the wavelength (λ) of the radiation:

$$f_d \cong 2v / \lambda$$

The optical signal is converted to an electrical signal by photo detectors PD1 and PD2. The use of two detectors minimises noise and drift. The resultant signal at the output of the operational amplifier is:

$$s(t) \cong A^2 \cos(2 \pi f_d t)$$

where A is the amplitude of the laser beam.

The Bragg cell or an electronic manipulation of the recombined beams can be used to determine the direction of the instant velocity vector. *[11.]*

5.3 Characteristics

The modern LDV can explore until 100 points at second and arrive to a total number of points higher than 100.000.

Most diffused LDVs have a maximum velocity range of 10 m/s, with a frequency upper limit of 200 kHz. The resolution of about 1 μm/s and All SLDS. Laser power is less than mW. Such a limited Power guarantees that the instrument of measurement isn't invasive and that the analysed object isn't damaged. Also, it doesn't cause any danger for the surrounding environment, so it doesn't require any measure of security.

The systems are managed by a PC which returns the results in various digital formats (images BMP or JPG, file UFF, videos AVI) that can be easily transferred to extern software packages of post processing or data analysis. *[11.]*

5.4 Structural Excitation

The preparation of the test is composed by a System SLDV, an excitation system and plus additional instrumentation such as a sound meter to monitor emitted sound level. The excitation system is generally executed with loudspeakers, shaker and impact hammers. [12.]

5.4.1 Loudspeakers

It is a completely non-invasive System, and it allows to measure objects located at some metres of distance from the operator without the necessity of a direct contact with the object. The waves emitted by a remote System of loudspeakers can induce vibrations on every point of the fresco if enough energy from the air to the wall is emitted. The waves can be generated in a wide frequency spectrum, so that it can excite at the frequency of the resonance the damaged area of the fresco. This type of structural excitement can be used for structures and objects relatively small. *[10.]*

5.4.2 Shaker

The shakers can be electromagnetic (often called electrodynamic) and the electro-hydraulic (or hydraulic). The electromagnetic shakers are controlled electronically compared to the others. The hydraulic shakers are constituted by hydraulic actuators controlled electronically, that can express elevated strengths which allows an optimal control of the law of motion.

With the electromagnetic shaker, force is generated by an alternating current that drives a magnetic coil. The maximum frequency limit varies from approximately 5 kHz to 20 kHz depending on the size: the smaller shakers have the higher operating range. The maximum force varies from approximately 2 lbf to 1000 lbf.

With hydraulic shakers, the maximum frequency range is much lower though – about 1 kHz and below. An advantage of the hydraulic shaker is its ability to apply a large static preload to the structure. It is useful for massive structures. *[12.]*

5.4.3 Impact Hammer

The impact hammers have a mass that goes from a few grams to 2 kg and are the most common instrument for the measurement of the mobility of the structure. The force of the impact can be controlled by the operator and can be limited by changing the inertial mass of the hammer. They have a strong limitation in the application of the frescos because of the soft surface of the fresco. The advantage is that it gives the precise value of the force of the impact and it allows to know the level of energy sufficient to induce vibrations in the wall without causing any damage. A big problem is the unavailability of the impact as regard the intensity and the point of application of the force. *[12.]*

5.5 Data Interpretation

The return of the data occurs mainly by means of color maps which report the values measured superimposed to an image of the analysed object, so that even non-professional staff can have a perception of the damaged area and of the state of degradation of the examined structure.

The use of the SLDV is based on the theory that it is possible to evaluate the state of health of an object by analysing its vibrations.

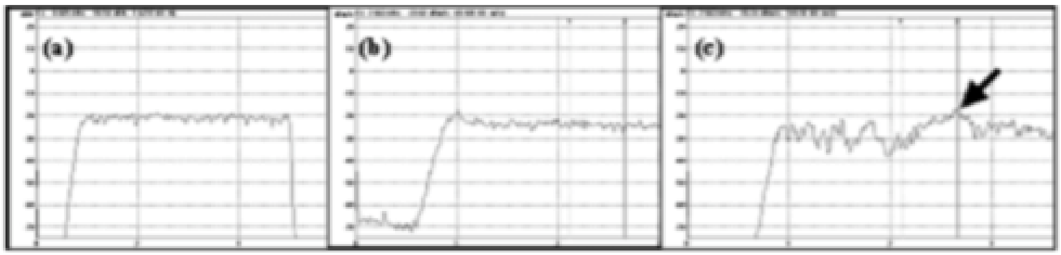
A medium value of the speed of the surface vibrations can be detected point by point with the RMS (Root Mean Square) analysis or information can be obtained with the FFT (Fast Fourier Transform) analysis to obtain a more accurate characterization.

The first one is used to identify the presence and the position of the defects. With the second one the punctual frequency spectrums can be obtained and with them it is possible to identify the frequencies of resonance of the damaged areas.

In the frequency spectrums it is possible to identify the frequencies of resonance of the structure and of the damaged areas.

For lower frequencies (< 100 Hz) there are resonances of the entire structure, meanwhile for higher frequencies (> 100 Hz) damaged areas are identified.

In the figure *(5-4)* there is an example relative of the measurement executed on a fresco, starting from the signal used for the acoustic solicitation (white rumour) a small defected area is identified thanks to the presence of a resonance peak at 2663 Hz. *[9.]*

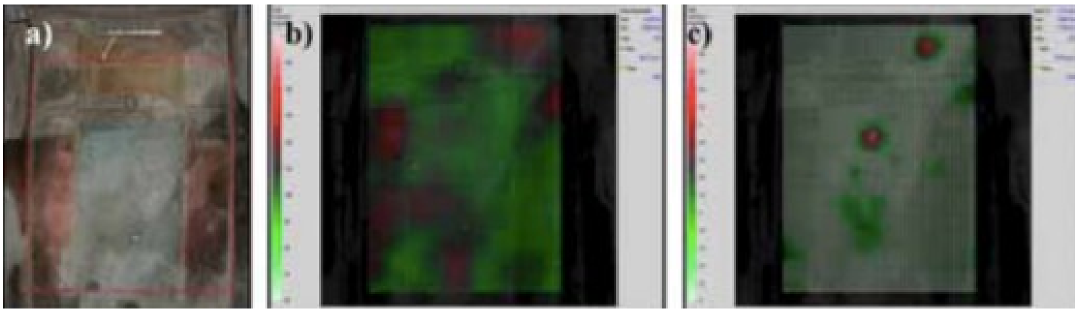


(Figure 5-4) (a) White noise signal input to the loudspeakers (b) spectrum measured on untouched area (c) spectrum measured on detached area. Notice the resonance peak found (black indicator) [9.]

