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AN OVERVIEW OF THE DEVELOPMENT OF THE ACOUSTIC IMAGING ACEADD TECHNIQUE: THE SOUND OF FRESCOES

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Abstract

To extensively characterize heterogeneous structures such as mural paintings on site, an experimental method and the relative device, denominated Acoustic Energy Absorption Diagnostic Device, were purposely implemented. The system provides acoustic images of the painted surface, localizing detachments and flaws where the acoustic energy absorption is considerable. Different phases from laboratory validation on suitable models, functional to the patenting process, to the field validation on real frescoes, glazed ceramic tiles and panel paintings, from the customization of the device's configuration, to the study of important metrological aspects were oriented to the realization of a suitable diagnostic tool for helping conservator scientists in the preventive field diagnostics. In the present paper the overall experience in the development of the acoustic imaging technique is reviewed in order to present some reflections regarding the way to support innovation in the Cultural Heritage domain. Few key factors for the advancement of innovative technologies are identified: a suitable metrological approach for the assessment of the method's applicability; the construction of a joint environment for a systematic and participated field experimentation; an accurate planning of significant comparisons between different methodologies; a constant attention towards protocols and procedures optimization as well as towards technical innovations.

Keywords: *Acoustic imaging; Detachments; Frescoes; Glazed ceramic tiles; Panel paintings*

Introduction

Since the last decades of the twentieth century, innovative technologies have increasingly been applied in the cultural heritage domain, leading to a growing sensibility and attention towards the innovation process in this field. This is especially true in diagnostic and conservation activities, where groundbreaking research advancements have disclosed new opportunities for more effective conservation actions [1-4]. A deep knowledge of pioneering technologies is thus required as well as an improved understanding of the significant factors addressing innovation in Conservation Science.

From this perspective, the present paper describes the different phases of the experience acquired in about fifteen years in the laboratory development and in situ application of an acoustic diagnostic method, denominated Acoustic Energy Absorption Diagnostic Device - ACEADD, for the determination of detachments and flaws in paintings [5]. The purpose of the author is to analyse a specific technology while attempting some general reflections regarding

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the transfer of innovative instruments to the end users, conservator scientists and other professionals of the cultural heritage field.

Indeed in all countries there are centres of excellence, where a fruitful synergy between all the actors of the cultural heritage value chain supports the innovation process, but there are also substantial differences in the adoption of best practices from region to region.

A brief description of the acoustical method is provided and the overall experience is reviewed from the laboratory validation to the field experimentation, with the study of the range of applicability, some metrological aspects and the integration of innovative elements in the measuring system. For each of these topics, few fundamental key factors will be highlighted for a more systematic approach to innovation. It is worthwhile to note that most of the scientific results, related to specific steps of this experience, can be found in literature thus they are simply mentioned, while their meaning is recalled since the proposed general considerations are formulated on this amount of knowledge.

Experimental method

To extensively characterize complex and heterogeneous structures such as mural paintings on site, an experimental method and the relative device were purposely implemented at the Institute of Acoustics and Sensors “O. M. Corbino” (CNR_IDASC). The method reveals detachments in multilayer structures composed of a substrate, few preparatory layers and the painted film, such as frescoes. This class of decay is due to the quality of the materials used in the preparation, as well as to the environmental conditions in which the artwork is placed.

Acoustically speaking, a detachment is a sub-surface air cavity beneath a superficial layer which behaves as a selective acoustic absorber, vibrating at specific frequencies when it is excited by an external pressure field. A physical model is a *mass - air spring* system, where the mass M is concentrated in the superficial layer and the spring rigidity k_{air} is that of the air volume in the cavity, whose fundamental resonance occurs at

$$f_0 = (1/2\pi)\sqrt{k_{air}/M} = (c_0/2\pi)\sqrt{\rho_0/(\rho_S td)} \quad (1)$$

with ρ_0 the density of air (1.292 kg/m^3), ρ_s and t the surface layer’s density and thickness, and d the air cavity depth.

