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# Advances in Microgeophysics for Engineering and Cultural Heritage

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**ABSTRACT: A large number of unconventional investigations have been implemented, tested, and validated in the field of microgeophysics, with the aim being to solve specific diagnostic and/or monitoring problems regarding civil engineering and cultural heritage studies. The investigations were carried out using different tomographic 2D and 3D approaches as well as different energy sources, namely sonic, ultrasonic and electromagnetic (radar) waves, electric potential fields, and infrared thermography. Many efforts have been made to modify instruments and procedures in order to improve the resolution of the surveys as well as to greatly reduce the time of the measurements without any loss of information. The main new methodologies here discussed are the sonic imprint, the global tomographic traveltime, the electrical resistivity tomography, and the control of external films (patinas) grown on stone monuments. The results seem to be very promising and suggest that it is the moment to dedicate time and effort to this new branch of geophysics, so that these methodologies can be used even more to diagnose, monitor, and safeguard not only engineering buildings and large structures but also ancient monuments and cultural artifacts, like pottery, statues, etc..**
**KEY WORDS: microgeophysics, engineering, cultural heritage, tomography, electrical, sonic, ultrasonic, ground penetrating radar (GPR).**

## INTRODUCTION

Microgeophysics, one of the most recent fields of geophysics, includes all the methodologies derived from geophysics and applied, with more or less miniaturized instrumentations, to small soil or masonry volumes, or even to simple artifacts such as statues, pottery, corbels, etc.. Microgeophysics was born following the miniaturization of geophysical instrumentation (mainly transducers), so that they could be adapted to small-scale and very small-scale applications. Indeed, the first attempts were carried out in the 1950s, when some researchers started to use physical models on a small scale to evaluate the new possibilities offered by some geophysical methods. In fact, at that time personal computers had still not been developed, so a lot of the problems encountered in the field of geophysics were simply solved by using physical models on a small scale rather than mathematical models. Such physical models were often built in appropriate tanks or, more rarely, in small pieces of subsoil. Furthermore, these kinds of studies did not allow researchers to obtain models with high-resolution details, thereby necessitating a great deal of collateral investigation over the years. However, this in turn contributed to the improvement of the studies and tests on small objects and, indubitably, to the birth of this new branch of geophysics. Moreover, the arri-

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val of digitization opened the path both to the simultaneous sampling of a large number of channels (multi-channel instruments) and to fast processing and interpretation by means of computers driven by extremely complicated software.

However, recent microgeophysics is an expanding field: major demands come from conservation and restoration in the fields of civil engineering and management of ancient monuments and cultural heritage artifacts, the science of materials being also a growing source of incentives and suggestions. This is especially true as far as works of art are concerned, where the choice of methodology has been greatly influenced by the non-invasive characteristics of the methodologies in question. In fact, microscopic methodologies that damage very small volumes provide a lot of information, but may turn out not to be representative, whereas geo-technical macroscopic methodologies involving large volumes are generally more or less destructive. Consequently, over the last 30 years many different types of investigation have been implemented, often derived from other fields of study, for instance, the electrical resistivity tomography for stone columns, which derives from medical diagnostics. Furthermore, these methods are non-invasive processes and are characterized by an in situ resolution power that can be defined between microscopic and macroscopic investigations, ranging from a few centimeters to a few decimeters, i.e., useful for artifacts having dimensions from a few cubic decimeters to a few cubic meters. Therefore, applied geophysics, if miniaturized, can well cover these kinds of small-sized targets (artifacts, columns, pillars, pottery, statues, museum objects, etc.), provided that a variety of different methodologies are used to evaluate the physical and chemical properties, sometimes also including biological aspects.

Microgeophysics is mainly applied to structures of civil engineering and to ancient monuments. The word “geo” is still present even though the investigated targets are not only sculptured rocks, but also include metallic, vitreous, ceramic, and even wooden artifacts. The main peculiarity of these investigations, compared with those of classical applied geophysics, is that the objects to be inspected generally offer more than one face, which can be looked into by injecting the necessary energy and by positioning the required external and/or internal probes in every point of the object.

One of the main technical problems encountered by microgeophysics is related to the miniaturization of all the transducers, both transmitters and receivers. Obviously, there are some important differences regarding the methodology to be used, i.e., potential fields (principally the electric fields) or wave fields, either mechanical or electromagnetic. Furthermore, if wave fields are used, the resolution required by microgeophysics generally demands the use of higher frequencies, in spite of the smaller waves' penetration depth. In fact, a compromise, if possible, should be made between the increase in the resolution and the decrease in the penetration depth. On the contrary, if lower frequencies are to be used to obtain a higher penetration depth, diffracted waves can be used to study small targets; however, the analysis of diffracted waves is complicated and represents an emerging field of microgeophysics.

Nowadays, the best utilization of microgeophysics is made when using tomographic techniques, both with potential and wave fields. These methodologies require the acquisition of a large amount of data, so multi-channel instruments are generally required.

## METHODOLOGIES USED BY MICROGEOPHYSICS AND SOME PRACTICAL UNCONVENTIONAL APPLICATIONS

The methodologies used most frequently to make diagnoses in the fields of civil engineering and cultural heritage (both monumental and movable units) are the following.

(1) Multi-channel Electric Resistivity Tomography (ERT), both in active and passive (self-potential) modes. These tomographies are generally carried out with one (or more) 2D acquisition arrays and sometimes numerous 2D profiles are simultaneously inverted in a 3D form. The “full 3D” ERT generally gives excellent results but it requires a lot of time to be carried out unless some practical ploy is tried to avoid this inconvenience (e.g., Fiandaca and Cosentino, 2008).

(2) Sonic and ultrasonic multi-channel tomography. These tomographic surveys are often carried out

with a 2D array, for instance, along longitudinal or transverse sections of columns or thin sheets, walls, etc.. Sometimes many 2D tomographic profiles are arranged to construct a 3D model. The “full 3D” sonic or ultrasonic tomographies are especially devoted to the internal study of artifacts (e.g., Gambardella et al., 2008).

(3) Electromagnetic tomography [ground penetrating radar (GPR), X ray, and nuclear magnetic resonance (NMR)]. In reality, these types of tomographies are quite different from each other, even though the main difference between GPR and X ray is the frequency of the waves used. NMR only works if there is some water in the investigated artifact. Electromagnetic inductive instruments are also used to inspect the inner parts of the artifacts in order to locate metallic inserts.

(4) Infrared (IR) thermography can be performed both in active (i.e., with artificial cooling or heating of the artifact under investigation) and passive modes (i.e., by taking advantage of natural heating by the sun).

(5) Acoustic emission (AE), both in the sonic and ultrasonic bands.