5.5.1 Case of Study: Pompei's Archaeological park

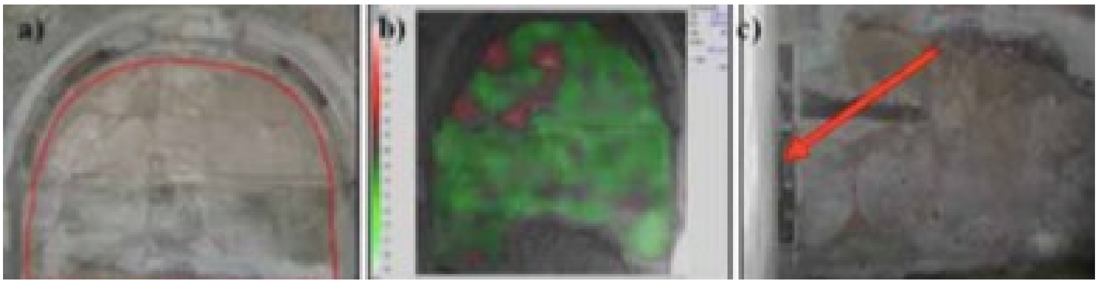
Below are illustrated two examples where it's easy to identify the area affected by a delamination of the plaster by its structure. Those investigations were made to estimate the state of conservation of the frescos in the house of the maze, inside the archeologic area of Pompei. Those investigation were carried out with a system of measurement of the vibrations with a VLSD.

In the figure *(5-5)* there is a wall analysed with the relative map RMS. The lecture is immediate: the color green is associated to a low level of vibration (the structure is in a good state of conservation); the color red is associated to a high level of vibration (the structure has pathological conditions in progress, as delamination or detachment).



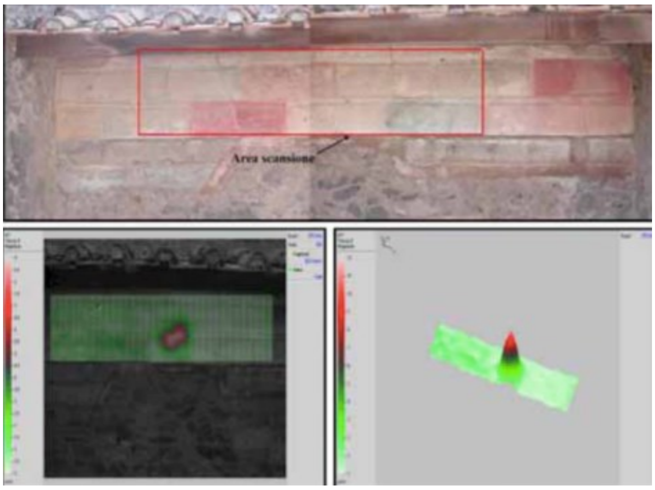
(Figure 5-5) (a) detail of the wall (b) RMS map (c) RMS map 1690-1740 Hz [9.]

In the figure *(5-6)* there is a picture of the wall with the relative map RMS. It is characterized by wide areas in phase of detachment from the support, in particular on the top right with a value of speed of vibration of 180 μm/s.



(Figure 5-6) (a) wall (b) RMS map (c) constructive detail [9.]

In the figure *(5-7)* an example of the FFT analysis is shown.



(Figure 5-7) FFT analysis at 275 Hz with 2D and 3D map. [9.]

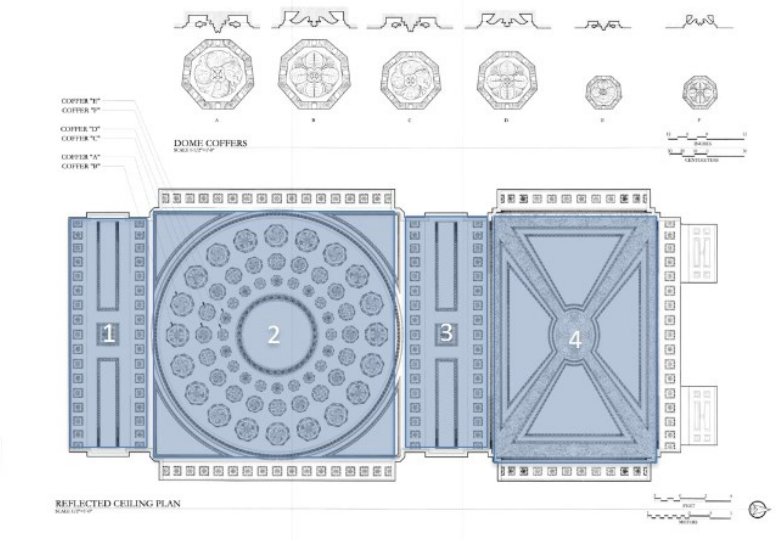
6 Analysis of Frescos and Decorative Plaster in S213

This analysis describes the results of a survey conducted in the summer of 2019 examining the structural status of frescos and decorative plaster in Room S213.

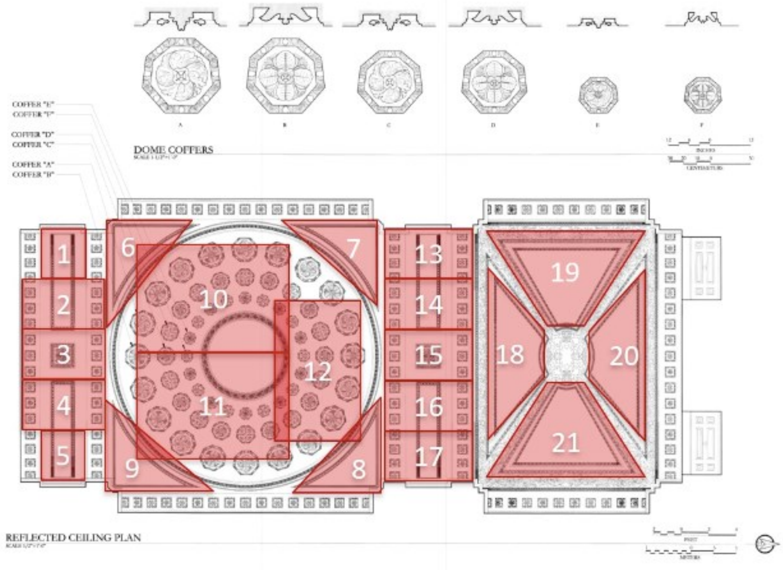
The scans reveal areas where the underlying plaster has separated from its substructure. Those scanned images contain a grid of blue or green which are overlapped with red point to identify the areas where there are anomalies. The original grid corresponds to the position of the acquired data, ensuring that the mapping is accurate to the location. For this analysis it is used a Polytec scanning Laser Doppler Vibrometer (LDV) was mounted on a rolling tripod and a set of two speakers on another tripod. Below will be shown, on the right the scanned area and on the left the post processed data. *[13.]*