The method reveals the presence of these cavities by measuring the acoustic absorption coefficient, using a non-contact setup. The device automatically scans an area, radiating towards the surface an acoustic wave with audible frequency content, and it records both the incident wave $p_i(t)$ and the reflected wave $p_r(t)$, constituting the composite pressure signal p(t)

$$p(t) = p_i(t) + p_r(t) = p_i(t) + k_r p_i(t) * h_s(t-\tau), \quad (2)$$

where k_r is a geometrical factor accounting for the beam spreading and the different paths between incident and reflected waves, and $h_S(t-\tau)$ is the impulse response of the surface under investigation. The Cepstrum algorithm is applied to p(t), thus obtaining the Cepstrum trace

$$C(t) = C_i(t) + k_r h_s(t-\tau) + \text{higher order terms} \quad (3)$$

from which the impulse response $h_S(t-\tau)$ of the analysed portion of the surface is extracted. After Fourier transform of the impulse response, $H_s(\omega)$, the reflection coefficient $r(\omega)$ and the absorption coefficient $\alpha(\omega)$ are calculated

$$r(\omega) = (1/k_r^2)\left(|P_r(\omega)|^2 / |P_i(\omega)|^2\right) = |H_s(\omega)|^2 \quad \text{and} \quad \alpha(\omega) = 1 - r(\omega). \quad (4)$$

At a first level of analysis, for each point the results are expressed in terms of the total reflected energy Σi (for the i-th point)

$$\Sigma_i = \int_{TimeWin} |h(t-\tau)|^2 dt \quad (5)$$

where the integration is over a suitable time window as wide as the value τ. The results are also expressed in terms of the absorbed energy percentage ABS%i with respect to the most reflecting point over the entire analysed area

$$ABS\%_i = (\Sigma_R - \Sigma_i)/\Sigma_R \quad (6)$$

For a deeper understanding of the deterioration degree a frequency analysis is required, where for each point the indicators are extracted as functions of frequency. This can provide indications about further details such as the size of the detached areas.

Finally the technique provides acoustic absorption profiles or maps, localizing the defects where the absorption coefficient is considerably high [5-7].

Results and Discussions

The way a new technology goes from the laboratory to field experimentation is not a straight way, not a linear process. The laboratory activity and the field experimentation are usually two parallel contexts, giving value to one another: the outcomes of one constitute the input elements of the other.

In our case, firstly the laboratory validation of the method was functional to the patenting process, afterwards the activity was oriented to field validation facing different experimentations. Mainly it was focused on the optimization of the measurement setup and procedure, the automation and software customization for data acquisition and processing, and the device portability [5-7]. The investigations have examined the applicability to different kinds of artefacts, ranging from frescoes to glazed ceramic tiles and to panel paintings, while the spatial resolution was recently improved employing a last generation and highly directive sound source. Some important metrological aspects such as the repeatability of measurements, the evaluation of the uncertainty and the device calibration procedure were carefully analyzed, gathering evidences for facing a potential standardization process [8-13]. A schematic view of the ACEADD history is shown (Fig. 1).

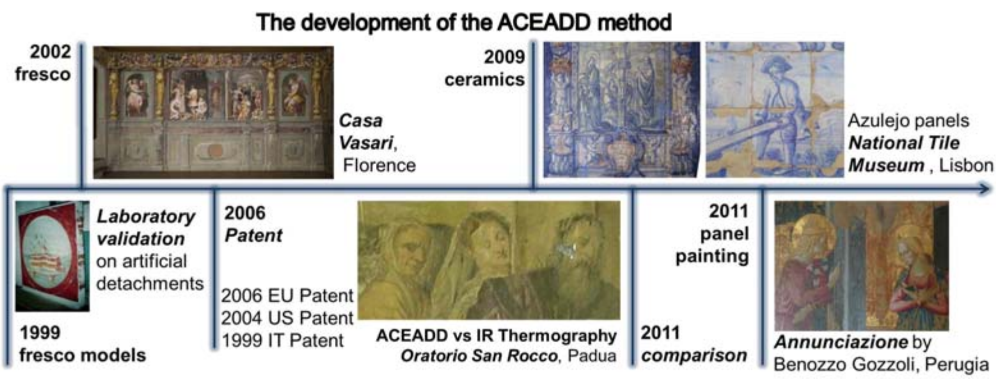

Fig. 1. Principal experimentations in the ACEADD history.