Some of these methodologies (e.g., NMR and AE) are still under study, at least as far as the previously mentioned purposes are concerned, because suitable instruments have not been created by geophysical companies. On the other hand, instruments useful for the other mentioned methodologies are easy to find, as they are already being used by some researchers working on the diagnostics of stone and/or comparable materials. Recently, we tested AE to study calcarenite samples during crack test, but the first results are not yet clear to be presented here.

Of the various case histories in this field, we focus our attention on unconventional applications that are able to reveal some very useful details and to address further interesting developments. In particular, we will illustrate some procedures that aim to detect both thin and very thin layers, as well as heterogeneities (not only pieces of iron, steel, brass, wood, but also humidity, change of lithology, fossils, voids, etc.) in relatively small stone artifacts such as statues, columns, balcony corbels, or other overhanging artifacts.

## ERT CARRIED OUT USING MULTI-CHANNEL INSTRUMENTS

Numerous 2D and 3D electrical tomographic surveys were conducted, mainly on walls and floors, using direct electric current. The acquired data were interpreted with the help of both fast back-projection inversion software (Martorana and Cosentino, 2005; Cosentino et al., 1998) and/or a 2D and 3D complete inversion procedure (software Res2Dinv, Res3Dinv, Loke and Barker, 1996). An unconventional type of electrical tomography was also tested on elongated stone structures (columns) having a circular or polygonal section (Cosentino et al., 2003). We used a 256-channel instrument (MRS256) developed by GF Instruments for all the surveys; it has input impedances higher than 10 GΩ for all channels. Today, an even larger number of channels are offered by the instrument MORE3D (each module containing up to 512 channels) developed by Diasis, which is indeed very flexible and extremely fast.

A technical problem affecting the measurements was caused by the contact resistances of the potential electrodes. In fact, we needed small-sized electrodes with limited but similar (i.e., to each other) contact resistances. When the electrodes are to be put in roughly vertical or upside down positions (i.e., walls, columns, ceilings, etc.), a good solution to the problem is offered by disposable electrocardiogram electrodes (with a diameter of about 1 cm) provided with external adhesive strips. A lot of enterprises around the world produce these kinds of electrodes, but of the ones we tested the best were those in Foam Ag/AgCl (adult type F 9047 manufactured by FIAB). This is because it is very important that the contact resistances (i.e., generally high, but very different from one type of electrode to another) remain more or less stable for the normal period of location on the wall or floor or body, which can be up to 100 to 150 min, depending upon the number of electrodes and the type of object being studied. The final typical values of contact impedances range from 0.1 to 100 MΩ depending on the investigated lithotype and the treatment of its exposed surface. Obviously, these high contact impedances have to be suitably reduced in the current electrodes in order to inject a measurable current intensity. This means that it is a good rule to use only a few current electrodes, which should be suitably treated (salt water, conductive gel, etc.) to reduce contact resistance.

An interesting case history regards an ERT carried out on an ancient wall (about 1.5 m thick) covered by a mosaic (Fig. 1a) in the Fountain Room of the Zisa Palace in Palermo. The problem was due to the presence of moisture in the wall, which was ascribed to improbable water upwelling from the subsoil. The data were acquired, using the "Maximum Yield Grid" array (Fiandaca and Cosentino, 2008), on a part of the mosaic surface of the wall (2 m×3 m, filled with a regular grid of 176 EGC potential electrodes, as seen in Fig. 1b, and 15 current electrodes—very small nails—located in many points among the tesserae of the mosaic). The 3D inversion (Fig. 1c) produced a 3D resistivity model up to about 70 cm inside the wall (half its thickness), giving some surprising information regarding a significant water leakage (moisture giving a low-resistivity zone) located about 70 to 80 cm inside the wall. The leak was connected to an ancient, previously unknown pipe, which collected water from the roof of the monument.

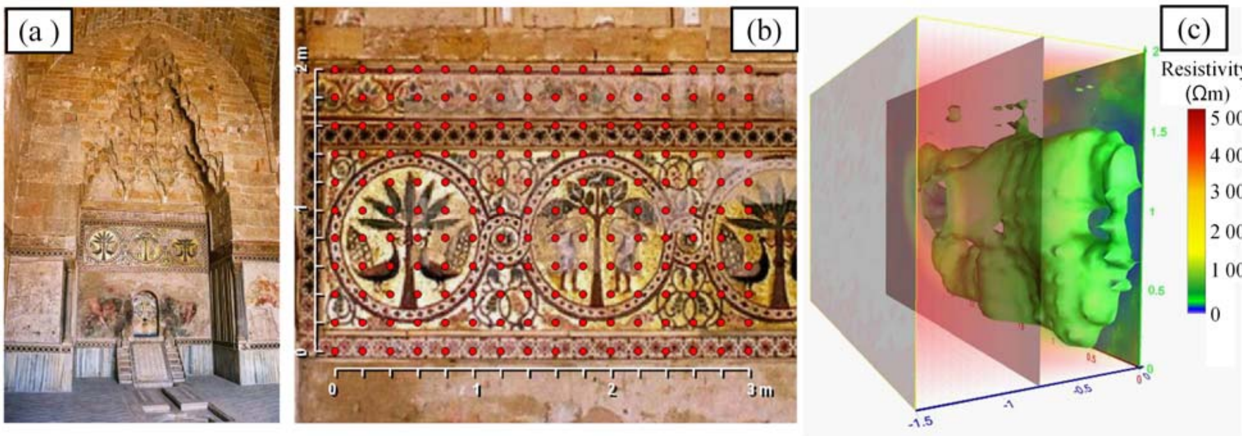


**Figure 1. (a) Frontal wall of the Fountain Room of the Arabian Zisa Palace in Palermo; (b) part of the investigated mosaic wall where the grid of 176 potential electrodes was applied (red points). The 15 nails used to inject the current were inserted in as many selected points along the small, mortar-filled spaces between the tesserae of the mosaic; (c) 3D inversion model of the acquired data observed from the back of the wall (1.5 m thick). Due to the size of the grid used (2 m×3 m), the inversion model is limited to 0.75 m of depth. All dimensions are in meters.**

**Sonic and Ultrasonic Multi-channel Tomography**

Sonic and ultrasonic tomographic methods are very important, because they provide values of velocity and damping of elastic waves, which are closely linked to the mechanical properties of the investigated samples. Consequently, they are of fundamental importance to the diagnostics of conservation and restoration of buildings, monuments, and artifacts.

Over the past decade we have only used "conventional" sonic 48-channel tomography, carried out on walls, columns, and floors using a seismograph Mark 8 (ABEM) with piezoelectric transducers manufactured by MURATA. However, we have recently gained new 16-channel ultrasonic equipment (manufactured by BOVIAR) with 55 kHz transducers. In fact, in ultrasonic tomography it is extremely important to be in possession of multi-channel equipment, as it allows you to avoid the displacements of the receiving transducers, thereby, minimizing the errors caused by the difference in matching between the transducers and the investigated sample.

