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Non-destructive diagnostics techniques for historical buildings: methodological guidelines and operations protocols
Técnicas de diagnóstico no destructives para edificios históricos: guías metodológicas y protocolos de operación

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END OF MASTER WORK

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Statutory Declaration

I herewith formally declare that I have written the submitted thesis independently. I did not use any outside support except for the quoted literature and other sources mentioned in the paper. I clearly marked and separately listed all of the literature and all of the other sources, which I employed when producing this academic work, either literally or in content. I am aware that the violation of this regulation will lead to failure of the thesis.

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Abstract

The aim of this End of Master Work is analysing the different methodologies and find out the most helpful norms to apply three specific non-destructive techniques, namely: Active thermography, sonic pulse velocity test and ground penetrating radar for the detection and evaluation of decays in historic buildings, structures and elements.

Nowadays, there is not a recognized source of knowledge to consult in order to apply these techniques for historical architecture. Some recommendations are given by specialized institutions as RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) or DGZfP (German Society for Non-Destructive Testing). Some initiatives tried to standardize the test procedures with no great success. The application procedures are currently applied on-site most of the time with personalized methods and applying modifications according to the limitations of each test project. Official universal standards do not cover the special cares of a historical element requires.

Therefore, a research about the most common procedures for active thermography, sonic pulse velocity test and ground penetration radar is compiled.

The available knowledge is very dispersed. The amount of case studies articles and reports provide vital information to improve the test efficiency and many experts are glad to share their real experience with these technologies with other professionals.

Diving into the literature and conversing with practitioners, it is noticeable the lack of standardization and the few standards that are applicable for building preservation, are usually not followed or even known. Why? Examining the available standards, it is clear the complexity of their structure. The limitations of their procedures invalid often their applicability on-site, i.e. very complex calibration method which required specific equipment not offered out of the laboratory. Thus, the user finds other solutions to accomplish the test with relative success.

For on-site application, recommendation guidelines are usually more complete that the proper standards, but still not sufficient to increase the efficiency of the tests.

Considering this report as an introduction to the three methodologies, there is still a lot of work to do in order to document and put together the isolated valuable information to improve the tests efficiency test on historical buildings.

1. List of abbreviations

NDT: non- destructive technique
MDT: minor destructive test
DT: destructive method
IT: infrared thermography
AT (AIT): active (infrared) thermography
PT: passive thermography
FOV: field of view
SPV: sonic pulse velocity test
IET: impact echo test
GPR: ground penetrating radar
EM: electromagnetic

2. List of Figures

3. Introduction

According to the American Society for Non-Destructive testing (n.d.), the non-destructive testing (NDT) “is the process of inspecting, testing or evaluating materials, components or assemblies for discontinuities without destroying the serviceability of the part or system”. These techniques are nowadays not only used in manufacturing processes, but also to study the state of buildings and the status of conservation in order to prevent future settlings or failures. In addition, they can evaluate the seriousness of failures, if already appeared, and the progress of expansion can be documented to ensure the best treatment and the efficiency of the applied solution.

As it is mentioned, the singularity of these techniques is the possibility to be performed without affecting the integrity of the studied specimen, without the need of taking testing samples, as known as destructive or minor destructive methods. This characteristic makes this kind of testing suitable in construction, especially useful for its application to historical buildings, due to the strict regulations applied to protect them.

This End of Master Work is focused in the methodology followed to apply determined NDT in historical buildings and structures. It tries to find possible improvements to increase the efficiency of the whole diagnostic process with NDT, the accuracy of their measurements through a better technical practice, the good understanding of results and to ease the communication among the professionals involved during the test application.

Therefore, an analysis of the state of the art of the current standards and protocol recommendations will be performed, searching the last updates from the last relevant related works to NDT for historical buildings. As well, some professionals of these techniques have been interviewed to know more about their practical experiences, and to point out common situations where the application procedures can be improve.
Like in most of the procedures, they are continuously updated with enhancements and corrections, and this analysis tries to find them from the latest relevant related work to this topic and if it is possible, to find the gaps or mistakes in the actual application standards or guidelines.

Apart from the ideal application of these technical methods, reality can differ a lot from the ideal testing practice. Therefore, experience is the most valuable source of knowledge to make improvements and increase the efficiency of any method. Thus, after consulting the latest updated standards and technical developments, the methodology used for this research is based on several structured interviews with professionals who have worked with thermography, radar scanning or sonic pulse velocity test. Today these three techniques are widely used for rehabilitation projects of historical buildings.
All of the three technologies are explained in this project; starting with their physical principles and how they work, when they should normally be used, which are the optimal targets of these methods and their recommended application protocols.

It is remarkable, that the aim of this investigation is not to analyse and develop the technic of these technological devices, but to examine their application protocols and procedures. This includes the previous evaluation of the building which determines the technique that should be applied or at least discard optional technologies which are not helpful for certain settlings. Furthermore, analysing the procedures will help to find flaws within the interprofessional communication and the results handed in to the client or interested stakeholders. With it, improvements are founded and the cooperation among the involved workers such as city council officers, architects, engineers, etc. and the boundaries of each work field are clearly defined.

3.1 Aim of Research

This research is centred in examining the real influence and effectivity of the current approved standards related to non-destructive techniques applied on-site to historical buildings. This techniques are Active Thermography test, Sonic Pulse Velocity test and Ground Penetrating Radar test. In comparison with onsite experiences, the report will make an approach to stress the weak and strength points of the available protocols. In addition, alternative practices from onsite practice to improve the test method will be pointed out.

3.2 Limitations

Due to the wide range of NDT applications and types of this techniques, the scope of this study is focussed on on-site application to historical buildings. Furthermore, the amount of test to be analysed was reduce to the three most common and previously mentioned: Active Thermography, Sonic Pulse Velocity and Ground Penetrating Radar test (last one also known as GPR radar). Therefore, laboratory test procedures are not in the scope of this work.

Another very important aspect to take into account is the lack of possibility to test and validate these techniques with practical experience. Thus, the external practice was not connected to the topic.

3.3 Methodology of research

As one of the main limitations of the author of this work is the lack of practical knowledge about these procedures. The methodology is based on research of approved standards and recommendations from official authorities, in comparison with previous case studies which applied Active Thermography, Sonic Pulse Velocity and Radar test on-site to historical buildings. Besides, personal interviews with experts on the subject have been made.

With previous on-site case studies, some divergencies from the standard method can be seen. It shows where the theoretical standard approach is not enough to detect decays and not realistic to be applied out of laboratory.

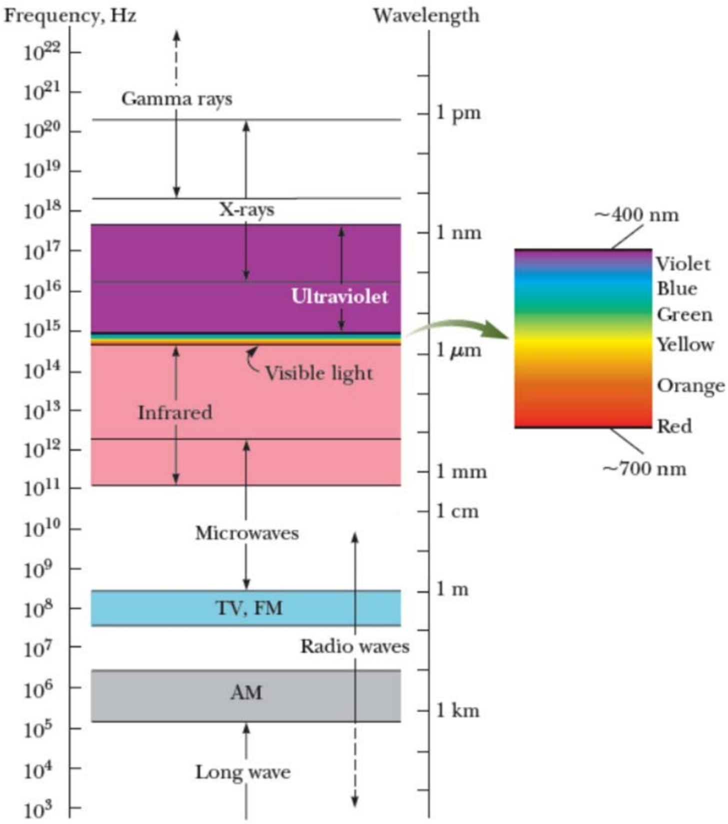
There is little information for best practices with NDT and even fewer specific protocols for historical buildings. Most of it is not organized and when it comes to application every professional personalizes the standard procedure on-site and at the end has his own practice method. Thus, starting from official norms, a flexible conversation with the experts about questions and doubts organized in theme blocks, such as personal preferences about technical requirements for the devices, consulted normative for its application, necessary personal involved during the procedure, in-situ calibration or verification techniques, for the three techniques has been done.
Therefore, experiences will be compared to the regulated norms, and vice versa, in order to find possible common problems, possible gaps not covered by the approved standards and to give alternatives or try to implement better practices into the procedure.

4. Non-Destructive Techniques and general physical principles

In order to find the weaknesses of these kind of techniques or possible improvements in the protocols used for the NDT application, a brief introduction to their physical basics and methodologies is presented to understand how they work. For the application of these tests, a full deep knowledge about theory of physics is not necessary, but a certain general knowledge about the behaviour and properties of waves can be helpful to select the right device according to their specifications.

All the three selected methods are working with waves; generating and receiving them, measuring the intensity, amplitude, phase, frequency or speed propagation through a physical media. Thus, valuable information about the state of the material can be interpreted.