6.1 The Ceiling

The ceiling is separated into four areas of two archways and two domes *(Figure 6-1)*. These areas include the south arch (1), the south dome (2), the north arch (3) and the north dome (4). *(Figure 6-2) [13.]*



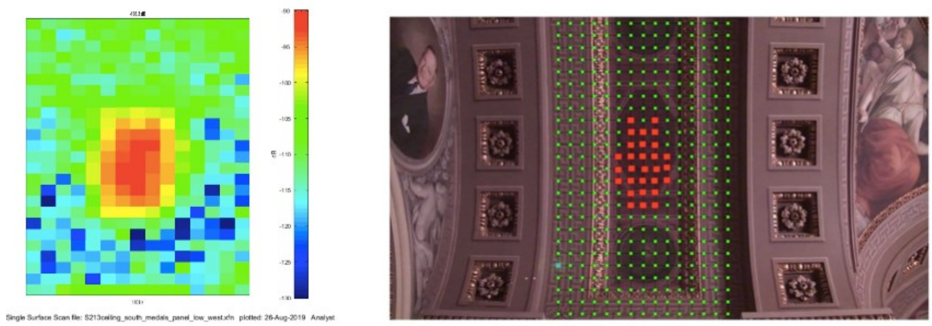
(Figure 6-1) [13.]



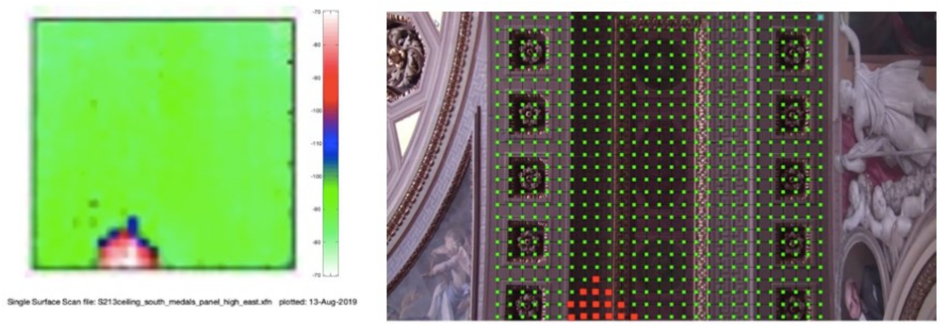
(Figure 6-2) [13.]

6.1.1 The South Arch

Two major anomalies were found in this area, one in the lower west portion (Section 1) and one in the middle of the east portion of the archway (Section 4). Sections 2, 3, 5 show little or no evidence of degradation. *[13.]*



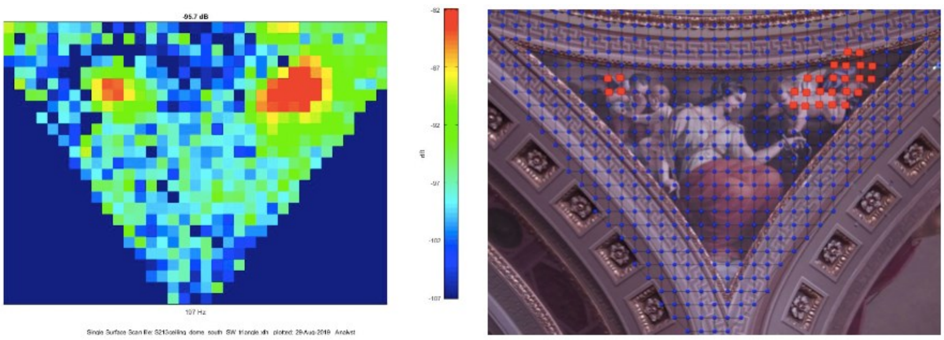
(Figure 6-3) Section 1 shows a large central anomaly positioned near the edge of the bordering plaster molding. [13.]



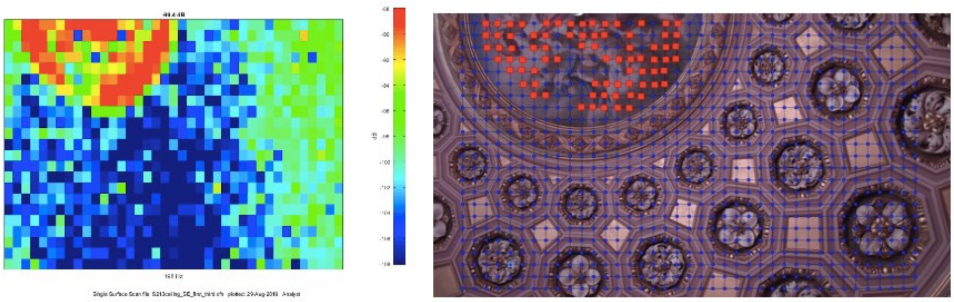
(Figure 6-4) Section 4 shows an anomaly in the bottom center of the panel, under and to the left of the central medal. [13.]

6.1.2 The South Dome

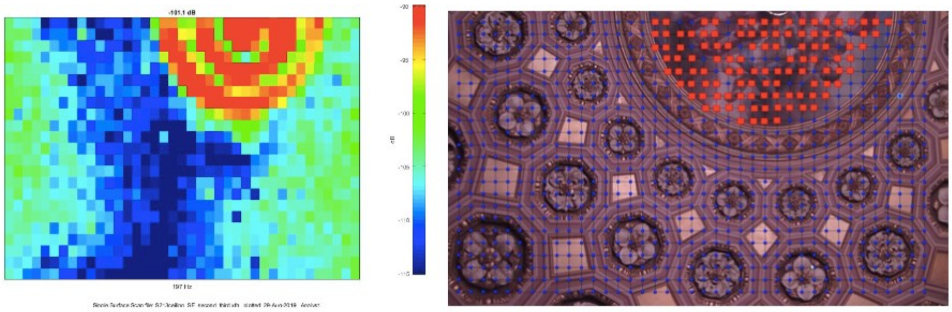
Two major anomalies were found in this area. One is considerably smaller in the upper right area of the south west portrait (Section 6). The other is considerably largest in the entire central portrait at the peak of the dome (Section 10-11). Sections 7, 8, 9, 12 show little or no evidence of degradation.