Validation

The first important phase regarded the validation of the experimental method, starting from laboratory tests carried out on three laboratory models, properly realized by the Opificio delle Pietre Dure (Florence), with a number of artificial detachments [5, 6]. The project was funded by the CNR in the framework of the Finalized Project Cultural Heritage. A basic configuration of the device was identified, and also a feasible setting for the measurement (Fig. 2). The laboratory tests gave information about the significant frequency range, the suitable physical model representing detachments, the measuring procedure, and an initial approach to data analysis based on relative measurements with respect to the most reflecting points.

Fig. 2. Advancements in the configuration of the ACEADD system: a – the initial system setup with manual motion of the transceiver unit, during the method laboratory validation (1998-2001); b – part of the 2D automatic system in front of a laboratory model of frescoed surface with detachments; c – transceiver unit with a full range acoustic source and an omnidirectional receiver (2002-2011); d – transceiver unit with a highly directional loudspeaker and an omnidirectional receiver mounted on the linear scan unit (2011-present).

These advancements were oriented towards the first field experimentation, realized in the little Church of Santa Passera in Rome, dedicated to Abba Cyrus [7]. The building presents a hypogeous crypt (II – III a.C.), a lower level church (V a.C.), and an upper level church (XIII a.C.). The measurements were carried out in the upper level church on the medieval frescoes of the apse. The kind of acoustical response obtained from real frescoes was investigated. A very rudimental and basic system with manual motion was employed, though showing a suitable portability for in situ measurements (Fig. 3). The integration with results from laser vibrometry helped us to investigate the resonance frequency range of real detachments, confirming that in the audible range lies a great number of cases. Thus the first 2D acoustic images of real frescoes were realized, indicating the relation between the absorption indicators, previously selected, and the degree of deterioration revealed. In particular a variation of the absorption percentage below

30% was observed also over an undamaged area, thus suggesting that critical zone has to be correlated to higher values. This occurrence was noted both on laboratory models, on reference surface, and on real artefacts.

Fig. 3. Different configurations of the ACEADD system during on site experimentations: a – first in situ validation in the little Church of Santa Passera (Rome, 2001), b – the automated system during the analysis of the frescoes in Oratorio of San Rocco (Padua, 2011), c – in situ investigation of azulejo panels in the National Tile Museum (Lisbon, 2009), d and e – the device during the diagnostic tests of two panel paintings (Perugia and Genua, 2011-2013).

Attempting some general reflections, it can be stated that since the very initial stages the most significant elements resided in the availability of realistic laboratory models properly realized by professional, and in an effective link to the territory with its peculiar patrimony. Indeed the accessibility of the cultural patrimony to field experimentation is a way of accomplishing its valorisation; from this point of view the cultural heritage of minor importance can either play a fundamental role, although it needs to be integrated into a system. Furthermore, when a territory with its patrimony is effectively connected to the technological capabilities and the professionals of the cultural heritage domain, that territorial system represents a basic model of Large Scale Facility.

The prototype

Basing on the experience of these initial stages, new advancements led to the development of the laboratory prototype; in particular great efforts were done in the automation of the measuring system, two different scan units were conceived for 2D scan and for linear scan; the transceiver unit was also realized using a standard full range loudspeaker and an omnidirectional microphone, finally a custom software package was developed in LabView environment. The procedure for wide area scan was optimized by means of multiple maps composition, including the choice of the reference point in order to correctly provide the indicator ABS% expressed in Eq. (5).

The improved system was effectively employed in a joint study in the Main Hall of Casa Vasari (mid XVI century), located in Borgo Santa Croce in Florence. This study saw the participation of a number of different research teams, most of them providing innovative technologies developed during the above mentioned Finalized Project, and testing them in a joint environment. In our case the improved system, equipped with the automated linear scan unit, allowed to realize a wide 2D acoustic map (1m×2m) of the Architect Angel. The comparison between the acoustic imaging results and the traditional visual inspection of the restorers proved a good agreement between the two analyses. This evidence led the author to adopt a way to display the data for helping the restorers in the interpretation of the results. Indeed the superposition of the acoustic map over the painting's image resulted quite effective when only the absorption percentage higher than significant thresholds are visualized. Basing on previous knowledge together with the outcomes of this study, two thresholds at 40% and 60% were chosen. The first level discriminates the typical variability of the indicator in an undamaged artefact (ABS% well below 30%) from an absorption corresponding to an early stage damage or a region next to a more serious defect; the second threshold, 60%, is related to more critical areas [7, 8].