Waves, according to the definition, are the motion of a disturbance and all of them carry energy and momentum (Serway, 2009). The waves which need a material medium to propagate are also called *mechanical waves*. The sound is an example of stress or mechanical waves: an emitter creates a difference of pressure in the air or any other medium and this difference is spread from point to point.
Other type of waves, which do not require a material medium to travel, are *electromagnetic waves.* There are different classes of waves depending on their frequency and wavelength: infrared, microwave, visible spectrum, ultraviolet, etc.



Thermography and radar scanning work with electromagnetic waves while sonic pulse velocity test is making use of mechanical sound waves. Specifically, thermographic technology uses electromagnetic waves in the wavelength range of infrareds (approximately 700 nm to 1 mm and frequencies between 430THz and 300 GHz), while radar scans work also with electromagnetic waves but with radio frequency waves (wavelength between 1 mm and 100 km, and frequencies between 300 GHz and 3 kHz).
Although the physical principles are similar for electromagnetic and mechanical waves, the way these disturbances are created, propagated and applied onto the materials are different and therefore, their protocols and inconvenient too.

Figure 1. Electromagnetic spectrum (Serway, 2009)

5. Active Thermography

In medicine, a variation of the body temperature, which is outside the normal temperature range, allows conclusion to possible illnesses and abnormal behaviour. Components of buildings and mechanical structures could be treated in a similar way, since all materials have a specific capacity to absorb (absorption), emit (emissivity) and conduct (conductivity) heat radiation. Heat radiation is a kind of heat transfer, where heat is transferred by electromagnetic waves. By measuring the radiated energy and its variation in time, information about the composition of building structures can be derived and analysed.

All the materials with a temperature above the absolute zero (0 ºK), emit a certain amount of heat radiation. The emitted amount of heat radiation is proportional to the temperature material. This heat radiation is measured with a device: The thermographer. This device can detect the received radiation emitted by a body and processes it into an electrical signal. With a computer, this signal can then be processed into a readable graphic, a coloured image or even automatically analysed.

Besides its main industrial purpose, this technic is mostly used in construction to detect and evaluate i.e. heat losses in buildings. However, heat loss analysis is not the only application. In the field of building conservation, thermography is very useful method to discover and test delamination, damps and other faults and decays, within a depth of approximately 10 cm into the structure (Maierhofer, et al., 2002).

The difference between active and passive thermography is the integration of a heating source device to increase the temperature of the specimen to study, and with it, investigating the following cool-down process.

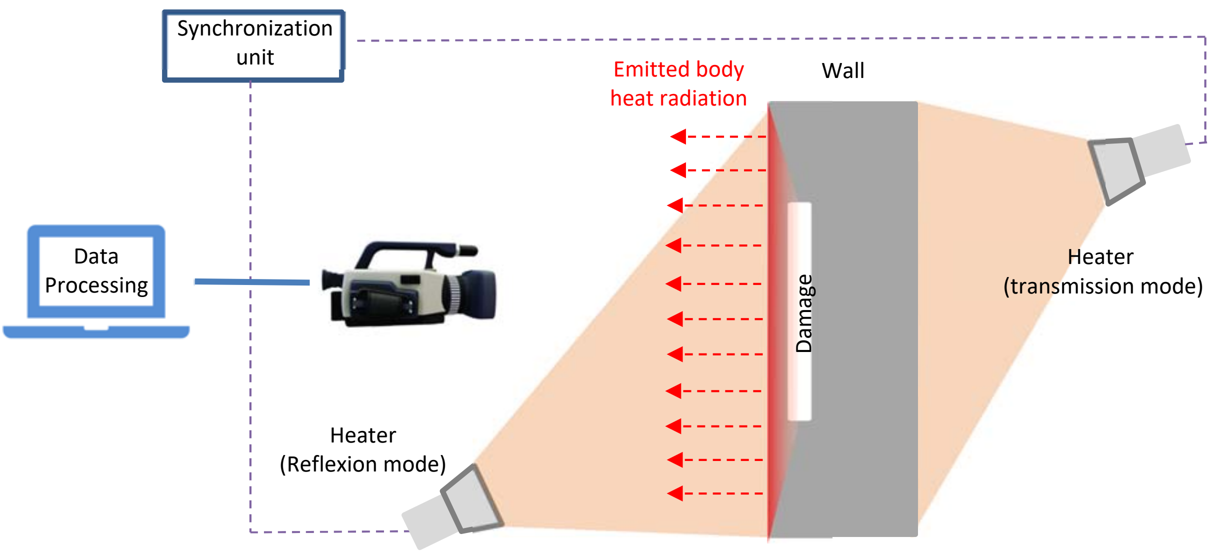


Figure 2 General set-up and working principle of active thermography.

Depending on the specimen to study and the methodology approach, the heating source can be regulated to apply heat with a certain intensity during a certain period. The active heating can be controlled by synchronization units to control the heating times. Depending on the method of application of AT there are different variants: Impulse Thermography, Pulse-Phase Thermography, Lock-in Thermogrpahy…
According to previous investigations like Onsiteformasonry (2004) the carried out work by Maierhofer et al. (2002) and the most recent by Ishikawa, et al., (2013), the most promising active thermography methods to investigate historic structures are pulse thermography (PT) and pulse-phase thermography (PPT), due to its evaluation depth and clarity of results.
PT evaluates directly the difference of temperature in real time, whereas PPT is based in Fast Fourier

Transformations, from the received heat radiation waves, analysing the amplitude and phase of the wave for each frequency.

In both cases, the method application and information gathering is the same: The component to be investigated is heated up with an external radiation sources, i.e. convection, radiation or conduction heating (fig. 3). After a certain time, the heaters are switched off and immediately afterwards, the infrared device records the cool-down behaviour of the structure in real time.

Different materials have different thermal properties like the previous mentioned emissivity, absorption, density or heat capacity and transmittance. Therefore, if there are inhomogeneities or defects that difference of temperatures will be detected by the infrared camera and the outcome of that data analysis is a tinted image, as it can be seen in figure 3. The colour scale gradient is related to temperature gradient. The image represents the different temperatures in the evaluated surface according that colour scale.

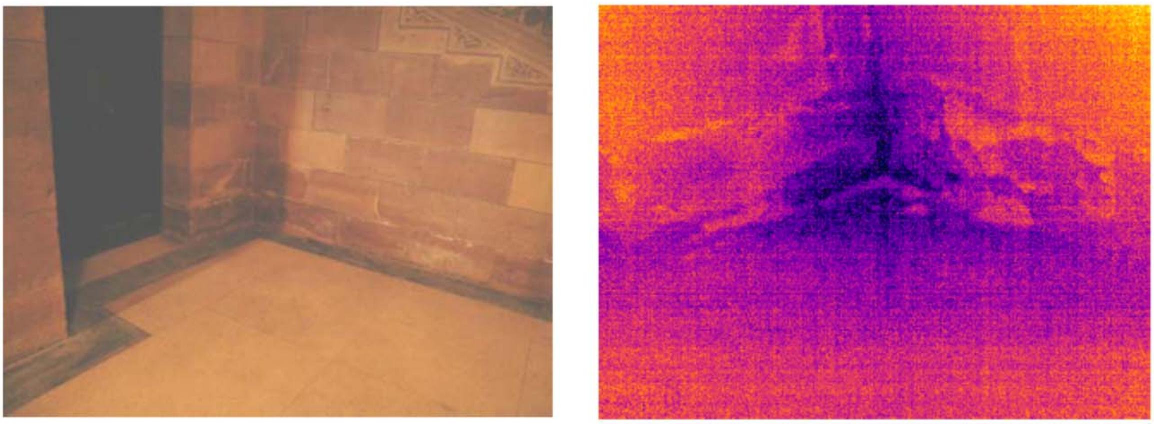


Figure 3. a) Real image b) Thermographic image showing damp areas (colder areas) represented by near blue colour gradient (López Higuera, et al., 2007) .

This variation of temperature in an region in comparison with the average of the surface, when it is supposed to be uniform, is an indication to possible faults, which should be analysed with IT. Because of this reason, it is meaningless to focus on the exact temperature of each single point of the specimen surface for this kind of investigations.

The selection of the right thermographic approach depends on several factors: The depth of investigation of the interest, the thickness of the specimen, the finishing of the investigated surface, the knowledge or unknowledge of defects presence and their possible geometry, etc. According to Weritz, et al. (2003) PPT is a more effective method in order to analyse concrete structures, because it provides a deeper analysis with a higher resolution of faults, improved visibility, and a higher probably of detectability for defects in comparison with simple pulse thermography. Therefore, it is recommended for a more complete and accurate investigation of decays. Furthermore, it is a quick image recording approach, with no need of a priory information of the location of decays.

The main defects which are pointed by thermography methodology are delamination of plasters and tiles, moistures, strength of materials and location of different structure location in the near surface region.
For its application to historical buildings a longer heating pulse duration and recording time is recommended, due to the sizes of structures and materiality.

5.1 Thermography equipment

As it has been mentioned before, the main characteristic of active thermography is the usage of heating units besides the infrared camera to warm up the examined surface. In addition, a computer or signal processing unit is required to collect, analyse and represent the data is necessary as it can be seen in figure 2.

The heating units are classified depending on their heating method (see figure 3). The warming-up of the examined body should be as homogeneous as possible. Because of the behaviour of heat, in some cases, e.g. when the examined surface is large, the heat must be applied dynamically to guarantee a homogenous heat input. With a static source of heat, intensity of heat input is lowered at areas further from the source. Thus, the results could be distorted. For it, infrared radiators are the most efficient in exterior spaces and fulfil the requested requirements (ONSITEFORMASONRY, 2004). Convection units are recommended for inner spaces, due to their heating speed and their ability to maintain the room temperature constant, such as electric fan heaters. In some cases, a synchronization unit to control the heating device is implemented to control the heat flow and temporal excitation.