A number of ultrasonic tomographic surveys were carried out with the aim of retrieving the mechanical properties of concrete, stone, wooden structures, etc.. The less conventional of these were those affected on particularly important statues that date back to ancient Greece and ancient Rome. In many cases they were restored a long time ago, so that little is now known of the restoration procedure, whereas this knowledge would be of fundamental importance to assure the best safety conditions during handling, transport, management, and conservation. We usually use ultrasonic multi-channel tomography, radar tomography, IR thermography (FLIR P40 thermal camera), and a very reliable covermeter (Elcometer Protovale 331 Model S) to check these artifacts. This last is very useful when studying some characteristics (i.e., position and dimensions) of metal (i.e., iron, steel or brass) inserts positioned by the sculptor or by the restorer during restoration. The integration of various methodologies increases the reliability of these non-invasive indirect examinations. For instance, metal inserts can also be detected by high-frequency radar profiles and/or a properly active thermography.

Ultrasonic profiles and tomographies are not only able to control the adhesion of eventual bond patches made of plastic or other natural or synthetic materials, but also to investigate how much a visible crack penetrates the body, constituting a critical point for safety conditions under static and dynamic stresses.

One of the most important ancient statues we have tested is located in Syracuse. It is the Grecian (or Roman copy?) “Venere Anadiomene” (Fig. 2a), a marble statue of human height. Figure 2c shows the 2D tomographic image acquired along the left arm (Fig. 2b). The picture on the right presents the inverted section, showing low velocity zones, typical of the degradation of the marble in that part of the statue. In fact the average velocity in the body of the statue is 6 000±180 m/s, characterizing a very “fast” saccharoid marble.

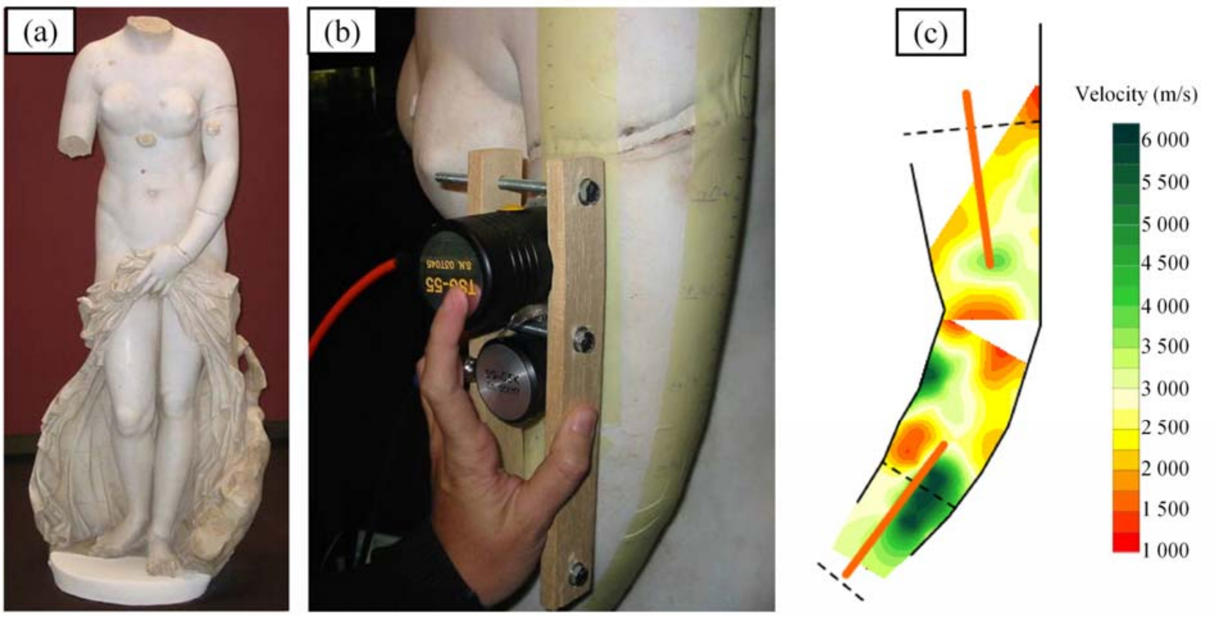


**Figure 2. The Venus statue (Museum P. Orsi, Syracuse, Italy) is presented in (a), part of the acquisition procedure (along the left arm) is presented in (b), while the 2D tomographic inversion obtained is presented in (c). The metallic inserts detected with the elcometer are also indicated.**

Recently, sonic and ultrasonic tomographies (Gambardella and Danesi, 2008) were carried out on the lower part of the broken statue called “Togato di Petrara” (1st century AD). The aim of the tomography was to control the state of the marble in the lower broken part and, eventually, to detect the “best” part of the marble, in order to locate the point where a steel junction-bar could be inserted that would connect it to the base of the statue. The data of the tomography were acquired in the lower part (about 50 cm) of the legs, using 96 probes placed along eight sub-parallel sections spaced 7 cm apart (Figs. 3a and 3b). The results of the tomography, presented in Fig. 3c, allowed the restorer to locate, very precisely, the point where the steel bars were to be inserted. The sequence of hard- and easy-drilling as well as the cores extracted during the drilling procedure confirmed the results of the tomography, with a tight correlation between higher velocity values and the consistency (stiffness) of the marble.

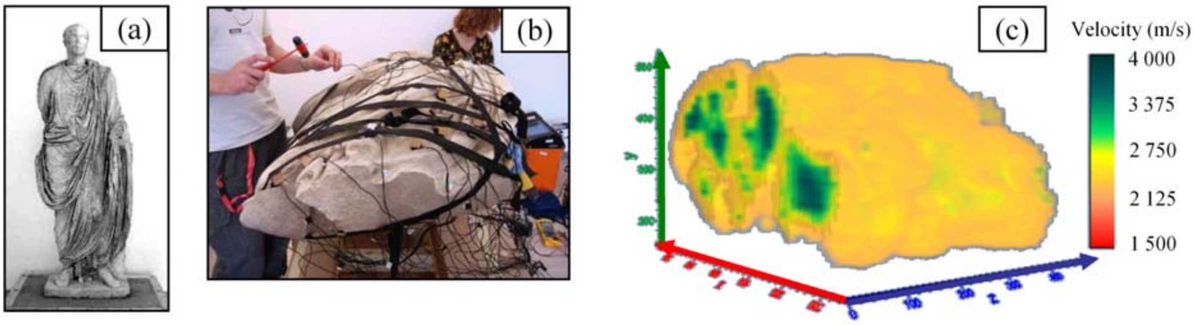


**Figure 3. (a) The Togato di Petrara (Museum of Locri, Italy), part of the acquisition procedure (lower part) is presented in (b), while the 3D tomographic inversion obtained is presented in (c). The steel rods were inserted in the green (high velocity) central areas of the base.**