From a generalized point of view, an added value must be recognized to those multidisciplinary contexts where a number of innovative technologies are applied on site in the same place. Thus cultural heritage can be seen as a joint laboratory of inestimable value shared by many teams, where coordination, comparison and integration can produce highly innovative actions in the conservation science domain. To a wider extent this vision feeds the fundamental attitude for sharing places, sharing instruments, sharing data, sharing knowledge.

The range of applicability

A new improved version of the software package was at this stage implemented: a general purpose software integrates different kind of measurements in the automated motion, including a sequence of preliminary tests and the standard acoustic measurements for the in situ investigation. Concerning the interpretation of data, three levels of analysis were purposely studied: the first level of analysis includes the determination of the degree of homogeneity of the acoustic response; the second level is based on the interpretation of the 2D acoustic maps; finally the third level is based on the determination of the absorption indicator as a function of frequency. Furthermore a first approach to the repeatability and uncertainty evaluation was set. This phase was oriented to the assessment of the applicability of the ACEADD method to other multilayer structures such as glazed ceramics.

This objective was accomplished thank to a collaboration with the Laboratório Nacional de Engenharia Civil (LNEC, Portugal), carrying out on site tests in the Madre de Deus Convent (XVI century), hosting the Museu Nacional do Azulejo. The investigation allowed an insight into the effect of different deterioration phenomena such as tiles detachment from the wall, using the low frequency range (100Hz – 10kHz), and the glaze delamination, using the high frequency range (5kHz – 15kHz). The employment of the two frequency ranges for discriminating the size and the kind of the damage was found very effective, so that it was successively used in frescoes and especially in panel paintings. The results were useful for the assessment of the validity of the method for this kind of artefacts, and for an estimation of the sensitivity of the method to the depth of the air cavity [10, 11]. For glaze delamination, in particular, few resonance frequencies clearly emerged in some specific areas of the analysed azulejo panel, the most evident ones occurring at about 12kHz. By means of equation (1) an evaluation of cavity depth from resonance frequency values was possible: assuming a density of $7.25E+3 kg/m^3$ and a thickness of 3.00E-4m for the glaze layer as a representative example for the panels under investigation, derived from a study of the characteristic properties of a great number of historical tiles, the evaluated cavity depth resulted about 15μm. This data indicates the ability of the method to detect cavities as thin as tens of μm, but further investigation including a great number of cases and models will provide clearer evidences of this instrumental capability.

In general, it can be stated that a museum can represent an accessible experimentation space of particular importance. The cultural patrimony is the attraction point where all the actors of the cultural heritage domain may converge and effectively interact. Hence it has a huge attractive potential for the consolidation of the Cultural Heritage Value Chain (CHVC); this means that the privileged place where the CHVC may be strengthened is inside and around the cultural patrimony.

Metrological aspects

Great efforts were done for the improvement of the measuring procedure, whose fundamental steps are listed in Table 1.

Table 1. The ACEADD measuring procedure.

ACEADD Protocol & Operating Procedure	
Test	**Function under test**
System functionality	Scan unit
	Acoustic source and transmission line
	Microphone and receiving line
Preliminary tests	Microphone calibration
	Acoustic source Frequency Response at working distance
	Environmental NOISE characterization
	Direct signal spectral analysis
	Cepstral background evaluation
	Identification of the area of analysis
	System alignment & Reference Points
	Repeatability test
ACEADD measurement	Scans
	Acoustic images

The above procedure and the data analysis take advantage of some important metrological aspects. In particular the repeatability test, based on four independent repetitions of few selected profiles, guarantees that the results are accurate and helps their interpretation. The repeatability condition of measurements is indeed defined as that condition including the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time. The maximum standard deviation σ_{max} of the values of the measured indicators, obtained from these four repetitions, provides an estimation of the uncertainty of measurement, so that two acoustic responses, which differ less than this σ_{max}, must be considered equivalent. This information is very important when the differences between the absorption percentages has to be classified as significant or negligible. Another important aspect is related to the calibration of the measuring system; this procedure can be realized using reference materials with known sound absorption properties, otherwise with synthetic impulse response. The scope of this phase is to gather evidences for a potential standardization process.