(Figure 6-5) Section 6 shows two anomalies, one major in the upper right corner, and one minor in the upper left corner. [13.]



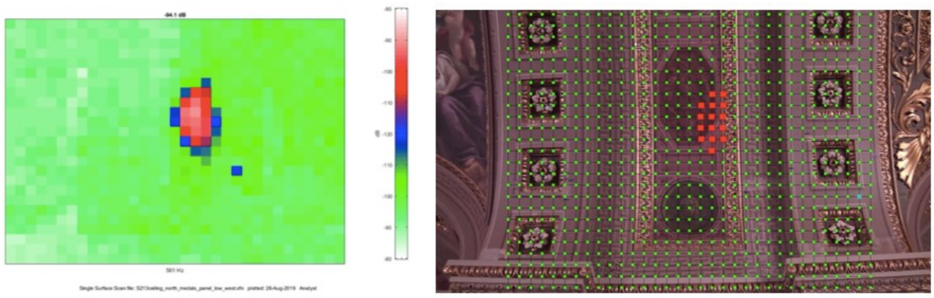
(Figure 6-6) Section 10 shows part of the large anomaly in the central panel.[13.]



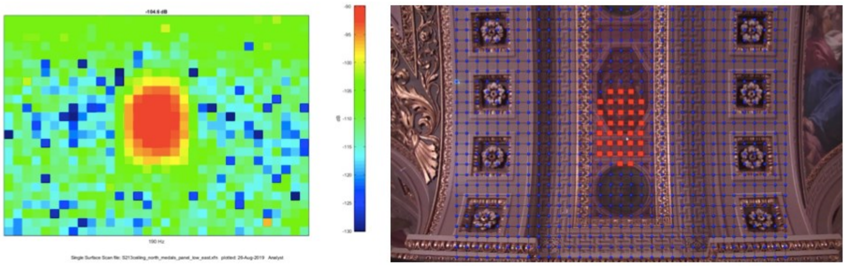
(Figure 6-7) Section 11 shows part of the large anomaly in the central panel.[13.]

6.1.3 The North Arch

Two major anomalies were found in this area, one in the center of lower west portion (Section 13) and one in the center of lower east Portion (Section 17). Sections 14, 15, 16 show little or no evidence of degradation. *[13.]*



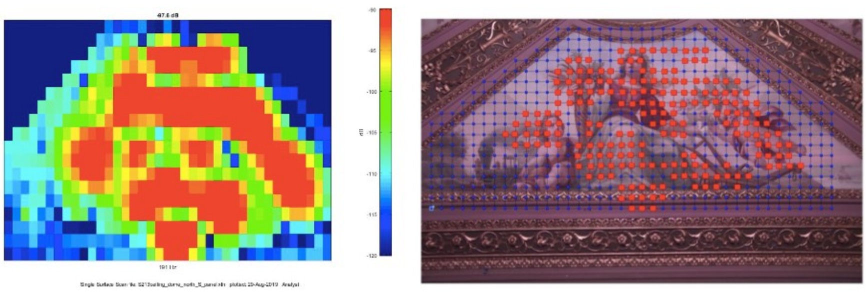
(Figure6-8) Section 13 shows a large anomaly in the center of the panel. [13.]



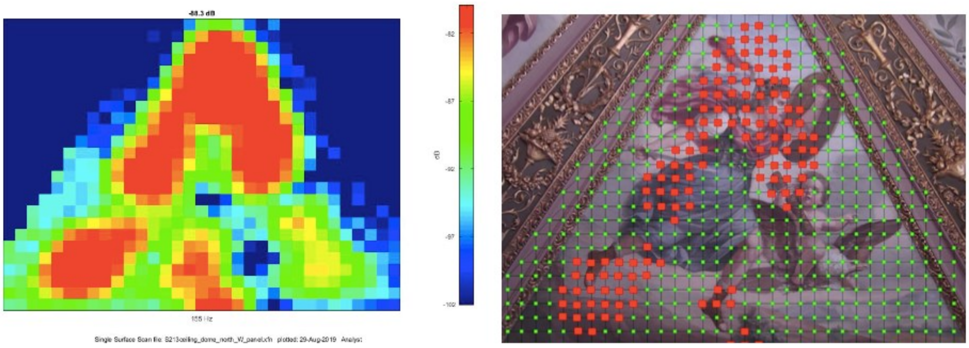
(Figure 6-9) Section 17 shows a large central anomaly that spans almost the entire width of the central panel. [13.]

6.1.4 The North Dome

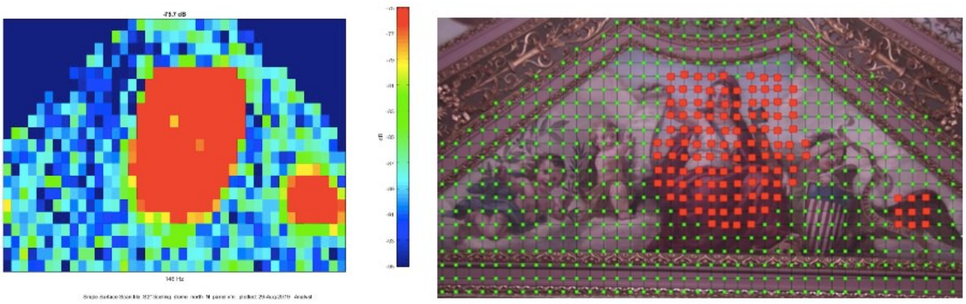
In this area all four sections showed major delaminations. There were four minor faults detected. One in the east panel (Section 21), one in the north panel (Section 20) and two in the west panel (Section 19). There was also one ambiguous area detected in the lower left side of the panel (Section 21). *[13.]*



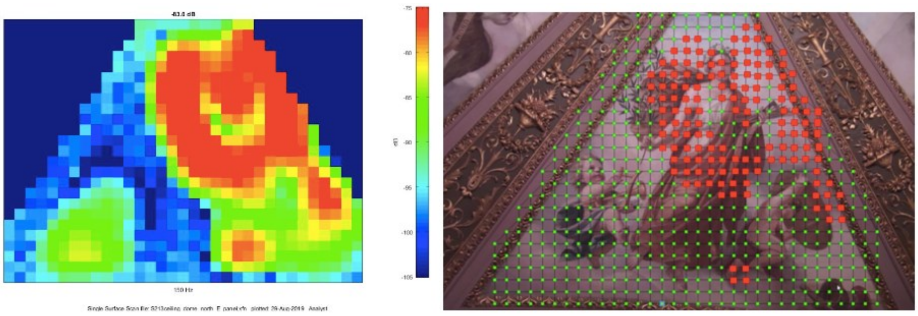
(Figure 6-10) Section 18 shows a large anomaly covering almost the entire surface. [13.]