**Sonic and Ultrasonic Global Tomographic Traveltime**

Having some formal analogies with refraction seismic methodology, global tomographic traveltime (GTT, patent pending) is a technique used to retrieve the characteristics of the external decayed layers of many artifacts. In fact, many stone artifacts (statues, bas-reliefs, friezes, etc.) have a more or less decayed external layer caused by many phenomena that accumulate over time. Starting with the sculptor's chisel and continuing with various agents such as adverse climate conditions (i.e., rain, wind, etc.), natural and/or artificial pollution as well as anthropogenic phenomena (i.e., carelessness, wrong treatment, incorrect social function, etc.), the list of possible destructive agents is very long. Even though the thickness of this layer and the level of decay are parameters that are useful when planning restoration and/or conservation, they are very difficult to evaluate without invasive or destructive techniques being applied to even very small samples of the artifacts. Furthermore, these techniques only take into consideration partial aspects of the decay phenomena (for instance, porosity, chemical composition, texture, micro-structural arrangement, etc.) which give little information about the mechanical resistance of the decayed layers.

As regards the various tests that can be applied to stone artifacts by means of ultrasonic analyses, GTT has been conceived as a 1D transformation of a 3D tomographic problem (i.e., a global tomography transformed in a simple traveltime problem, saving a lot of working time); it works very well, provided that the thickness and velocity of the external layer are regular in the entire artifact (pre-model). In this case, GTT is a fast and precise method capable of retrieving information on the thickness and P-wave velocity of the decayed external layer.

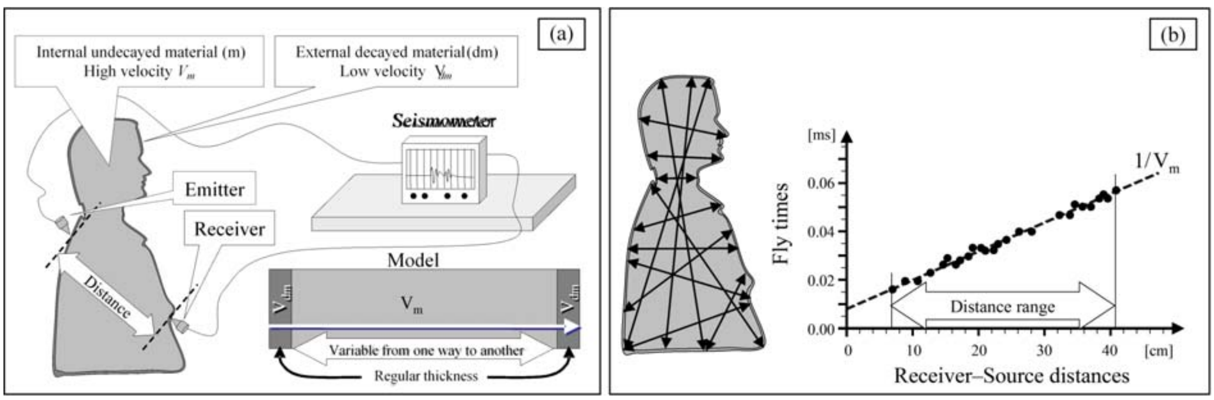


**Figure 4. The pre-model is shown in (a), i.e., the 1D transformation of the 3D tomographic analysis. (b) shows the "far" measurements carried out in any direction. They are plotted together, using only one distance axis. The distance range obviously depends on the shape and dimensions of the statue.**

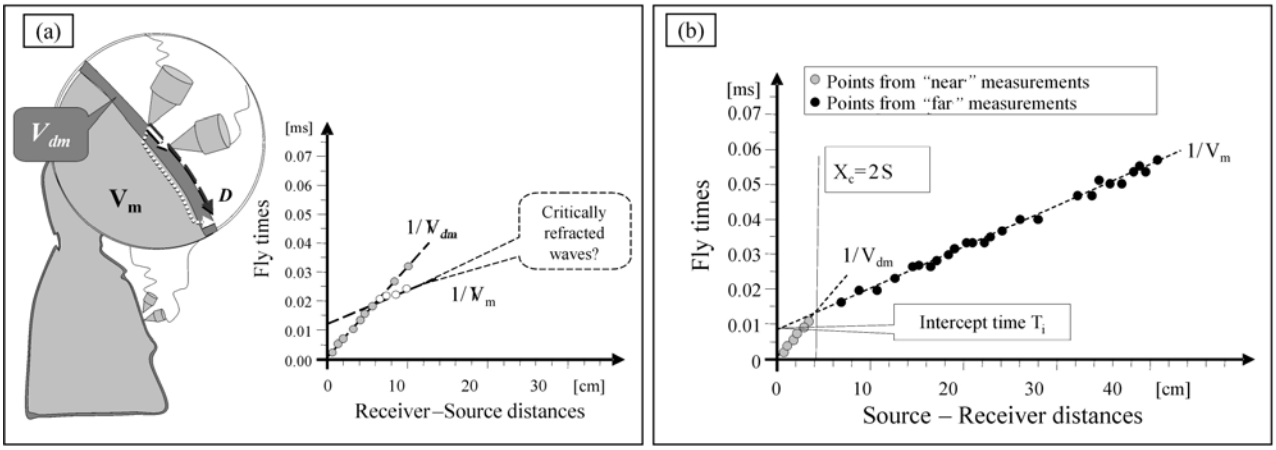


**Figure 5. The "near" measurements are shown in (a). The graph is similar to that of a two-layer seismic refraction profile with zero offset. Finally, the entire GTT is presented in (b). It has been drawn in such a way as to collect all the "far" and "near" measurements in only one traveltime. The assessment of thickness *S* and velocity $V_{dm}$ of the decayed layer is quite simple.**

GTT consists of carrying out a predisposed set of P-wave velocity measurements on the selected artifact using ultrasonic (but sometimes sonic) waves and of constructing a time-distance global graph (travel-time). For instance, the supposed pre-model (Fig. 4a) is characterized by a high internal velocity (typically 3 500–6 000 m/s, corresponding to good mechanical and elastic conditions) surrounded by a quite regular "slow" layer (the decayed layer, typically characterized by a velocity below 2 500 m/s).

It is advantageous to initially carry out a set of "far" measurements (transparency ray paths, Fig. 4b), for which the increasing ways correspond to increasing lengths traveled in the internal marble, which is at a higher velocity.

Afterwards, a set of measurements using small distances is carried out (Fig. 5a). These small distance ways are characterized by "direct" waves, because the critically refracted waves (head waves) are very difficult to produce and detect for small distances using normal low-energy ultrasonic transmitters.

The simple mathematical expression for the direct waves is the following

$$t_n = x/V_{dm} \tag{1}$$

where $t_n$ is the arrival time delay of these waves; $x$ is the distance between transmitter and receiver; and $V_{dm}$ is the velocity of the decayed external marble. Eventual arrivals, due to critically refracted waves (for distance, larger than 7–10 cm), are easily recognized and eliminated.