Another important metrological characteristic of new technologies is the comparison with different methods measuring the same physical quantity or revealing the same phenomenon. This problem was studied thank to a collaboration with the Institute of Inorganic Chemistry and of the Surface of CNR (ICIS) and the Construction Technology Institute of CNR (ITC), carrying out a comparative analysis on the same frescoes between the acoustic technique and the IR Thermography [12]. The investigated frescoes were two painted surfaces in the upper hall of the Oratorio of San Rocco in Padua, during the restoration project. One area OSR1, mainly containing thick detachments, was analysed by means of a low frequency sound wave (100 Hz – 10 kHz), and a second area OSR2, containing thinner delaminations of the pictorial film using a higher frequency sound wave (4 kHz – 15 kHz). An example of the heterogeneity evaluation on the two maps is here reported (Fig. 4). The thermographic investigation was carried out using an IR camera FLIR SC660 (640 × 480 thermal pixel) with a 0.05 K sensitivity, and a FLIR SC3000 (320 × 240 thermal pixel) with 0.02 K sensitivity. The IR thermograms, obtained with two different heating procedures, were analysed by means of the Principal Component Analysis (PCA), applied to thermograms of both the heating and cooling phase, and the Pulsed Phase Thermography (PPT), separating the amplitude and phase components of the dynamic thermal response Fourier Transform. Evidences emerged indicating a good agreement between the acoustic and the thermographic methods when fine details are studied, employing the high frequency range and a small spacing between adjacent points in the resulting matrix, for example 1 cm. The results were also compared with the restorers investigations, based on the traditional manual inspection: this last indicated the most deteriorated areas where the ACEADD system revealed sound absorption ABS% greater than 60%. Finer details revealed by both methods were not found during the restorers' traditional investigation, indicating a wider sensitivity to defects of the instrumental methods [12].

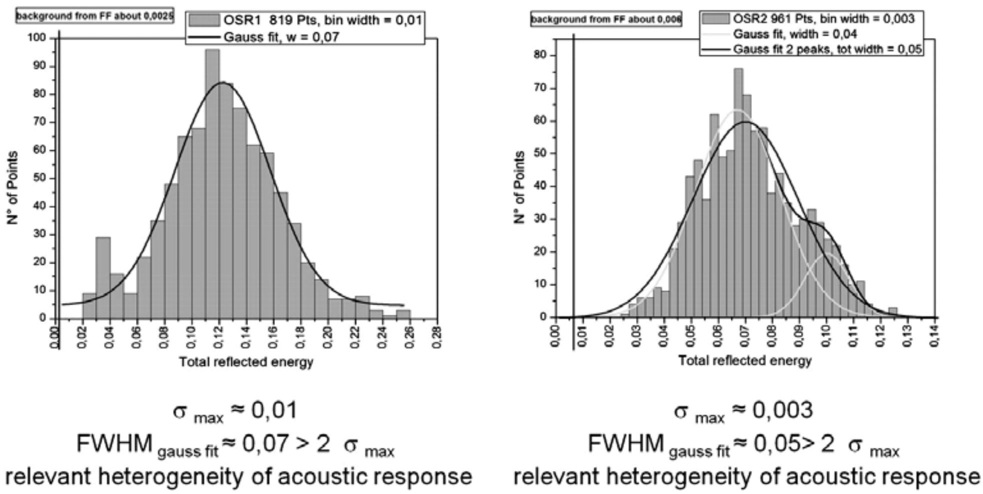

Fig. 4. Histogram of the acoustic response of the two maps OSR1 and OSR2, for the heterogeneity evaluation. The dispersion of the total reflection indicator, derived from the FWHM of the Gaussian fit, is compared with the uncertainty of measurement, σ_{max}, obtained from the repeatability test.

A participated experimentation, merging the expertise of restorers – conservation scientists – developers, leads a restoration yard to become an accessible experimentation space. To a growing attention and increasing requirements in the reliability and standardization of methods, from the professionals of this sector, the response of the scientists must be based on the principles of scientific metrology, to guarantee the quality of the methodologies and of the results.