(Figure 6-11) Section 19 shows a number of large and small anomalies that cover a large section of the surface. [13.]



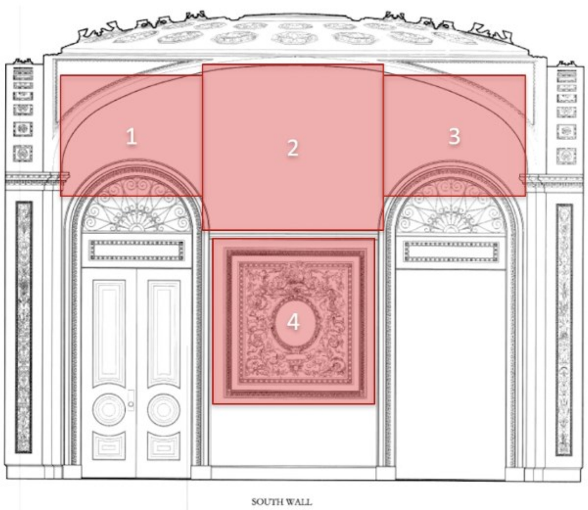
(Figure 6-12) Section 20 shows a large central anomaly and an additional smaller anomaly near the bottom right corner. [13.]



(Figure 6-13) Section 21 shows a large anomaly that covers a large section of the right and center surface. [13.]

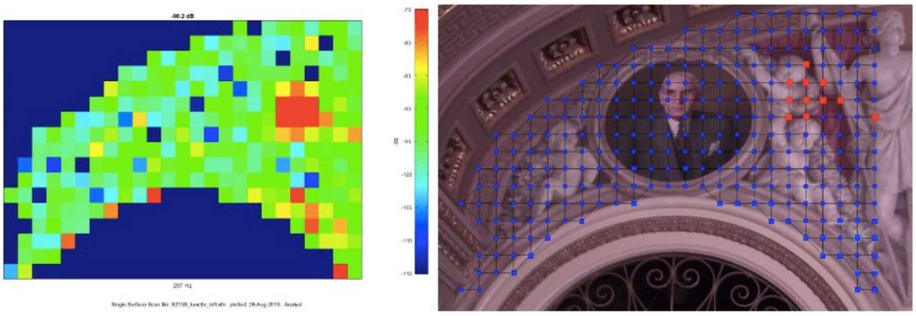
6.2 The South Wall

The south wall is separated into three sections of the lunette (Section 1-2-3) as well as the portrait of the Senator Clay in the center (Section 4). *(Figure 6-14) [13.]*

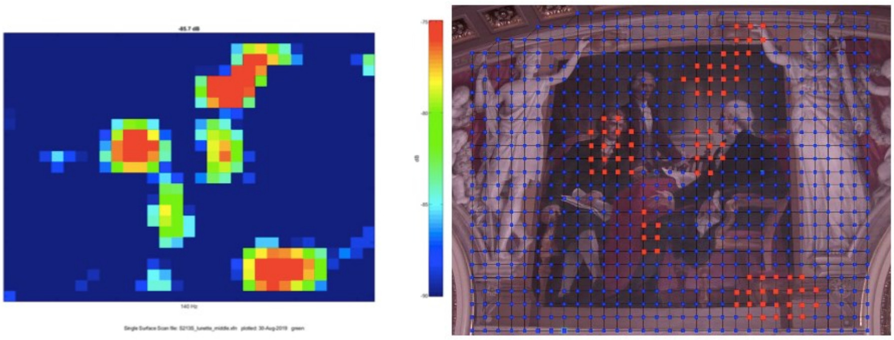


(Figure 6-14) [13.]

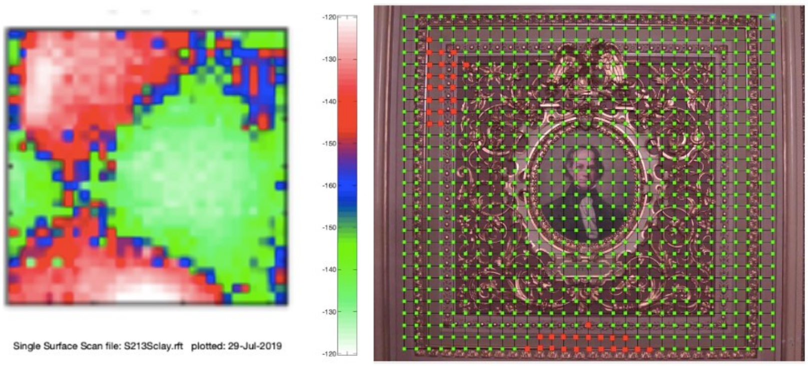
The wall shows a number of small anomalies in the center of lunette (Section 1-2) and two large anomalies around the border of the portrait (Section 4). Section 3 shows little or no evidence of degradation.



(Figure 6-15) Section 1 shows a small anomaly near the top right side. [13.]



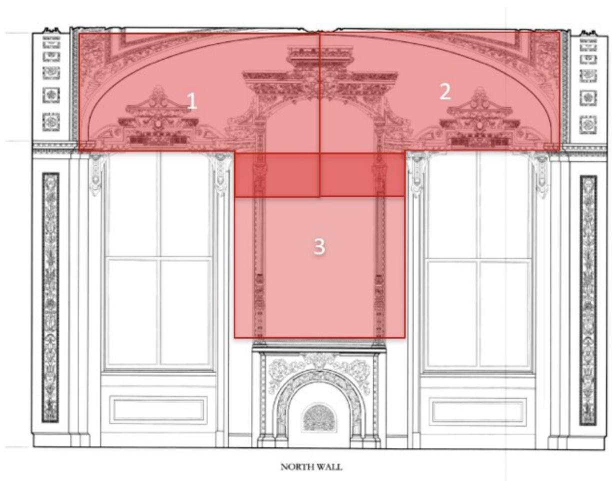
(Figure 6-16) Section 2 shows five small anomalies over the central region of the portrait. [13.]



(Figure 6-17) Section 4 shows an anomaly in the top left corner and the centrally along the bottom. [13.]