	Heating Source	Recommended temporal excitation	Typical application
Optical radiation Units	Infrared radiator	Step thermography (t >1s)	Deep delamination Volumetric discontinuities
	Halogen lamp	Step thermography (t >1s) Lock-in thermography (0.001Hz < f < 2Hz)	Delamination Volumetric discontinuities
	Flash lamp	Pulse thermography	Delamination Volumetric discontinuities in the near surface depth
	Laser	Pulse thermography Step thermography Lock-in thermography (0.1Hz < f < 100kHz)	Crack (orthogonal to tested surface) Delamination
	Microwaves	Step thermography Lock-in thermography	Delamination Volumetric discontinuities
	LED mosaics	Pulse thermography Step thermography Lock-in thermography	Delamination Volumetric discontinuities
Convection Units	Hot air heater/blower	Step thermography Lock-in thermography	Cooling duct penetration
Conversion of mechanical waves	Ultrasounds/Sonotrode	Pulse thermography Step thermography (t >1s) Lock-in thermography	Crack detection
	Induction	Pulse thermography Step thermography Lock-in thermography	Defects on conductive materials
Conduction units	Electric resistance	Pulse thermography Step thermography Lock-in thermography	Interface and defect detection in conductive materials
	Heating mat	Pulse thermography Step thermography Lock-in thermography	

Figure 4. Table of type heating sources.

The infrared cameras are the most complex components of the thermography equipment. In 2004 some technical specifications were recommended (spectral sensitivities in the range of 3-5µm or 8-12 µm, minimum temperature resolution of 0.2 K…), the devices have been improved since then.
The most common detector sizes are 160x180, 320x240 and 640x480 pixels with a wavelength detection range between 0,7- 14µm and temperature sensitivities are already lower than 0,03 K at test environment at 30ºC. Software to process and display the data are usually developed by the camera provider and are included with the purchase of the hardware. However, several companies offer independent image processing software, such as the image processing toolbox by MathWorks MATLAB. Thus, analysis can be adapted individually to the user's preferences and purposes.

5.2 Standards and protocols

Nowadays, there are no specific standards for the application of active thermography on historical architecture, just few guidelines based on general thermography norms. The main approved norms for AT generally explain main testing systems of this technique performed for general purposes. While the most studied are focused on industrial pieces, civil engineering is focused on tests for bridge decks or material test in laboratories. In the case of historical buildings, there are some guidelines with recommendations for best practice, but nothing written on stone yet. Like most of the NDT, all the standards and guidelines mention the qualitative outcome of the test.

In practice a very interesting guideline with instructions for on-site application related specifically to historical buildings, is the European project ONSITEFORMASONRY founded by the European Community. There is a specific work package studying just active thermography application.
Since 2004 when this work was published, the main official standards related to Active Infrared thermography which are relevant and up to date for further application to historical architecture are:

- European Norm EN 17119:2018: *Non-destructive testing. Thermographic testing. Active thermography*
- American Norm ASTM D4788-03 (Reapproved 2013): *Detecting delamination in Bridge decks using infrared thermography.*

5.2.1 Standard EN 17119:2018

This norm is today the main European standard for the application of Active Infrared Thermography. It is a general explanation of thermographic procedure which includes heating sources in several fields of investigation, from industrial production of elements and products, analysis of installations and maintenance, laboratory investigations, civil engineering to architecture. It briefly describes the available options to gather and process data and the existing heat sources that can be implemented to IT (figure 5). On the contrary, it does not point any specific defect to be more suitable to be detected or any technical requirement to perform the test.

Type of active thermography set-up arragenment
- Direct Transmission
- Reflexion

Type of temporal excitation
- Pulse thermography
- Step thermography
- Lock-in thermography

Data Interpretation
- thermal contrast in time domain
- thermal contrast in frequency domain

Final Report
- General Information:
  - Stakeholders and client.
  - Work identification Number.
  - Description of testing object.
  - Time of testing.
  - Standards norms which are followed
- Test procedure information:
  - IR camera specification
  - IR parameters
  - Type of heating source
  - Test limitations
- Test results
  - Image identification data
  - Resulting images link to the object (real photo)
  - Description of results

Annex – Heating sources

Figure 5. Scheme of main information provided by Standard UNE-EN 17119

Apart from the explanation of the available heating options in an annex, such as convection, radiation or induction, and the different types of AT that can be used (impulse thermography, lock-in thermography, …), it is worthy to highlight the explanation of set-up arrangement of equipment: Reflexion arrangement or transmission arrangement as it can be seen in figure 6. However, in reality, test configuration will depend on the accessibility to the testing structure and its nature.

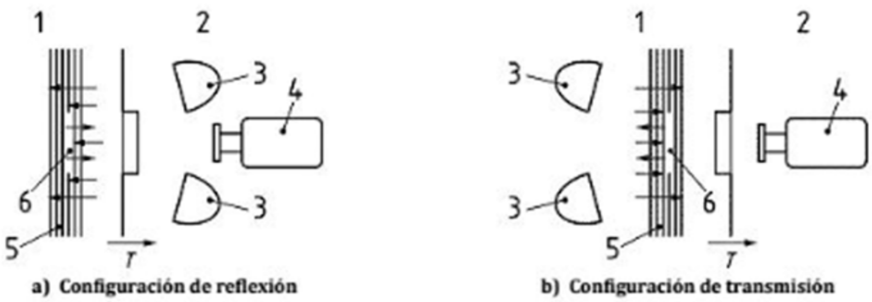


Figure 6. Configuration of different arrangements for Active thermography. (Image from norm UNE-EN 17119)

Moreover, the norm stipulates the information that must be included in the procedure development report:

- Heating Source: Type of source and method, energy intensity and duration and frequency.
- IR camera: Thermal resolution, spatial arrangement and time scales. Spectral range and temperature measurable range.
- Gathering, processing and analysing information: Method of analysis. Software.
- General Set-up arrangement: Position IR Camera - Heating source – Tested Specimen. Arrangement of analysis within the surface area

and, more important, in the final report that is given to the client and sum up the results from the test. It must specify the information listed in figure 5.

Other Standards consulted for this project are ISO 10880:2017 and ISO 9869-1:2014. However, the first is mostly focused on the industrial field and the second examines the energy losses, air flow behaviour of buildings and their thermal insulation; studying its thermal transmittance and resistance and, the heat flow through them, etc.
They do not include extra relevant information or recommendations for active thermography applied to historical buildings.

5.2.1 Standard ASTM D4788-03

Although this standard is not directly applied to buildings, the clarity of its procedure can be considered to develop an alternative guideline to the EN norms for ancient structures.
Comparing the scale of investigated bridges with buildings, this normative can give further information on analysing historical structures since it is one of the few standards that directly points out how to detect explicit construction failures like delamination of materials. In addition, it gives technical parameters, i.e. minimum view width of the camera of 4.3 m for the case of bridges, minimum temperature resolution of 0,2ºC, etc.

Although, the apparatus specifications and the procedure recommendations are very helpful to establish main ideas and questions for the interviews with experts, they will be adapted for the investigation of buildings.
Therefore, some requirements that must be taken in consideration to execute AIT are:

- Minimal thermal resolution in ambient air conditions of the Infrared scanner.
- Minimum viewing width
- Calibration of the device in-situ
- Surface condition
- Weather conditions
- Heating periods
- Results interpretation and presentation

It is noticed that all the standards give high importance to the information that the final reports should include, but none of them mention any previous visual or documental analysis necessary to increase the accuracy and efficiency of thermography testing. First assumptions about it suggest a reduction of time and economical costs by planning the best targets for testing. Without a priori analysis the effectivity of the test just relies on the good eye of the practitioner.

5.3 Extracted information from interviews

5.3.1 Testing defects

Although literature recommends active thermography for a wide problematic range like determination of layer thicknesses, strength of materiality, cracks and moistures, professionals agree on the low significance of IT application for detailed cracking detection (Lanza and Blanco, 2019) Just under ideal conditions the cracks can be clearly defined with thermography.
This evaluation is based on the comparison between crack size and the building scale. Cracking defects are too small to create a significant difference of temperature to be clearly shown in a thermal image. Neither is IT recommended to appoint quantitative values of defects in buildings. It may be possible to detect small cracks with very high quality devices, with very high temperature sensitivities (up to 0,03 K in ambient conditions), a minimum resolution of 640x480 pixels image and performing the test at a closer distance to the investigated surface than the recommended length, but still the test will provide qualitative results, instead of 100% accurate quantitative values of the defect. Alternative test should be considered to provide quantitative values (Carrera, 2019).
The same does not apply for industrial processes where more compact materials like metals are used and where temperatures are much higher, and the contrast of temperature differences within cracks inside materials is also bigger.

Despite the general rejection of IT for crack detection, it is worthy to point out the possibility to increase the efficiency of this technique to show that kind of decay. In the thermography project carried out at the Palace of Comillas (2007, 2008), crack patterns were detected using a combination of AIT in transmission mode with the appropriate investigation design; it is possible to take advantage of the time of the day during an specific season to enhance the temperature contrasts, i.e. recording the natural cold down behaviour of a not active heated building in the evening when the sun goes down or recording the warming up behaviour very early in the morning during winter, using the natural heat radiation of the sun. (Madruga, 2019)

Active Infrared Thermography is unanimously accepted, based on case studies and experience, as a perfect tool to detect easily moistures, delaminations and voids within the near surface region of structures. Any decay that has water implicit will be detected quickly and easily. Due to its area and geometry, parallel to the examined surface, delamination is large enough to create a detectable good thermal contrast from long distances.
The case study in Comillas demonstrated the very good performance of this methodology to discover moistures at the palace with a very good result, assessing also the quality state of the structure materials (Madruga, 2019)

5.3.2 Previous historical studies, investigation planning and reporting

A preliminary assessment about the building to examine, including materiality, structure, construction typologies, previous interventions or rehabilitations among other characteristics, is much appreciated for the investigation planning of active thermography. With it, the practitioner save time and testing attempts, not going blindly to search for inhomogeneities.
Although the initial stage of rehabilitation projects always implies a preliminary analysis, none of the standards related to IT refer to this option that can save time according to the experts. There is no mandatory rule to write down all the previous needed researched information for IT execution as part of the final technical report, just a brief description of the area or object that is being tested.