Innovative elements

A recent important improvement of the measuring apparatus was the integration of a new generation acoustic source, a parametric loudspeaker or parametric array, which combines a high directivity with a small size. The parametric array emits ultrasonic waves in air generating audio frequencies in the medium because of the nonlinear propagation. In particular the source used in this study operates in the so called self-demodulation regime, i.e. the emitter generates an ultrasound carrier frequency primary beam f_c, with low audio frequency amplitude modulation, at f_0,. The nonlinear propagation distorts the wave so that at a certain distance only the audio modulation persists. The high interest in the parametric array in air is in the production of audio frequency waves, having a directivity pattern as narrow as the generating ultrasonic waves without their side lobes. Therefore a highly directive audio frequency source is obtained with smaller size than one directly emitting f_0. This class of sources is an attractive investigation tool for non-destructive testing (NDT), even if they were not conceived for such purposes but to provide localized sound in public places or exhibition spaces. Innovative applications mainly in the field of material's characterization are recently emerging. The motivation of this choice is to enhance the spatial resolution and improve the signal to noise ratio SNR of the ACEADD system. The laboratory activity was focused on the characterization of the pressure field of a commercial parametric array, the Audio Spotlight by Holosonics with custom size 8". Due to its size, smaller than the standard product, the characteristic frequency response, the acoustic pressure field, the beam aperture have firstly been determined before integrating the new acoustic source into the measuring system. This project was funded by the Department of Production Systems of C.N.R. in the framework of an industrial research initiative.

Among the first applications of a parametric array in air for NDT, a study of a renaissance panel painting the *Annunciazione*, by Benozzo Gozzoli, was carried out. The peculiarity of this study involves two distinctive facts: for the first time a parametric loudspeaker was used as excitation source in a diagnostic tool, the ACEADD system, on heritage objects; moreover, for the first time the acoustic imaging technique was applied to a panel painting [13]. The experimentation took place in the C.B.C. restoration laboratory at the end of the restoration work; thus the amount of knowledge regarding the painting acquired during restoration oriented the realization of the acoustic measurements and the successive results interpretation, in order to assess the technique applicability to panel paintings. For this study a high frequency wave 4 – 15kHz was selected, cutting off the characteristic vibration frequency of the substrate, trying to excite possible delaminations of the superficial layer. The analysis was restricted to two profiles, L1 and L2 with 109 points, carrying out the repeatability test and gaining precious information about the variability of the acoustic response with respect to the estimated uncertainty of measurements. This approach was preferred to a wider investigation but with less information on the quality of the data, in order to provide the results with a known degree of accuracy. It was observed that some areas, which underwent heavy consolidation work, still presented relevant absorption percentage, up to 47% for L1 and to 63% for L2 (Fig. 5). The two profiles were also compared with a third profile, of equal extension, acquired in laboratory on a homogeneous and highly reflecting reference surface Ref L, clearly showing absorption percentage below 25% (Fig. 6). The presence of significant absorption areas may indicate some residual effects of previous detachments, also due to the elastic properties of materials used for consolidation. Regarding the indicator Σ, the dispersion of values found in Ref L reaches 5.8%, indicating the response of a uniform material, while in L1 it resulted equal to 13.7% and in L2 as high as 21.7%, with a maximum relative uncertainty of 10%. The results confirm the localization of critical areas where the indicator ABS% exceeds 40%, even when a residual effects of detachments remains; furthermore visible highly reflecting areas lays near the panel's junctions, which means that also the status of the junctions might be evaluated. Actually this last point needs more evidences to be confirmed as general statement for panel paintings' diagnostics.