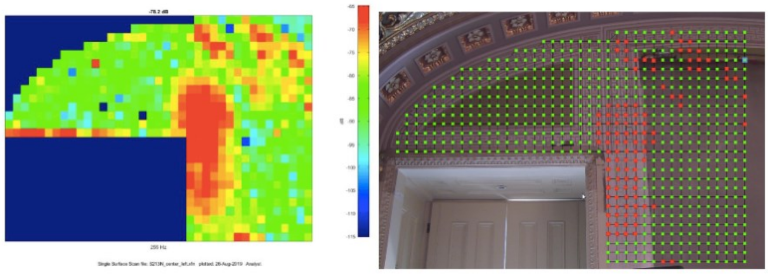
6.3 The North Wall

The north wall is separated into two sides of the lunette (Section 1-2) as well as the center portion of the wall between the windows (Section 3). *(Figure 6-18)*

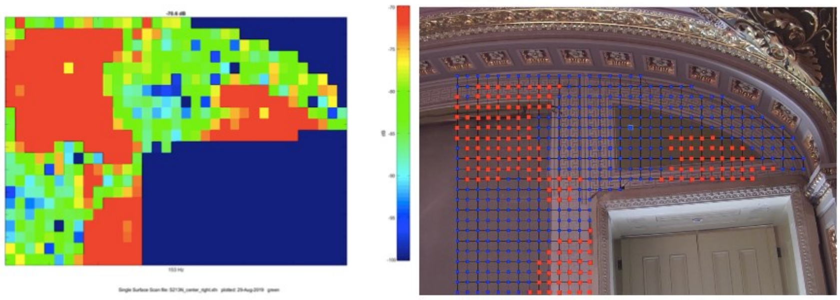


(Figure 6-18) [13.]

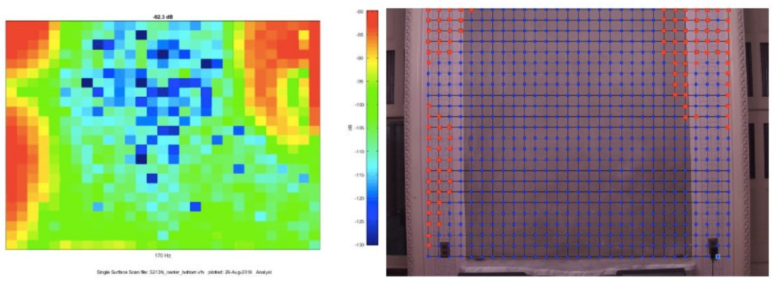
Anomalies on the north wall include three large areas along the windows (Section 3) and few small areas in the top of the lunette (Section 1-2). *[13.]*



(Figure 6-19) Section 1 shows a large anomaly in the center at the top right corner of the window and two smaller anomalies in the top right corner of the scan. [13.]



(Figure 6-20) Section 2 shows an anomaly in the top left corner, along the side of the window and above the window. [13.]



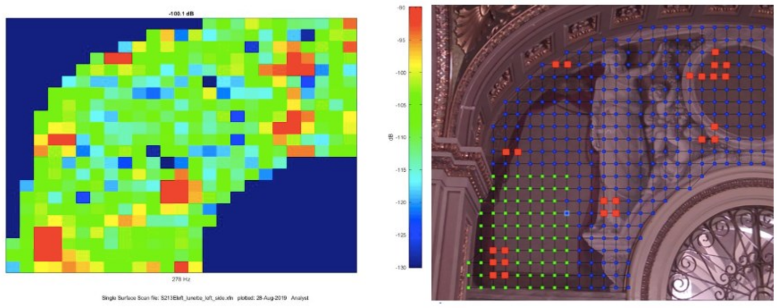
(Figure 6-21) Section 3 shows two large anomalies along the left side and a large anomaly in the top right corner. [13.]

6.4 The East Wall

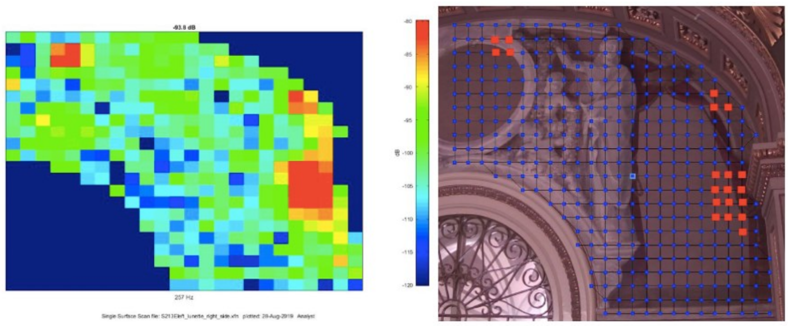
The south wall is separated into four sections. These areas include both lunettes (Section 1-2-3-4), the panels surrounding the north door (Section 5-6-7-8), the north and the south medals panels (Section 9-10) and the two portraits of Senators Taft and Calhoun (Section 11-12). *(Figure 6-22) [13.]*

(Figure 6-22) [13.]

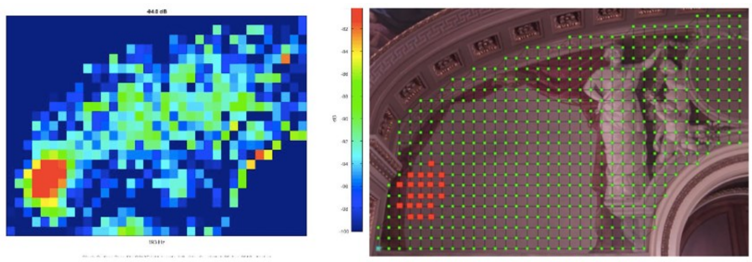
The wall shows a number of small and large anomalies along the upper edges and bottom corners of the lunettes (Section 1-2-3-4). Both medals panels have large single anomalies (Section 5-6-8). The northern door panel shows a large central anomaly while the southern door panel shows four (Section 9-10). The outer plaster surrounding the portrait of Senator Taft shows a large anomaly running along the bottom edge (Section 11). Section 7, 12 shows little or no evidence of degradation.



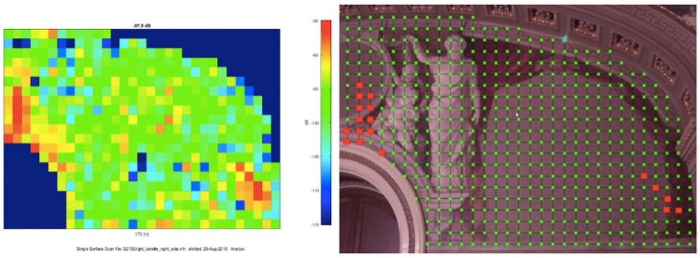
(Figure 6-23) Section 1 shows several small anomalies across the surface of the fresco. [13.]