The transparency "far" ray paths should follow the following relation

$$t_f=(x-2S)/V_m+2S/V_{dm}=x/V_m+2S/V_{dm}-2S/V_m= x/V_m+2S(1/V_{dm}-1/V_m)=2S(V_m-V_{dm})/V_{dm}V_m+x/V_m \tag{2}$$

$V_m$ is the velocity of the internal marble and $S$ is the thickness (or mean thickness) of the decayed external layer. If $S$=0 (no decayed layer), the intercept time $T_i$ of the straight line (2), that is

$$T_i=2S(V_m-V_{dm})/V_{dm}V_m \tag{3}$$

should be equal to zero, so that the presence of a decayed layer is easily recognized by the value of this intercept time. It can be easily verified that $t_f=t_n$ (contact point of the two lines) at a distance $x=2S$.

The GTT graph is constructed (Fig. 5b) using all the collected data (far and near measurements). The whole set of data looks like a classic two-layer refraction seismic traveltime, but it is different in principle due to the unlike acquisition techniques and the consequent unlike physical meaning. In this traveltime graph, after the identification of straight sections obtained by means of a fitting procedure, some characteristics such as slopes and scattering of data, as well as the critical points of the traveltime (intercept and contact points) can be studied.

The following estimates, together with their confidence limits can be obtained from these data: the mean velocity of the P-waves in the inner part of the artifact (from the slope of $t_f$); the mean velocity of the P-waves in the decayed external layer (from the slope of $t_n$); the mean thickness of the decayed external layer (from the contact point); the space variability of the P-wave velocity in the inner part of the artifact (mainly from the standard deviation of $t_f$ data); the space variability of the P-wave velocity in the decayed external layer (mainly from the standard deviation of $t_n$ data); possible zones of anomalous thickness in the decayed external layer.

To date, GTT has been carried out on numerous marble statues (Cosentino et al., 2008), among them Eleonora d'Aragona and the Boy (Laurana), St. Michele Arcangelo (Gagini's apprentices), Venere Anadiomene, and Mozia's youth. The results were significant and in line with the historical vicissitudes of the statues, both known and presumed, as the changes were generally to be referred to the flawed conditions of the statues in question caused by possible decay. The GTT results regarding St. Michele Arcangelo (Fig. 6a) are presented in Figs. 6b and 6c: in this marble statue the velocity of the decayed layer was 2 300±200 m/s and its thickness *S* was 6±2 mm. The inner marble had a velocity of 5 620±140 m/s.

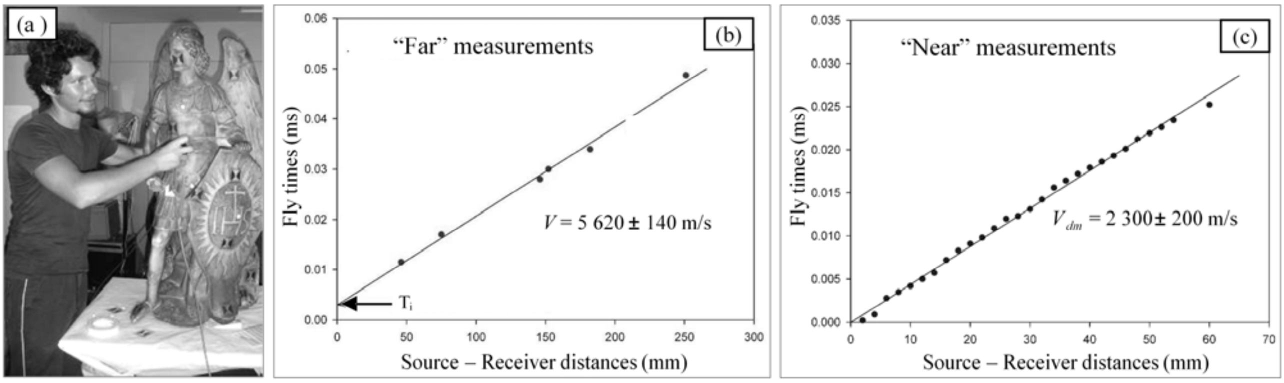


**Figure 6. Making measurements on the St. Michele Arcangelo statue (a) and the results obtained in (b) and (c).**

**The Sonic Imprint**

We have developed a new non-destructive investigation method that, in principle, has been derived from the studies affected in the fields of applied seismology, volcanic tremors, etc.. It aims at both identifying the artifacts and monitoring their integrity. The precious artifacts that can be submitted to this method are those made of "rigid" materials, like pottery, statues, and objects crafted in stone, metal and glass and some "hard" organic materials like bone, ivory, or wood. This study answers the ever more urgent requirement of art collection cataloguing that not only needs to be able to identify artifacts without a shadow of a doubt, but also needs to establish their integrity. In fact, over the past few years, there has been a trend in cultural heritage management towards loaning precious artifacts, both on a national and an international basis. These artifacts are therefore subject to transport stress and other connected risks (i.e., damage, substitution, physical deterioration, etc.). Furthermore, a lot of art exhibitions nowadays are itinerant, therefore, the artifacts are continuously subject to transport and/or displacement.

The general characteristics that identify an object, such as shape, dimension, aspect and texture of the surface, colors of the surface, etc., can easily be cloned using laser technologies; in fact, it is possible to obtain quasi-perfect copies of an artifact. On the contrary, it is almost impossible to clone other physical parameters based on internal properties (i.e., chemical composition, atomic structure, internal defects, etc.) such as the distribution of resistivity, permittivity, dielectric constant, hydraulic permeability, etc..

However, mechanical parameters (i.e., density, elastic moduli, damping parameters) are more suitable when endeavoring to make a unique identification of an object and when monitoring its integrity. Indeed, the study of the propagation of elastic waves in artifacts makes it possible to construct a sort of signature, called the "Sonic Imprint" (patent pending), that identifies the objects and, eventually, establishes their mechanical consistency (or integrity).

A way of studying the resonance and the damping of an artifact is to generate elastic waves in it by means of a suitable source (for instance, a small neurological hammer or a loudspeaker) and then to measure the induced free damped oscillations by means of piezoelectric transducers coupled to the surface of the object. The vibrations are closely linked to the geometry of the artifacts and the spatial distribution of their elastic parameters, and are subject to change, even in the presence of small structural modifications of the object.

Virtually all objects present a continuous distribution of vibrational modes and decay times, and oscillate with a superposition of vibrational modes of different frequencies. In fact, the distribution of the frequencies shows resonance peaks linked to the shape, dimensions, and elastic parameters of the object itself. Furthermore, the deterioration of a handmade artifact caused by a crack generates significant variations in its vibrational modes; these variations are simple to check by comparing the sonic fingerprints acquired before and after the deterioration.