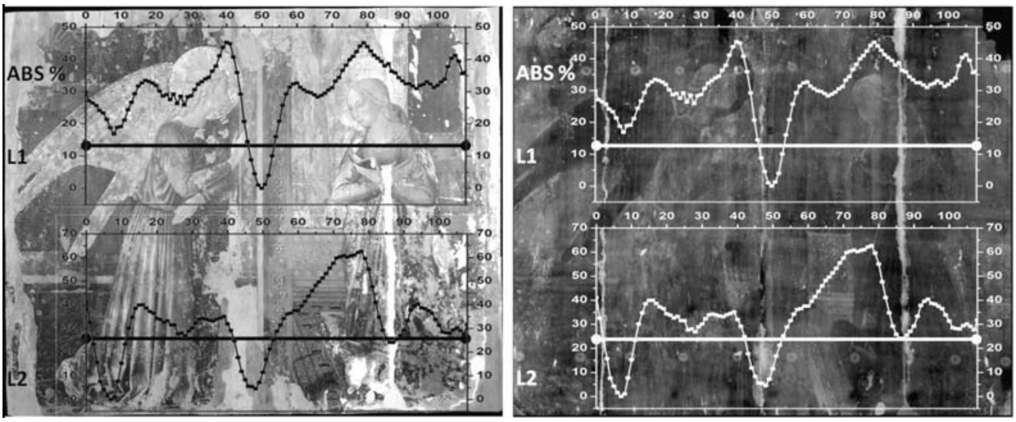

Fig. 5. Acoustic absorption profiles overlaid on the image of the painting (left), and on its X-radiograph (right).

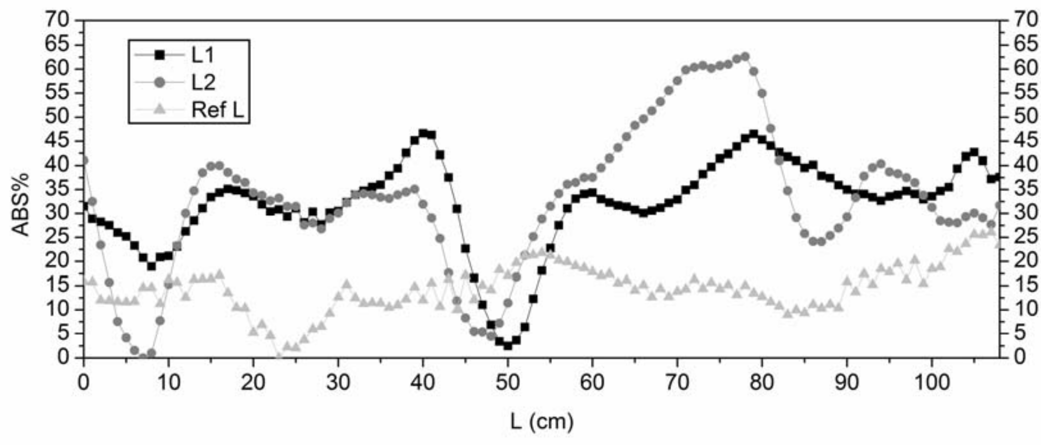

Fig. 6. Comparison between the L1 and L2 profiles and the reference profile Ref L, obtained on a highly reflecting surface.

As a general rule, a constant attention towards innovative solutions in any scientific and technological field, with a basic approach crossing different applicative fields discloses high potential in terms of innovation. It is worthwhile to note that, often tackling challenges due to the extreme measuring and operative conditions, conservation science can lead to innovative insights also in other fields of science. Thus an effective Cultural Heritage – driven development in science and technology can be thought as reliable.

Conclusions

The overall experience in the development of the acoustic imaging technique, ACEADD, has been re-examined in its historical progress in order to reflect on some common key factors enhancing the attitude towards innovation in conservation science.
The following points resulted fundamental in our particular case and, since they were found to be consistent with other researchers' experience, the author wishes to propose them as a little set of good practices:

- an effective link between the technological capabilities and the territory builds the territorial system;
- a joint and accessible environment for field experimentation contributes to build the sharing attitude among professionals of the field;
- a systematic, extensive and participated field experimentation discloses its potential in building the Cultural Heritage Value Chain;
- a plan of significant comparisons between different methodologies, and a suitable metrological approach are the bases for assessing the reliability of new methods on solid principles;
- a constant attention towards the improvements of the measuring procedure and towards technological innovations, also in other fields of science, contributes to build the transversal approach to innovation;
- finally, opening the cultural patrimony to a systematic flow of experimental activities, so that it becomes a laboratory for a synergic and integrated approach to conservation science, has an enormous potential particularly when it is seen as a Large and Distributed Research Infrastructure.

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