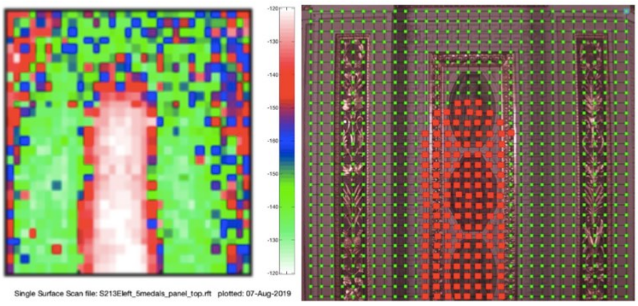
(Figure 6-24) Section 2 shows one large anomaly near the bottom right corner, as well as two smaller anomalies along the top of the lunette. [13.]



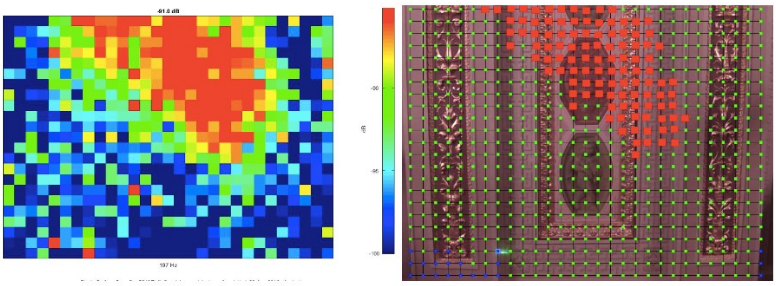
(Figure 6-25) Section 3 shows one large anomaly near the bottom left corner of the lunette. [13.]



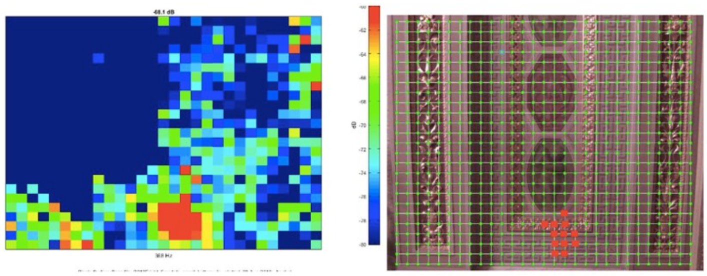
(Figure 6-26) Section 4 shows one large anomaly near the bottom left corner of the lunette and one small anomaly near the bottom right corner. [13.]



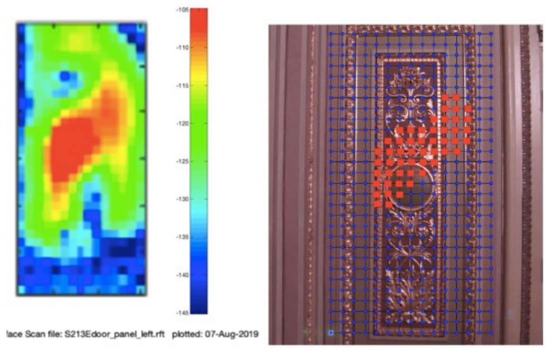
(Figure 6-27) Section 5 shows one large anomaly that covers the entire bottom of the central panel. [13.]



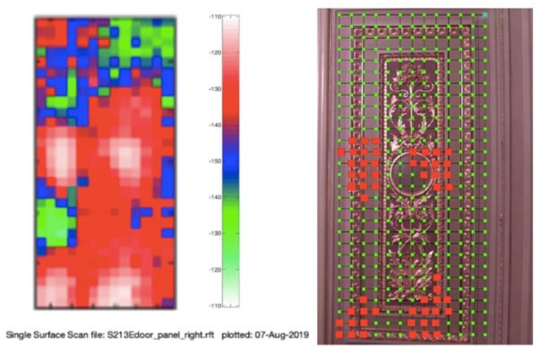
(Figure 6-28) Section 6 shows one large anomaly that covers the entire top of the central panel and extends half way down the fresco. [13.]



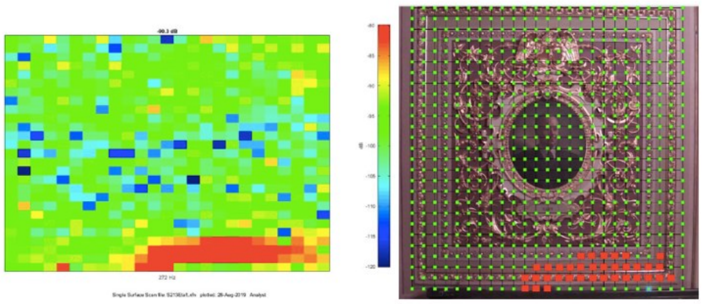
(Figure 6-29) Section 8 shows one large anomaly at the bottom of the outer panel and extends through the inner molding and into the very bottom of the central fresco. [13.]



(Figure 6-30) Section 9 shows one large anomaly at the upper center of the panel. [13.]



(Figure 6-31) Section 10 shows two large anomalies in the bottom left, bottom. Center, and middle left of the outer fresco as well as the middle center of the inner decorative molding panel. [13.]



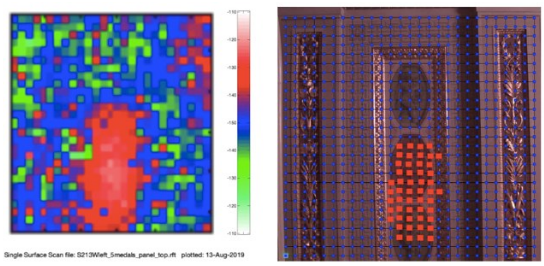
(Figure 6-32) Section 11 shows a large anomalies along the bottom of the external fresco. [13.]

6.5 The West Wall

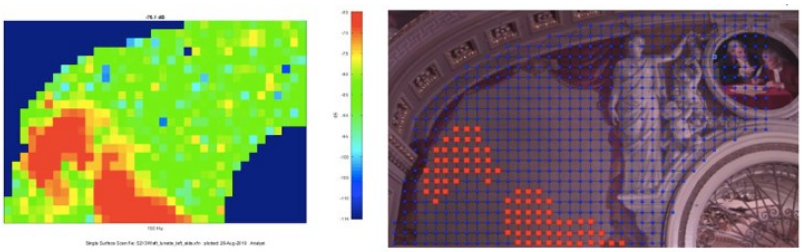
The west wall in separated into four sections. These area include the south medals panel (Section 1-2), the south lunette (Section 3-4), the north medal panel (Section 5-6), the north lunette (Section 7-8) the portraits of senator Lafolette and Webster surrounding the south door (Section 9-10) and the panels surrounding the north door (Section 11-12). *(Figure 6-33) [13.]*

(Figure 6-33) [13.]