The lack of previous information can lead to false result interpretations and to plan a wrong approach with the consequent unproductive test.
A claim resulting from this, is the integration, of a mandatory documented pre-assessment, including

visual inspection and documentary research, insofar as possible, clarifying from the beginning the different materials and construction techniques. In terms of finance, it saves money from working time and unnecessary tests, to finally assure the selection of the most interesting areas for testing.
By good investigation planning, with detailed information of the materiality and an appropriate set-up, the depth of investigation that can be reached is around 40 and even 50 cm (Madruga, 2019).

5.3.3 Normalization procedure

Despite the existence of a standard it is not common to strictly apply step-by-steps the suggested stages. The lack of procedures for construction field make IT less accurate and forces the professionals to adapt the methodology for their investigation aims.

Furthermore, set-up arrangement is more complicated when it is applied to architecture because of the accessibility to the testing areas; for example, areas located too high and require scaffolding of large surfaces which need dynamic heating.
As well the technical limitations of the device force to adapt the testing distances, i.e. to improve the resolution at the defect.

By experience some good practices can be extracted for IT application, in order to speed up the procedure planning and execute always similar tests to compare later the output. Some recommendations are:

- Similar size of investigation (i.e. 2,5x2,5 m)
- Recording periods 4-5 times (approx.) the length of active heating time (usually 20-30 min for architectural testing with halogen lamps of 1300W as heating source).
- Step-heating Thermography is recommended for historical architecture.

5.3.4 Previous calibration

The importance of calibration procedure envisaged by standard ASTM D4788-03 is confirmed by experts (Blanco and Madruga, 2019). Different systems are used on-site to detect the surface temperature in parallel to the infrared camera.
The most extended is the manual temperature measure with a laser or a contact thermometer at different points of the surface. It can be useful to compare the right temperature accuracy of the device and being able to correct any later deviation respecting the temperatures (Blanco, 2019). This procedure might not be necessary due to the automatic calibration that most of the devices have implemented and the annual calibration of thermographic cameras, it an important aspect to grantee robust results (Carrera and Madruga, 2019).
The best practice in order to correct data deviation is by far the usage of thermocouples (regulated according to ISO 17025) to correct the different emissivity of the materials (Madruga and Lombillo, 2019)

6. Sonic test

The technology of sonic pulse velocity test is based on the behaviour of mechanical waves, to be more exact acoustic waves.
As it has been mentioned at the beginning, acoustic waves are a kind of stress wave, which needs a physical media to propagate. They can be classified depending on their frequency; named infrasound below 20 Hz, sonic if it lies between 20 Hz and 20 kHz and ultrasound above that limit.

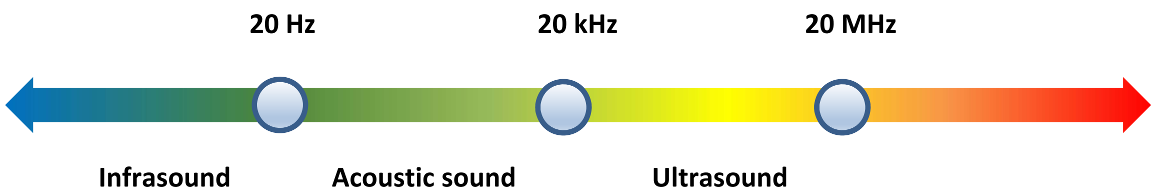


Figure 7. Sound waves bands classification.

The physical concept of this technique is the measurement of the sound wave velocity through a material or body. The transmitter device sends a mechanical stress wave pulses with determined known frequency and wavelength, it propagates through the material, and the receiver tool measures the time needed for the impulse to travel through the material.

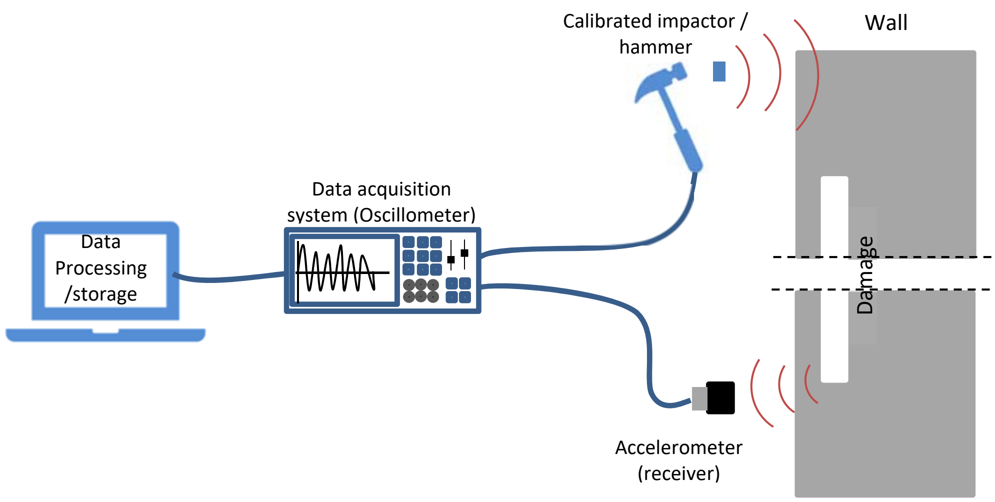


Figure 8. Scheme of Sonic pulse velocity test

With the travelling time, the wave speed can be calculated and information about the density and mechanical properties of the investigated body like elasticity module can be extracted.
In general, considering the L as the distance between the transducer and the receiver devices and T as the transit time of the wave through the investigated material, the basic formula to calculate the pulse velocity V is:

$$V = L/T$$

Equation 1. Fundamental equation of wave pulse velocity.

Apart from this formula, which is extracted from ASTM standard C597-16, for specific measurements in concrete materials, there are other numerical calculations to correct deviation that should be applied depending on the test approach of each case study.

In general words, the propagation velocity of an acoustic wave is directly proportional to the density of the material where it travels through and it is related to its elastic properties too. Consequently, the propagation speed of the waves is lower when the investigated structure is not in good condition. Decays as breaks, voids or density losses in mortars theoretically give lower speed propagation than the standard estimation for each material in good conditions. On the contrary, moisture materials usually provide higher velocity results (ASTM, 2016) (because water fills the voids) and this can lead to confusing results if they are not well evaluated

Because of its physical principles, general acoustic technology (sonic and ultrasonic) is very useful to detect cracks, also to check the presence of voids inside compact materials and its consistency. Specially, Sonic pulse velocity tests are recommended for homogeneous structures and materials. Thus, it is commonly used to assure the effectiveness of injected reparations (Bind, et al., 2001) and suitable to be applied on historical buildings. Sonic pulse tests are not competent to get quantitative results but are very helpful providing qualitative information about the material or element conservation estate.

As it is explained above, the main difference between sonic and ultrasonic tests are the frequency and the wavelength used and the technical characteristics of the tool to produce that specific wave, but the procedure is the same. While ultrasound, with its higher frequencies and shorter wavelength, should be avoided to check multilayer structures and it is suggested for very compact materials such as marble, metal, timber or reinforced concrete, sonic velocity pulse is suitable for masonry testing. The reason for that is, that the higher frequency waves are attenuated by discontinuities (Bind, et al., 2001).

The wavelength is directly related to the size of defects or voids within the material; the smaller the defect size is, the smaller wavelength is required to detect them, and consequently a higher frequency is needed. If the flaw is very small, but stress waves with long wavelength with low frequencies are used, the defects will not be seen on the sonic tests' analysis.

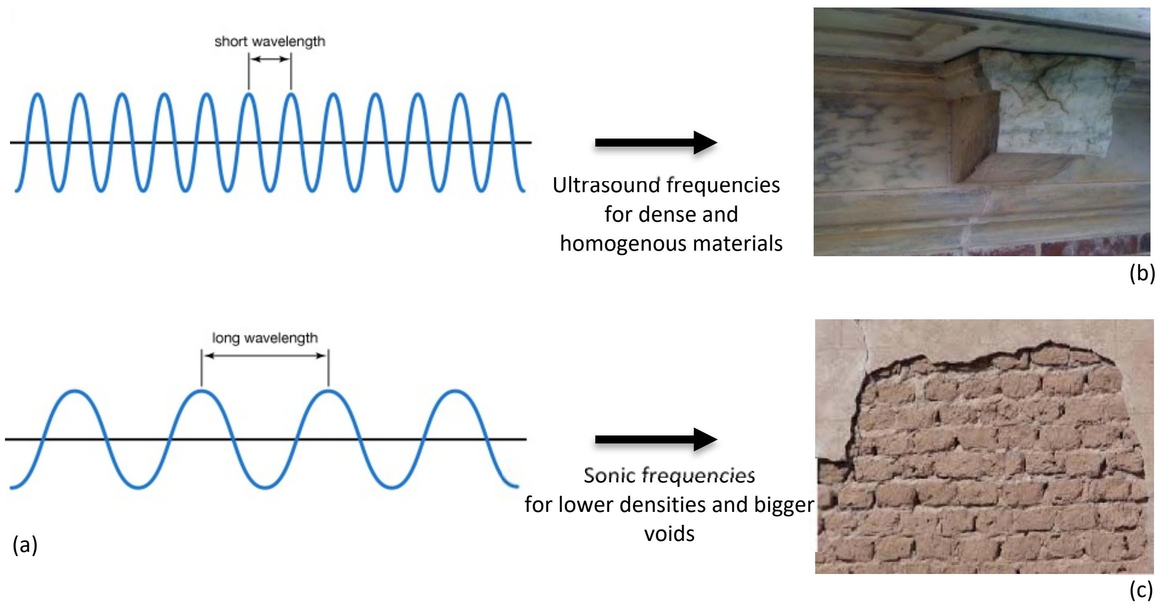


Figure 9. Relation between wavelength and frequency. Suggested size flaws/densities to analise. (a) ©Encyclopaedia Britannica, Inc. [Online] https://www.quora.com/What-is-the-relationship-between-frequency-and-wavelength (b) Marble material element [Online] http://brickbybrickrestoration.com/historic-masonry-repair/ (c) Historic Masonry with different layers and densities [Online] https://yestermorrow.org/learn/courses/historic-masonry-and-plaster-repairs

5.1 Transmission application methods

In combination with the wave characteristics there is another factor that conditions the test. The method application. For acoustic pulse velocity test, there are three different device arrangements, namely direct transmission, semi-direct transmission or indirect transmission, depending on the position of the receiver respecting the transmitter.