The target of the study on recent handmade objects was to validate and standardize the acquisition technique. The measurements were carried out to verify: the repeatability of the measurements, notwithstanding the problems of coupling sensors and object, the repositioning of the sensors and the small differences in their response; the influence of the object's support on the resonance frequencies; the actual ability to discriminate between different objects made of the same material and having the same shape and dimension; the ability to distinguish between the responses of an object before and after a crack; the real non-invasiveness of the method, i.e., the absence of damage caused by the analysis using resonance frequencies.

The analysis affected on unbroken and cracked plates and vessels confirmed all the previously mentioned points with very reliable results. Furthermore, the results also confirmed that each point on the surface of the artifact had univocally determinable vibrational modes, even though with small differences (although not significant for the "fingerprint"). It is also possible to univocally determine the series of frequencies of the artifacts' vibrational modes. In this way, it is also possible to obtain information regarding the overall physical-mechanical status of the object under study.

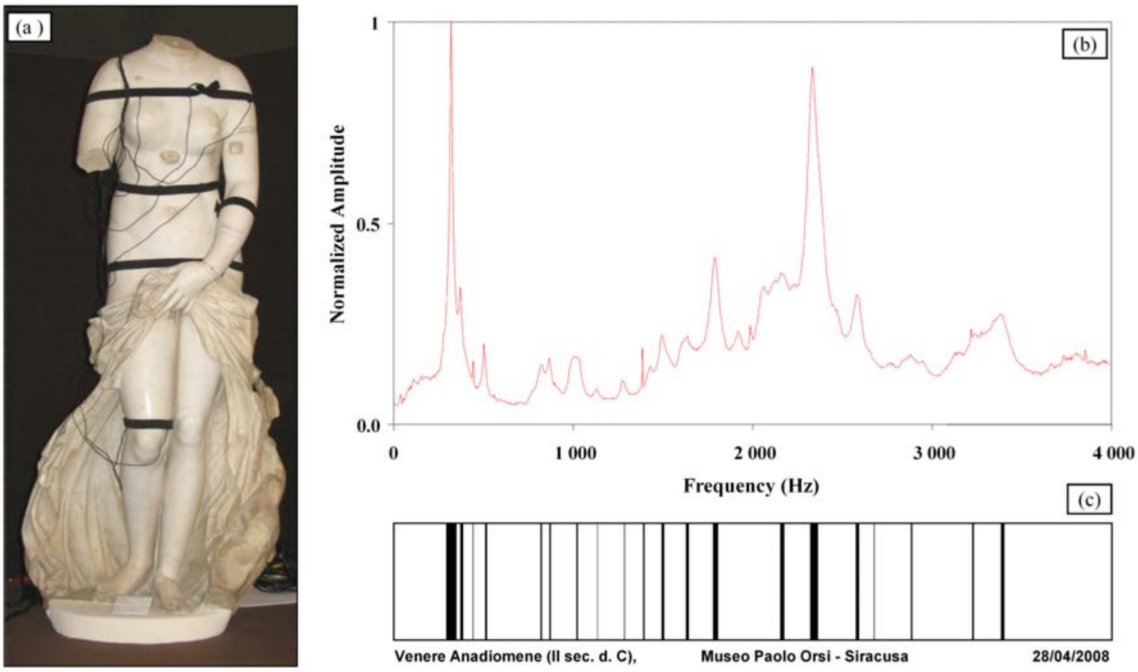


**Figure 7. Sonic imprint of the Venus of Syracuse (a) covered by piezoelectric probes; (b) shows the total spectrum of damped vibrations constituting the sonic imprint of the statue; (c) shows the spectrum in terms of a bar code.**

A number of precious artifacts have been studied, among them the Eleonora d'Aragona bust (F. Laurana, 1471), the San Michele Arcangelo statue (Gagini's apprentices, XVI century), the Niobidi Crater (Niobidi painter, V century B. C.), some bronze busts (A. Ugo, 1930), the Venus of Syracuse (II century A. C.), a pottery vessel of Bes God (IV century B. C.), antique plates and vessels, etc.. The results seem to be excellent.

The sonic imprint (i.e., spectrum and corresponding bar code) retrieved from the Roman statue of Venus of Syracuse (Figs. 2a and 7a) is presented in Figs. 7b and 7c.

**Electromagnetic (Radar) Tomography and Special Surveys**

As regards non-invasive testing, we have acquired and interpreted many radar profiles for various applications, both in standard and unconventional ways. The aim of this study was to solve problems regarding civil engineering buildings and infrastructure, as well as cultural heritage monuments. Of the various applications developed and currently in use (2D and 3D velocity tomography for walls and columns; see Cosentino and Sanfratello, 2004; Cosentino A et al., 2000; Cosentino P L et al., 2000), we mention two types of unconventional uses, both executed with high frequency antennas (typically, 1.0–2.0 GHz) and based on the classical reflection of electromagnetic waves. The instrument we use is the GSSI SIR 3000 System and/or IDS Aladdin System, equipped with GSSI (Radarsystem) and IDS antennas.

The first application aimed at studying lapideous balcony corbels that, in many countries, were widespread from medieval times onwards. Most of the ancient buildings made of masonry have overhanging balconies that are generally borne by lapideous corbels (in particular, made of calcarenite, limestone, granite, marble, etc.), which are sometimes supported by columns. The integrity of these corbels can deteriorate for many reasons, although they are generally triggered by moisture and humidity. However, sometimes fossil discontinuities or previous mechanical stresses may be the cause. In some cases these corbels break and consequently balconies fall down potentially causing serious injury to people or damage to cars and other things. The only way to prevent this from happening is to check the corbels from time to time in order to be sure of safety conditions and, in case of cracks or defects, to reinforce them or to substitute them with new ones.

The methodology used to check corbels (Cosentino et al., 2002) involves a first step, which is the calibration with a reflecting iron bar moved at various distances along the external side of the corbel (Fig. 8a), to obtain the value of the dielectric constant of the masonry. A subsequent phase is the acquisition of a "rotational" file, to detect possible reflective surfaces inside the corbel (an acquired file is presented in Fig. 8b). The first reflective surface is always the beginning of the corbel, the last one being the end of the corbel inside the building (in Fig. 8b at about 1.15 m). Any other possible intermediate reflection patterns (see the red lines in Fig. 8b) are always signs of dangerous areas (discontinuities such as moisture, cracks, fossils, etc.) that should be thoroughly evaluated, though they are potentially dangerous whatever the origin is (in fact, in any case they are mechanical discontinuities along the corbels).

Compared with the classical ultrasonic method for testing the corbels, this GPR procedure presents the following advantages: (1) matching of source and receiver with the surface of the corbel is always optimal; (2) calibration to retrieve distances of reflecting surfaces is simple (time-depth conversion); (3) the procedure uses polarized waves, so that further information can be obtained, e.g., the orientation of the reflecting surfaces.