The wall shows multiple large anomalies in the upper medals panels (Section 1-5) and smaller anomalies in the door panels (Section 11-12). The northern lunette shows three small anomalies around the edge (Section 7-8). The southern lunette contains two large anomalies (Section 3). Section 2, 4, 6, 9, 10 shows little or no evidence of degradation. *[13.]*

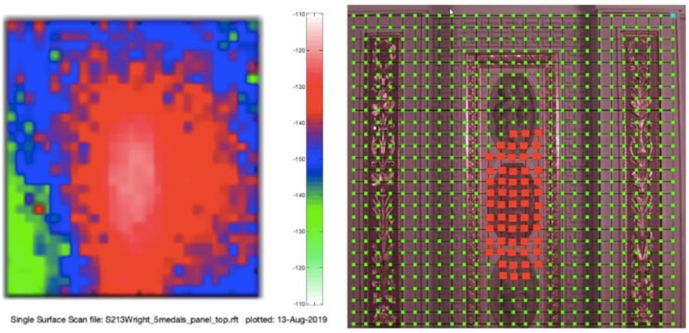


(Figure 6-34) Section 1 shows one large anomaly in the center of the interior medals panel. [13.]



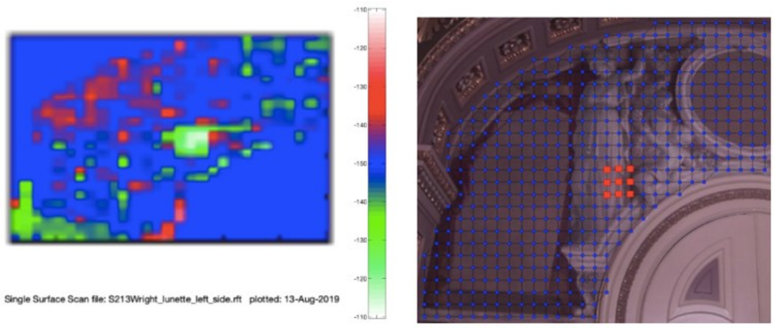
(Figure 6-35) Section 3 shows one major anomaly near the bottom left corner.

[13.]

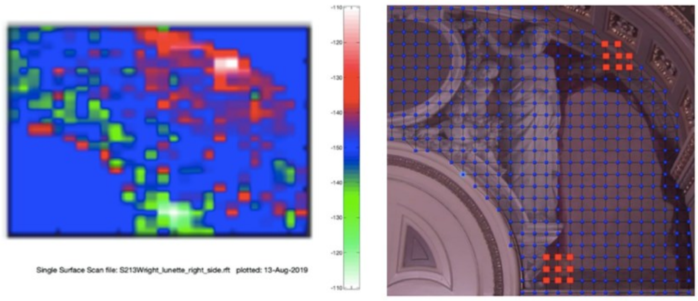


(Figure 6-36) Section 5 shows one major anomaly in the center of the fresco.

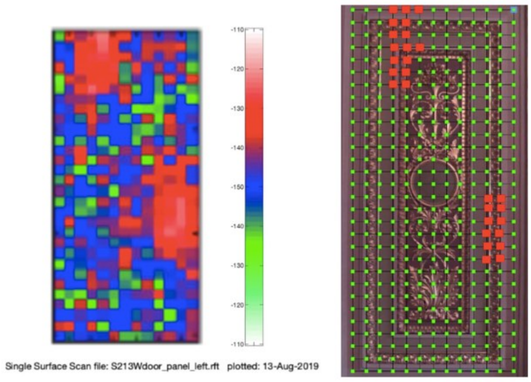
[13.]



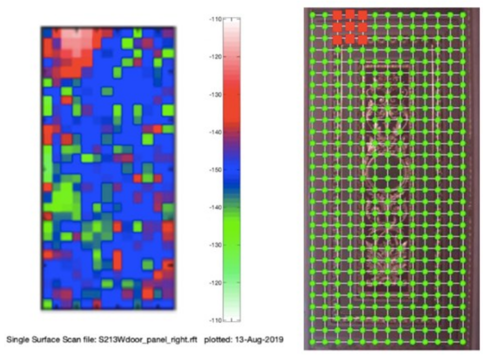
(Figure 6-37) Section 7 shows one minor anomaly in the center of the fresco.[13.]



(Figure 6-38) Section 8 shows two minor anomalies, one in the lower left corner and one near the top right edge of the fresco. [13.]



(Figure 6-39) Section 11 shows shows two major anomalies, one on the top left of the panel and the other on the center right side. [13.]



(Figure 6-40) Section 12 shows one minor anomaly at top let corner of this panel.

7 Conclusions

In this document the various non-invasive techniques for the characterisation of the frescoes are analysed, particularly the Laser Doppler Vibrometry. Based on these researches and on what is written for the different technologies:

- Visible test: it is a technique used for the characterisation of the frescoes mainly on the surface layers, so it is really limited.
- Radiography: it is a technique used for pieces of small dimension which need to be removed from where they are normally based, for this reason it is limited.
- Ultrasound: it is used on grain materials which limit its use.
- Holographic interferometry: even though it is a versatile technique, at the same time it has a difficult configuration on the optic used and a low spatial resolution of the sensors which limit its use.
- Ground penetrating radar: even though it is used to evaluate different problematics, it is usually used for the characterisation of the underground and building work, so it doesn't fit the case.

The Laser Doppler Vibrometry, in particular the Laser Doppler, can examine a various range of structures, which goes from the little one as icons, to the ones of great magnitude as big buildings. It is possible thanks to the versatility of the instrument for high or low frequencies which allow to acquire data for a long or short ray. It also represents a well-established technique of investigation in the sector of the structural works. Talking about the data collected, numerous anomalies have been identified on the frescoes of the S213, in particular in the central panel of the southern dome, in all the panels in the northern dome, in the north medals panel in the eastern wall, in the southern lunette on the western wall and in the lunette on the northern wall. Anyway, those results are preliminary, so they need more studies and investigation in order to identify more specifically the areas that need an intervention.

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