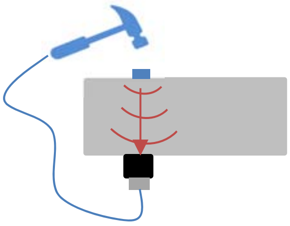


Figure 10. Direct transmission arrangement.

For direct transmission, the transmitter and receivers are located in straight line at the opposite's surfaces of the body to investigate (figure 10). The wave travels straight through the complete thickness of the building element. Although it is the most accurate method, often the on-site accessibility does not allow it. However, it is recommended to test:

- Masonry inhomogeneities and cracks
- Detached surfaces
- Inner voids
- Effectiveness of repair works

Semidirect transmission arrangement locates the hammer transmitter on a 90º angle respecting the accelerometer (Figure 11). The information about the stress wave is a little less accurate than direct transmission, but still quite reliable. It is commonly used onsite because of the easier access to both sides. This method is suitable to analize:

- Effectiveness of repair works

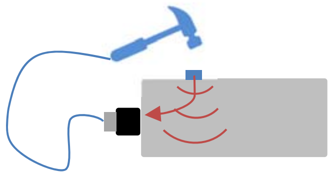


Figure 11. Semi-direct transmission arrangement.

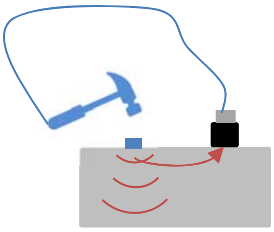


Figure 12. Indirect transmission arrangement

Indirect transmission is the least desirable method to apply due to the depth of investigation. The transmitter and receiver are positioned in the same face of the element of interest (Figure 12). Therefore, it will mostly give information from the layers at near surface level but not about the inner state of the element. It is recommended for this preparation to make several tests; some in vertical line direction and other in horizontal line. On the other hand, it is the easiest procedure to install because of the accessibility. (Bind, et al., 2001). Indirect transmission is usually performed to test:

- Damaged areas and cracks on near surface depth

The information received by the accelerometers is translated into a waveform graphic by the electronic device and shown on a digital screen (figure 13). The time that pass, since the pulse is emitted by the hammer until the first signal is received by accelerometer, is the wave pulse speed which is interesting for the evaluations.

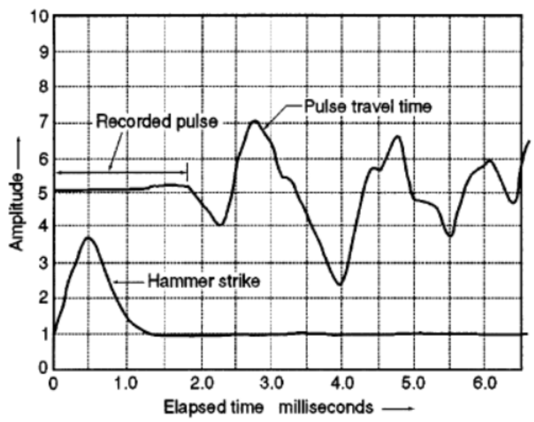


Figure 13. example of resulting waveform graphic of both signals: Generated hammer pulse and a received pulse. (RILEM Recommendation TC 127-MS-D.1)

When all the planned coordinates are tested, data acquisition is recorded and the propagation velocities are calculated (figure 14 b and c), the results can be presented as a visual representation of velocities distribution inside the material (Figure 14 c). A clear example of this data analysis can be seen in figure 14 where a direct SPV is carried out to test the consistency of a collapsed masonry pier at Noto's Cathedral (Bind, et al., 2001).

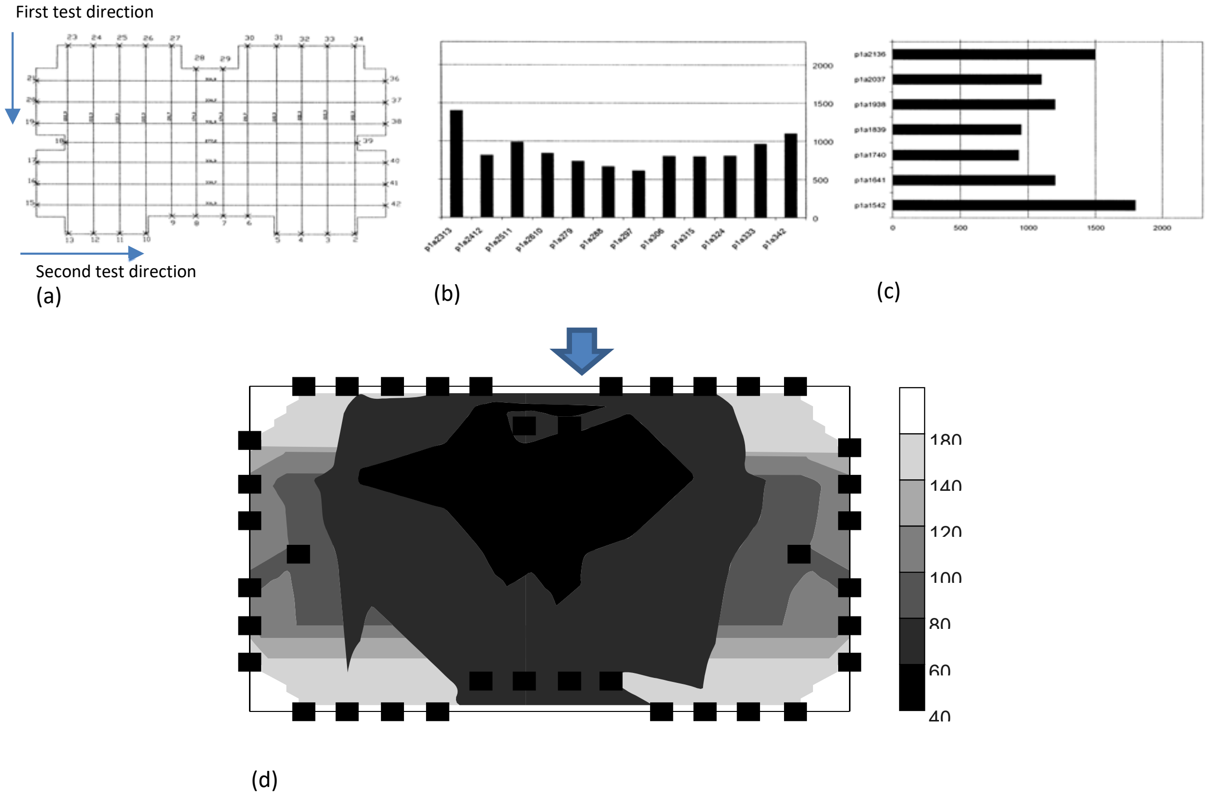


Figure 14 a) representation of hitting points and accelerometer receivers' locations on the perimeter of a pillar. B) representation of single path velocities in the first test direction. C) representation of single path velocities in second test direction. D) visual representation of velocities distribution inside the structure; showing clearly the bad condition of the inner part. (Bind, et al., 2001)

5.1.1 Sonic tomography

Another methodological approach that gives results with higher resolution is the sonic tomography. The difference lies on the usage of many receivers simultaneously located at different points of the structure to detect the same sonic pulse, instead of measuring one by one single wave paths.
It is suitable for all the detectable target defects mentioned before with the other three previous named sonic methods.