However, there is also the disadvantage that the electromagnetic waves do not supply parameters that are directly related to the mechanical properties of the investigated rocks, and give no information about the safety of the supporting function of the corbels.

Finally, an unconventional procedure should be mentioned that allows us to use GPR to retrieve particularly thin films (Cosentino, 2006; Cosentino and Deganello, 2003). In fact, films (patinas) of a variety of substances often grow on the various substrates that constitute the external surface of commercial and historical artifacts (monuments, buildings, etc.). These films grow in various shapes and forms according to different growth kinetics, a process that is closely

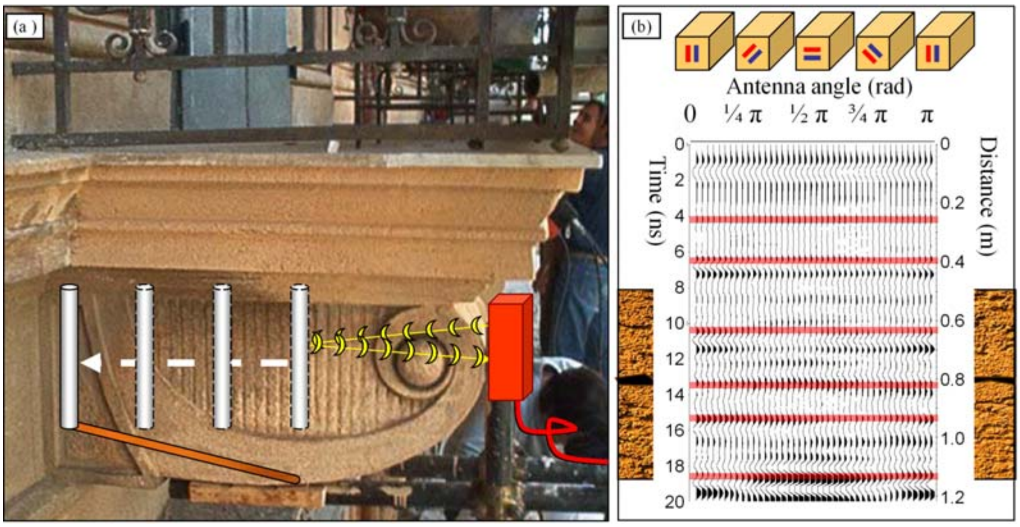


**Figure 8. The pictures present the corbel control procedure. The calibration procedure is shown in (a). The reflections due to an iron bar moved at various distances are recorded for the calibration (velocity analysis). The data acquired using a copolarized broadfire rotating antenna are presented in (b), with interpretation (red lines are reflections at various distances from the front of the corbel). Finally, the corbel investigated was disassembled, showing the internal fractures that had previously been recognized.**

related to a number of physical (i.e., type of substrate) and local parameters (i.e., availability of sulphates, acid rain, urban pollution, specialized exposure, etc.). Certain micro-environmental conditions may, over time, foster the juxtaposition of different patinas on a common substrate, especially in urban environments. Patinas may range from a few angstroms to a few centimeters in thickness. Usually they become embedded with other materials (silicates, carbonates, pollution material, trace elements, etc.) during growth; this is characteristic of the particular micro-environment where growth takes place.

This methodology consists of the positioning of the radar monostatic antenna on the surface of the artifact (with or without patina) in order to receive waves reflected by possible different targets inside the wall (Fig. 9a). The first set is reflected by the most external surface layer (this being a patina—if the latter were to be present—or, otherwise, the carbonatic surface). Such a wave set corresponds to the first wave arrival that is recorded on the signal trace. The following wave sets are, instead, reflected by potential intrastone planes that discriminate local variations in wave velocities. Should no intrastone plane be present? There will be, however, at least one reflecting plane; this coincides with the innermost surface of the wall.

The waves thus reflected arrive a few nanoseconds after the first wave set (Fig. 9b). This delay to a large extent depends on the depth in the stone of the first reflection plane whose precise location, in actual fact, is unknown. As a consequence, an additional variable is introduced into the process of data interpretation and this, in principle, could jeopardize potential comparisons.

The semi-transmission approach only works when the passage of the electromagnetic waves through the patina layers significantly influences the dynamic characteristics of the crossing waves, thus resulting in resonance (or absorption) phenomena that selectively amplify (or damp) particular values in the radar frequency range.

We use three high-frequency antennas, whose bands are centered on 1 000, 1 500 and 1 600 MHz, respectively. The bands of the incoming waves vary slightly from antenna to antenna, but, at least near their transmitting dipoles, they range between a few hundred and 2 500 MHz.

Generally the data acquired show excellent reproducibility within the limits of the experimental errors. A typical profile crossing the separation between patina-rich and patina-free areas is presented in Fig. 10 (left side).

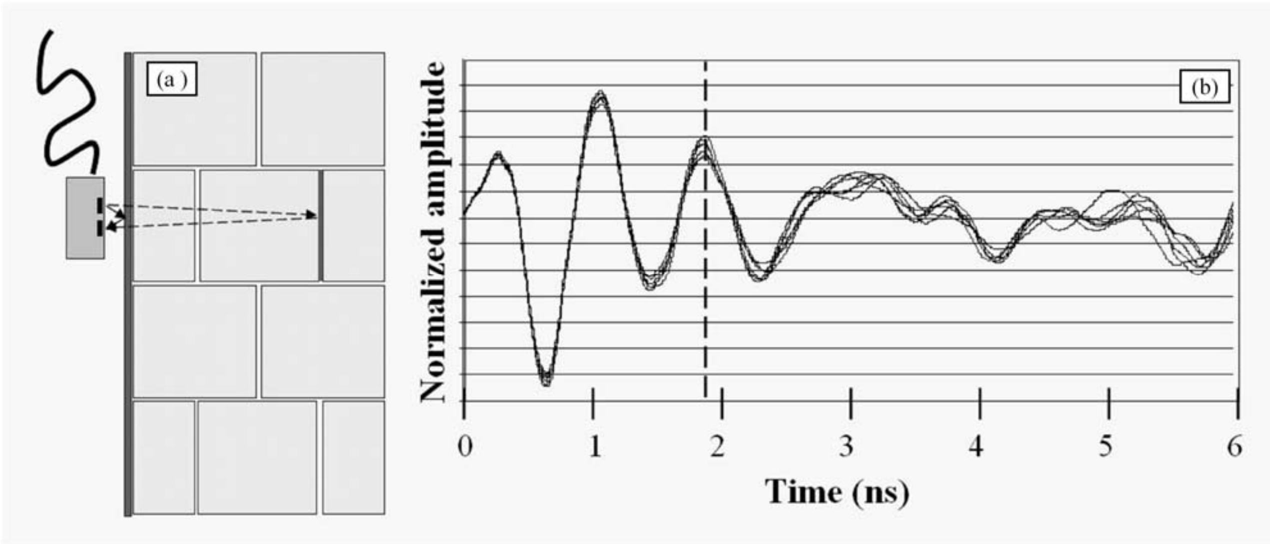


**Figure 9. (a) Sketch of a typical GPR acquisition along the surface of a wall using semi-transparence techniques; (b) traces of GPR signals showing the shape of the first arrivals (first part, up to the vertical broken line) and that of later arrivals (about 2 ns delay). The ways of the latter waves, in the presence of an external patina, cross the patina layer twice (after Cosentino and Deganello, 2003).**