For this method the set-up and the equipment required is quite different to the previous described method. The number of required accelerometers is much higher than for direct, semidirect and indirect sonic test. This time all of them are needed at the same time while for the basic arrangements transmitter and receivers work in pairs (Figure 8). In consequence, if a supporting structure is not planned, several workers are required.
From the propagation time of each wave their single pulse velocity is calculated and putting together the different speed of wave paths (from point of impact to each accelerometer location point) the result is an image of velocity distribution inside the material or element (see figure 16). It is applicable when the access to all the surfaces of the structural element is possible. (Zanzi, et al., 2001)

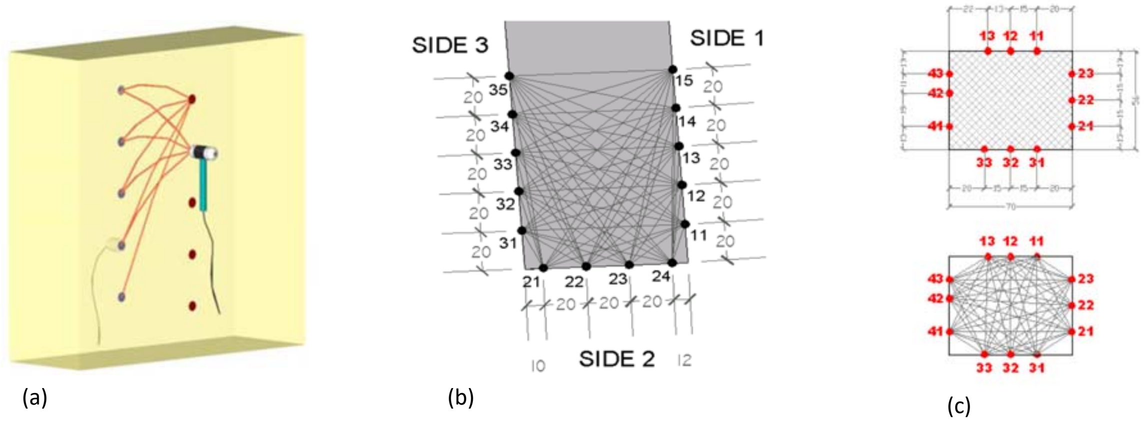


Figure 15. Sonic pulse tomographic arrays. a) Vertical section application. b) Arrangement of receivers on the faces of a wall. c) Horizontal section and pulse paths inside from 4 accessible faces. (ONSITEFORMASONRY, 2004)

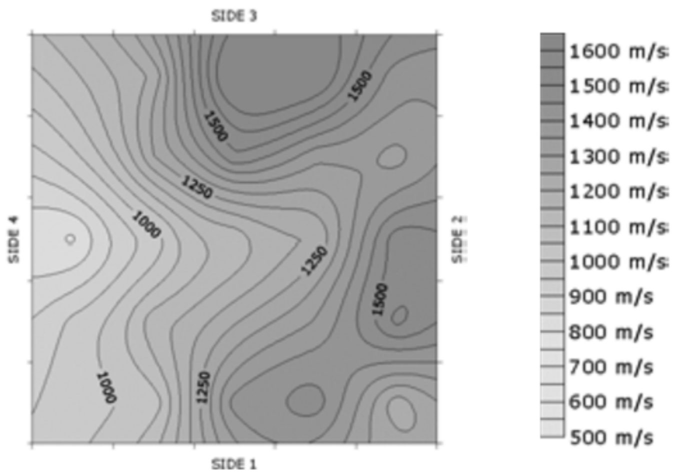


Figure 16. Resulting velocity map from sonic pulse tomogrpahy (ONSITEFORMASONRY, 2004)

5.2 Reflexion application method (Impact-Echo test)

Although Impact Echo Test is considered to be another different acoustic technique with other protocols, sonic pulses are involved and therefore this brief explanation can be helpful to contrast this method with other like direct sonic test or ground penetration radar (section 6) and avoid misperception.
Impact-echo tests work like sonic pulses with frequencies between 1 and 80 kHz (Sansalone & Streett, 1998). While the explained methods in previous sections calculate the propagation speed of a stress wave pulse by transmission mode (side to side through the studied structure), IET procedure can determine the depth of inhomogeneities, voids or cracks inside the material or the thickness of structure by reflexion mode.

That means; the impact hammer generates a stress wave pulse that goes through the body. This mechanical wave has three different wave fronts: P-waves (the target of the measurements), S-waves and R-waves (shown at the start of the Displacement-Time diagram). The different velocity of the front waves allows to differ the signal of P-waves, which are the fastest and the first one to be read by accelerometers located near to the impact point.

When the pulse hits other material, for example at the interface of layers, air voids within the material or the opposite surface of the element, with different acoustic impedance (mechanical property of each material to attenuate mechanical waves) part of the wave pass through with different speed and part is reflected to the initial impacted surface as an echo (Krautkrämer & Krautkrämer, 1990) (see Figure 17).

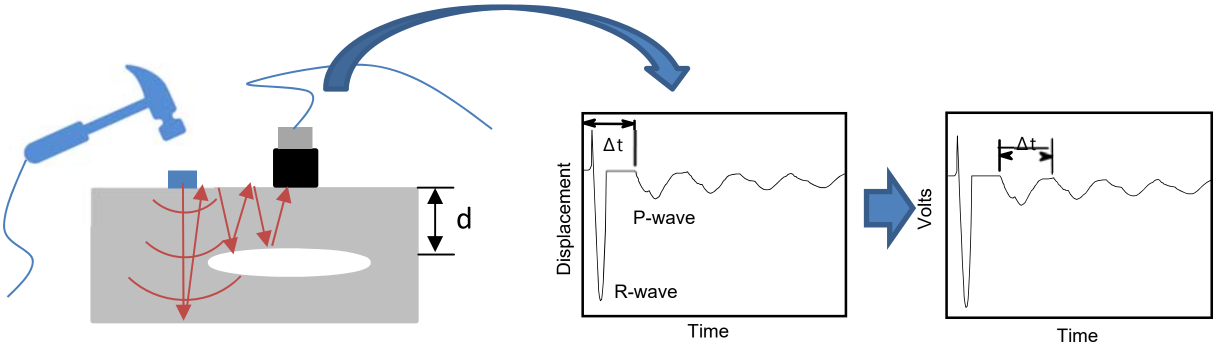


Figure 17. Impact-echo method and lecture of receiver which transforms the mechanical energy into electrical signal

The receiver transforms and digitalise the displacement or mechanical energy of these wave reflexions into electrical signals in the time domain. Those data values in function of time are translated into amplitude values in the frequency domain by Fast Fourier Transformation (Figure 18). (Taffe, et al., 2010)

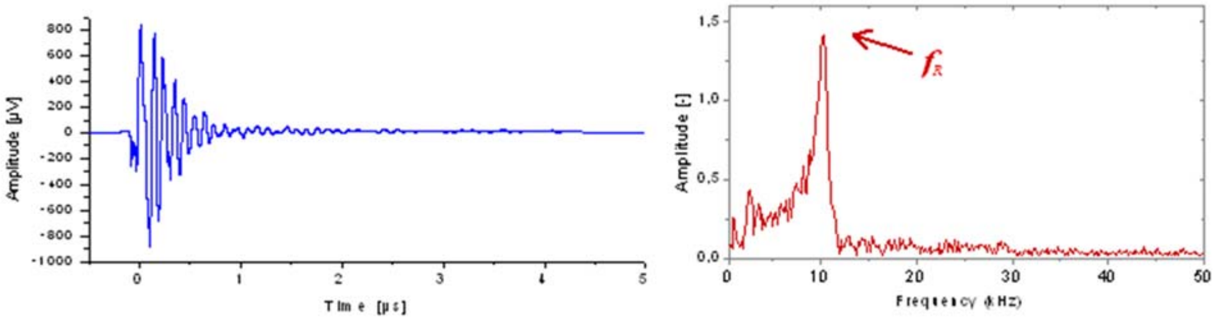


Figure 18. Converted data analysis (Motz, et al., 2003)

The characteristic frequency given by the peaks of the representation image is related to the depth of the flaw by the general equation 2.
With the previous knowledge of the wave speed through the thickness of the element and the fundamental equation of Impact-Echo test, the depth of the interface or void (d) can be calculated (Motz, et al., 2003). The wave speed must be calculated previously by other method (Lombillo, 2019).

$$d = \frac{v_p}{2f}$$

Equation 2. Fundamental equation for Impact Echo Test.

Where v_p is the propagation speed of the wave through the thickness of the element and f is the frequency.
This acoustic technique has a specific application standard to evaluate P-wave speed and the thickness of concrete plates (ASTM C 1383-15).

5.2 Sonic test equipment

The equipment required to carry out a sonic pulse velocity test comprises a mechanical wave transmitter, which can be a calibrated hammer or impactor which can measure the initial impulse, one or more accelerometers as a receiver device to measure the incoming wave information, a digital acquisition system and a laptop or PC to store the data results. The scheme is shown in figure 8.

Figure 19. Impact hammer, accelerometer and Integrated data acquisition device

There are many different types of impactor. Usually a calibrated hammer is used to generate long wavelengths for sonic testing and their weight is related to the pulse properties. The available weights in the market are approximately in between 1 and 6 kg and its characteristics determines the energy content and frequency of the original pulse. The head's material of the impactor defines the amplitude of the sonic wave and the thickness span able to be tested (RILEM, 1996).

There is a huge variety of accelerometers to select from, depending mainly on the frequency that has to be studied. For sonic velocity test with low frequencies, receivers with a range between 0.1 and 4800 Hz or 0.2 and 6000 Hz are suitable, according to several manufacturers. Broader ranges for general purposes are consider from 0.2 until 10000Hz approximately. The sensitivity of the accelerometers is important. Maierhofer, et al. (2004) consider a sensitivity between 100 and 1000 mV/g to be good enough to carry the acoustic tests.

To process, transform and record the wave impulses the minimum required equipment is an oscillometer; roughly, it is a sensitive dispositive that transforms stress pulses into electrical pulses. Those electrical signals are shown on the digital display screen as a waveform in function of time and all of it is store in a PC. Lately most of the test are carried out with integrated adquisition devices (Maierhofer, et al., 2004). In any case, all the parts must be connected by cables, long enough to allow wider onsite investigation.

5.3 Sonic pulse velocity test standards

The main recognized source of information for sonic pulse velocity test procedures for on-site application are the national ASTM standards and the published recommendations from RILEM.

- ASTM C597-16 – *Standard Test Method for Pulse Velocity Through Concrete*
- RILEM Recommendation TC 127-MS-D.1 - *Measurement of mechanical pulse velocity for masonry*

Although the ASTM standard is the most famous, it gives a brief description of the technique and a superficial explanation of the practical procedure (figure 20), without deep explanations of the different application methods and, their advantages or disadvantages.

Apart from that standard, the guideline with recommendations developed by International Union of Laboratories and Experts in Construction Materials, Systems and Structures which is much more complete and clearer to follow.

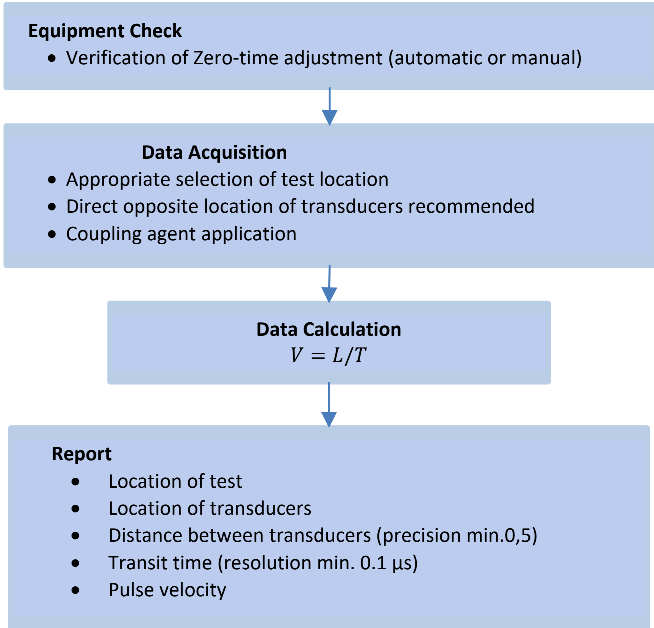


Figure 20. ASTM procedure scheme

Main differences between both documents are:
Opposite to RILEM and many others NDT standards which do not include a previous minimum analysis of the historic building, it is remarkable that ASTM C597-16 makes a singular mention to study accurately the existing constructions. In order to select the best locations for the SPV test, it is suggested to follow another standard, named ASTM C823-00. *Standard Practice for Examination and Sampling of Hardened Concrete in Constructions.* It is a guideline to perform visual examinations and selection of hardened concrete samples in constructions before onsite test methods.

While ASTM standard is a general guideline for pulse velocities between 20 and 100kHz, RILEM already specifies the procedure for lower frequencies until 5 kHz, which are more suitable to be use in historical building.

What is unique at ASTM norm is that it dedicates a numbered section to describe different equipment calibration options, which need to be taken into account and RILEM does not include.
RILEM also goes deeper to explain the different sonic methods, target testing problems, conditions of testing and set-up arrangement and interpretation of data graphics.

For the calculation of velocity, the main given equation in both documents is the general calculation of wave speed propagation (see equation 1).
Exceptionally, ASTM explains the general relation between modulus of elasticity and the pulse velocity (equation 3) but does not recommend the method to establish the modulus of a material from on-site conditions. It commends other kind of tests to determine in a quantitative manner the strength of materials.

$$V = \sqrt{\frac{E\,(1-\mu)}{\rho\,(1+\mu)(1-2\mu)}}$$

Equation 3. Relation of Pulse Velocity and material mechanical properties

Equation 3 to describe pulse velocity, where E is the elasticity modulus, µ is Poisson's ratio and ρ is the density of material.

RILEM gives, once again, more detailed information about the preparation and execution of the procedure on-site and about the resulting report from the testing process and the information that should be included (see figure 21).

Comparing the two most followed standards for sonic pulse velocity, it is more appealing to follow the RILEM recommendations. It is clearer to understand and therefore it is easier to follow in practice by stuff who is not familiar with this technique. In addition, it provides recommendations to deal with more specific building decays, which is an advantage to save time and resources.

Very important is the lack of information about sonic tomography methodology. None of those two guidelines consider that possible method.

Equipment Check
- Hardness of hammer tip
- Sensitivity of accelerometers (between 100 and 1000 mV/g)

↓

Data Acquisition
- Selection of SPV method: Direct (through-wall) transmission, Semi-direct transmission or Indirect transmission
- Accuracy of each path distance (min. 0,5% of the length)
- Coupling agent application

↓

Data Calculation and Interpretation
- General equation: $V = L/T$
- Recommended verification of material strength with additional techniques
- X-Y plots (mostly for Indirect method)
- Contour maps (mostly for direct method)

↓

Report
- Reference to the followed standard
- Date of testing
- Test conditions as location, environmental, etc
- Building identification and date of construction
- Name of the professional responsible for the test
- Type, model and last calibration of the device
- Identification and description of the specific test and the investigated element
- Detailed information of each testing point: distances, individual wave pulse description
- Compilation of results for customer presentation
- Explanation of results, specifying the founded flaws or defects
- Results and comments from/for complementary tests

Figure 21. Scheme of SPV procedure according to RILEM recommendations

6.3 Extracted information from interviews

During this work, several interviews with experts have been conducted. The target was to point out testing defects, previous experience with the methods and normalization and calibration procedures.

6.3.1 Testing defects

In contrast to active thermography which has a very good performance to detect moistures and humid materials, the results from sonic pulse velocity are severely affected by water presence in structures.
If there are doubts about the water content of a material or structure that can affect the SPV results, other kind of test such as thermography or ground penetrating radar should be performed. SPV is not recommended for moisture detection or cracks recognition in damped materials (Blanco, 2019).
Although it gives a reliable result about the consistency of materials, minor destructive test like flat jacks should be done in combination with SPV to confirm the strength.
Thus, this method is suggested for confirm the reliability of supporting masonry in general and historic buildings in particular.

6.3.2 Previous historical studies, investigation planning and reporting

There is no agreement about the need of previous documentation in order to apply the SPV test.
It is generally accepted that a previous visual investigation is enough before SPV test is carried out to select best locations. Actually, NDT are used during the pre-diagnosis stage and maintenance stage of a structure, therefore the result of these tests can be included in the preliminary documentation for a rehabilitation (Lombillo, 2019).
Regarding the investigation planning, weather conditions are not determining except in case of exterior testing with rain; the material to be tested must be dry.
In practice, final report is a free-format document with the information that the expertise considers more interesting for the client. The application of standard and guidelines recommendations is up to the professional, but RILEM final report scheme is the most complete.

6.3.3 Normalization procedure

Although the existence of standards it is known, there is a high adaptability for its application and professionals may be more interested in other personal experiences to increase the accuracy of the test than in protocols.
Despite direct transmission is recommended, many times the location does not permit that set-up arrangement. Semi-direct transmission is preferred when through-wall is not possible, to avoid the more time-consuming estimations for indirect test system.
The minimum number of workers involved is two for SPV and more in case of tomography according the amount of working receivers, but the same person should always proceed the impact with the hammer, in order to hit with the same energy (Blanco,2019).

6.3.4 Previous calibration

As the standard recommends, calibration of correct measurement acquisition is done before the test by all the users. Prof. Lombillo (2019) prefers the term *verification* to define it. Most of the devices come with a calibration bar that is made of a material with pre-known properties and characteristic, giving always an equal velocity. A first sonic pulse must be checked through it before test is carried on-site.
It is significant to also test the calibration bar with the coupling agent to calculate the deviation time through it. A recommendation for a coupling agent is the medical ultrasound gel due to its very low velocity attenuation.

7. Ground Penetrating Radar test

The principles of the radio detection and ranging (radar) technic are based on the properties of electromagnetic waves in the frequency range between 300 kHz and 300 GHz as it is shown at the beginning in figure 1. Ground penetrating radar is a type of radar technique characterized by its working frequency range in between 100 MHz and 2 GHz (RILEM, April 2001) (Binda, et al., 1998) (figure 22).

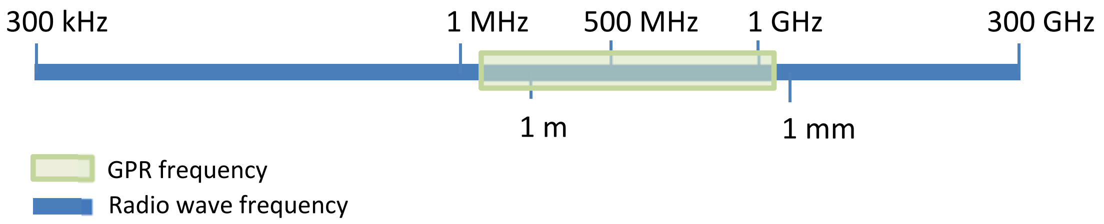


Figure 22. Ground penetrating radar frequency range.

Electromagnetic waves are a combination of electrical and magnetic fields. Inside a vacuum, they are transverse waves. The interaction between electromagnetic waves and materials depends on their frequency, which can vary by a wider range. Unlike acoustic sound waves, electromagnetic waves do not depend on a medium to travel. Thus, they can overcome very long distances in space, since electromagnetic waves travel with the speed of light inside a vacuum. However, the waves can spread through different substances like liquids, solid materials or gasses. In that regard, the speed is decreased inside the different matters. The ratio between the phase velocity of electromagnetic waves inside a medium and the speed of light inside a vacuum is described by the index of refraction or dielectric constant, as it can be seen in equation 4.

$$n = \frac{c_0}{c_M}$$

Equation 4. Equation refraction index

Where C_0 is the speed of light in vacuum, c = 299792458 m/s and C_M is the phase velocity of wave in the medium.

The radio detection and ranging has its origin in the military aviation with the purpose of recognition and location of objects and has been adapted for geophysical examination and at latest for non-destructive structural building tests. Over the time several radar systems have been developed to achieve various purposes, for example the ground penetrating radar, weather radar, radar for ground control intercept and many more. The systems are based on the same principles: An emission, reflection and detection.