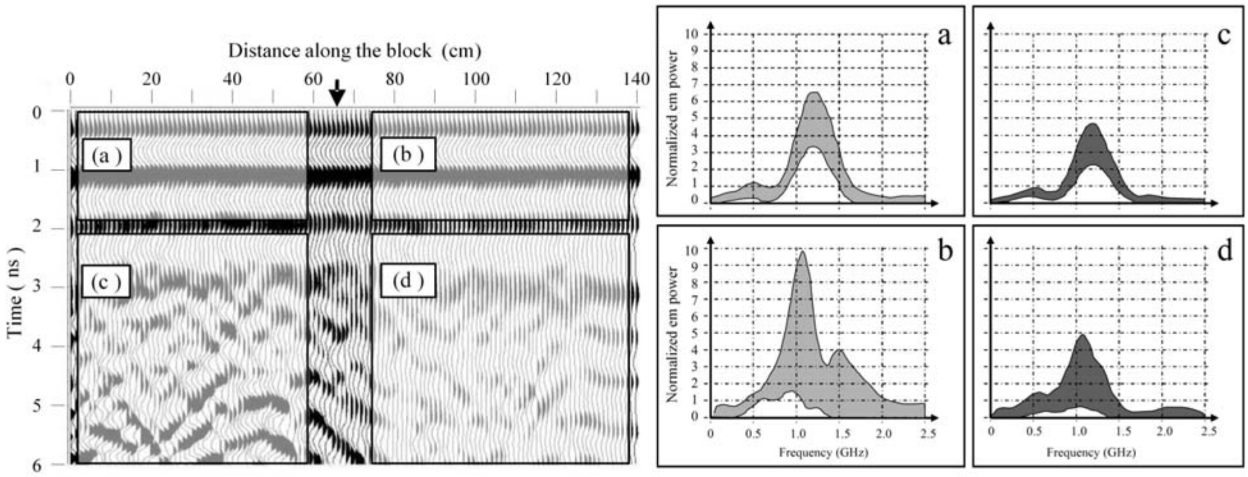


**Figure. 10. A typical file recorded in the left part of the figure (a to d). The profile crosses the separation between patina-free (signals a and b) and patina-rich (signals c and d) areas at about 65 cm (arrow). The spectral responses of those parts of the signals contained in frames a, b, c, and d are presented in the right diagrams, the areas representing the envelope of the spectra of the various recorded signals (after Cosentino and Deganello, 2003).**

Furthermore, before analyzing the spectral characteristics of the various wave arrivals, we impose a stacking procedure in order to build a data set of high stability. The signals are then evaluated and the sections comprehending the reflections from the most external surface (first signal arrivals) are analyzed separately from those producing the reflections from inside stonewalls. In this case, the discriminating time was estimated at about 1.9 ns (see the vertical broken line in Fig. 9b). This value should mark the boundary between the signals from the most external surface (which are very stable since the two-way time travel is in air) and those traveling within the sample. However, it should be stressed that such an evaluation is subjective, and may be prone to potential adjustments from site to site, depending on the depth of the shallowest reflection and the permittivity of the sample.

The results show that the amplitudes of the waves reflected by the most external surface of the wall are systematically smaller if the latter is covered by an alteration patina, even though the general characteristics of the spectra are similar to those produced when the external surface is patina-free. This effect may be due to a lower reflectivity on the part of the patina layers. Furthermore, and most importantly, the waves reflected by the inner planes are not only characterized by overall smaller values of amplitude when the patina is present (compare spectra d with the b ones in Fig. 10, the diagrams being in the right side) but, in addition, they show that such a relative amplitude decreases strongly in the frequency range from 1.3 to 2 GHz.

Because of the regular transition of the decay process between patina-free and patina-rich areas, and even between the relatively modest extent of the decay process, the first results obtained in a very clear situation presented an almost ideal testing opportunity. Thus, it is not surprising that the results obtained were particularly impressive and easy to correlate with crystallographic observations. However, they cannot and should not be generalized yet, or correlated to other occurrences. We need much more integrated work on other patina models in order to collect meaningful data sets covering different situations. Only then will it be possible to assess the limits of these studies. However, this represents a useful step towards a regular application of spectral analysis to GPR data, aimed at recognizing thin (or very thin) strata that can significantly affect the frequency content of the microwaves, wherever the strata are located (at the surface or inside the artifacts). The reference to the big problem of detecting carbonatation and/or oxidation around the iron bars inside the reinforced concrete seems very easy to be recognized. In fact, the method now used to solve this problem—executed using electric imaging—is only a probabilistic approach that gives only semi-qualitative information.

## CONCLUSIONS

The results reachable through the various presented methodologies have been presented together with the respective methodologies so it is perhaps unnecessary to stress them once more. The purpose of this presentation is rather to communicate how microgeophysical techniques and methodologies are developing, at least in our research center of Palermo, where geophysicists have strong collaborations not only with colleagues studying the microstructures of rocks and stone artifacts but also with restorers, conservators, and engineers.

The general target, however, is to refine the methodologies in order to obtain investigation tools that can be applied and interpreted as best as possible. The time necessary for the investigation is also becoming a very important aspect, because time reduction implies cost reduction and, in turn, fosters the diffusion of microgeophysical investigations as support for engineering and restoration projects.

The presented methodologies give only an insight on the topics faced by microgeophysics, but they are probably sufficient to understand how microgeophysics could be expanded in many different fields of diagnostics. Much more than this could be done if the number of microgeophysicists would increase around the world. Unfortunately, the field is considered not so notable by many applied geophysicists, despite the demands coming from civil engineering and cultural heritage management.

At the same time the artifacts we are requested to investigate are becoming smaller and smaller; consequently, the resolution required is now higher than that requested for previous cases: it would appear that we are participating in a race to continuously overcome our own best results.

In addition, considering the financial support available in this field (not only coming from civil engineering—buildings and structures like roads, bridges, harbors, airports, etc.—but also from conservation and restoration of historical monuments and cultural heritage artifacts), it is important that new instrumentation be as cheap as possible both as regards construction and operational costs so that the application of microgeophysics can expand. Our efforts to develop methods and techniques aimed at improving the quality of the information and at reducing the time of acquisition are indeed addressed to this expansion.

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