The ground penetrating radar works with very short electromagnetic waves. The emitter antenna generates a vectored electromagnetic wave with specific or varying frequency and wavelength into the building (Daniels, 1996). Furthermore, the phase speed is known. The electromagnetic wave is influenced according to the physical laws of divergence, refraction, reflection scattering und absorbance. When the wave meets inhomogeneities, interfaces between different materials or the opposite surface of the structural element with different electrical properties, the incoming wave breaks. Part of the energy is reflected due to the difference of the dielectric constant mentioned before and other part of the energy penetrates through the thickness until the next change of material. However, the reflected signal from the incoming wave is detected by the receiver and thus can be evaluated, processed in function of time and analysed (Livingston, 2001) (Ayala Cabrera, 2009). That echo also contains electromagnetic information

from the crossed material that is represented on the final images.
The sequence of recorded wave signals is processed by software and later represented by radargrams images. This process is shown in the figure 23.

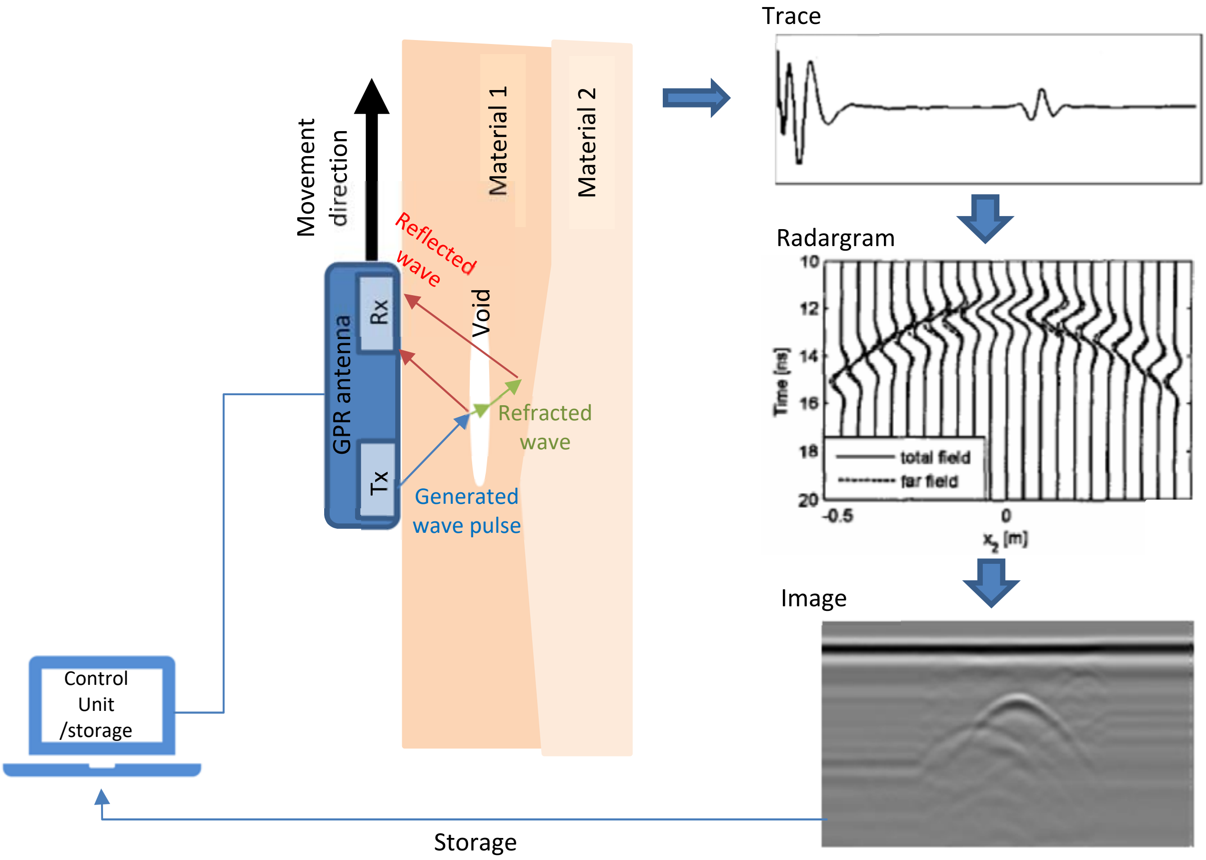


Figure 23. GPR working scheme in reflection method.

Metallic components are the easiest to detect, since the electromagnetic waves will be reflected completely. Unfortunately, they might prevent a deeper penetration of the impulse. Though, all different materials can be detected according to the electric and dielectric properties of the materials, such as for example wood, stone, concrete or air, which can indicate cracks or other damages of a structure.

Also, GPR allows quantitative determination of inhomogeneities depth. As it is mentioned before, knowing the phase speed of the wave and the time-of-flight until the reflection is received, the distance to the flaw can be calculated quite accurate with the following equations (Livingston, 2001).

$$V = \frac{c}{\sqrt{\varepsilon_r}}$$

Equation 5. Speed propagation equation to calculate the dielectric constant

Where C is the speed of light in vacuum and ε_r the dielectric constant of the material

$$d_i = \frac{c}{\sqrt{\varepsilon_{r,i}}} \cdot \frac{t_i}{2}$$

Equation 6. Fundamental depth of penetration equation

Where $d_i$is the thickness of the layer, t_i the travel time, C the speed of light

7.2 GPR equipment

Any experiment that involve ground penetrating radar technique requires at least one GPR unit, triggering tool, connection cables and a control unit (PC).
The GPR unit is composed of a transmitter antenna (Tx) to generate the electromagnetic wave and a receiver antenna (Rx) to detect and evaluate the returning wave signal. The GPR antennas work with accuracy of nanoseconds (ns). Depending on the disposition of these parts, the radar unit is monostatic or bistatic. Monostatic devices contain the transmitter and receiver in the same antenna shield box as it can be seen (figure 24) whereas bistatic GPR works with two physically separated antennas (Carrick Utsi, 2017).
The data calculation is simpler with the single antenna box, because there is no need of later distance correction between transmitter and receiver to determinate accurately the depth of the inhomogeneity.

Figure 24. Example of monostatic GPR unit (http://www.betagroupgc.com/services.html)

The selection of the antenna should not only be based on the simplicity and comfort of the method. Usually the size of the antenna is directly proportional to the wavelength emitted, and in consequence, inversely proportional to the frequency. As an approximate rule of GRP producers, the width of the antenna is the half of wavelength size (Carrick Utsi, 2017).

Frequence	Depth
2.6 GHz	0.3 m
1.5 GHz	0.45 m
900 MHz	0.9 m
400 MHz	2 m
200-16 MHz	30-40

Figure 25. Table frequency-depth relation

Exactly like sonic velocity test, the selection of ground penetrating radar antenna is a matter of the desired depth to be achieved and the expected image resolution. The higher the frequency is, the higher the resolution which is provided, but the depth of penetration is lowered, the longer the chosen wavelength is (lower frequency), the deeper is the penetration distance but the resolution is reduced.
Depending on the method of application, there are recommendations as:

- 1 GHz antenna used in reflection mode for a depth range of 0.5-1.5 m
- 1 GHz antenna in transmission mode for a depth range 1- 3 m

Extracted from the project Onsiteformasonry (2004). See also figure 25.

The triggering tool is usually an odometrical wheel attached to the GPR unit and in compact or more modern machines it is already integrated. It is used to locate the position of the antenna in context and serves as origin reference for further movements.

Nowadays the control unit is in charge of processing, displaying and storing the data, but sometimes those steps are performed by separated devices: a control unit, display screen, etc.
Connection cables are also needed to connect all the devices if they are not included in the GPR unit from the manufacturers.

7.3 GPR transmission method

Ground penetration radar has, like thermography and sonic pulse velocity tests, different methodologies of application. It depends on the location of the transmitter and receiver antennas with respect to each other.
To select the appropriate methodology there several parameters to consider. Such as objective decays, accessibility to the target to test, probing depth or material conditions. According to the selected method, the required equipment can vary.

7.3.1 GPR reflection method

GPR reflection method is the most common method and it implies also the simplest set-up.
GPR transmitter and receiver antennas are located on the same surface of testing. Its working procedure is the standard method of radar application (section 7): the antenna emits a wave pulse, that pulse is reflected and sent back to the receiver, located on the proximities of the transducer. This procedure can be seen in figure 23.

This method can be performed with a single monostatic GPR unit (figure 24). In case of using a bistatic GPR device with separated antennas, the arrangement must consider the distance separation between them to correct the calculations afterwards. The two-time-travel is longer in this case than for a monostatic unit (figure 26).

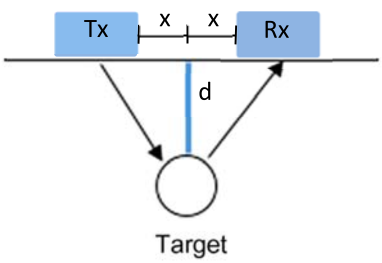


Figure 26. Two-time-travel length

This methodology can be applied to all kind of suspected decays in historical buildings:

- Masonry thickness determination
- Multiple leaves detection and their thickness
- Inclusions and installation detection
- Masonry inhomogeneities
- Detached leaves
- Inner voids
- Material characterization
- Crack detection and characterization
- Moistures

The recommended frequencies for masonry analysis for this system is in between 900 MHz and 1.2 GHz (RILEM, April 2001)
The minimum number of workers to carry out the test is two. Using a monostatic device, one person manipulates the control unit while the second person move the antenna. For bistatic units three people are recommended: one to operate the control unit, and the other two are responsible for transmitter and receiver locations (ONSITEFOR MASONRY, 2004).

As an example of application in reflection mode, figure 27 shows the plan procedure (a) and the resulting 2D radargram (b) of the GPR test carried out on the floor at the Basilica of Santa Maria del Mar in Barcelona (Perez-Gracia, et al., 2015). The aim of the survey was analysing the internal structures in constructive elements and to detect possible damaged areas.
The image 27a reports graphically the GPR paths on the floor; the two yellow paths P_1 and P_2 represent the radar tracks follow to extract the resulting radargrams 27b and 27c.

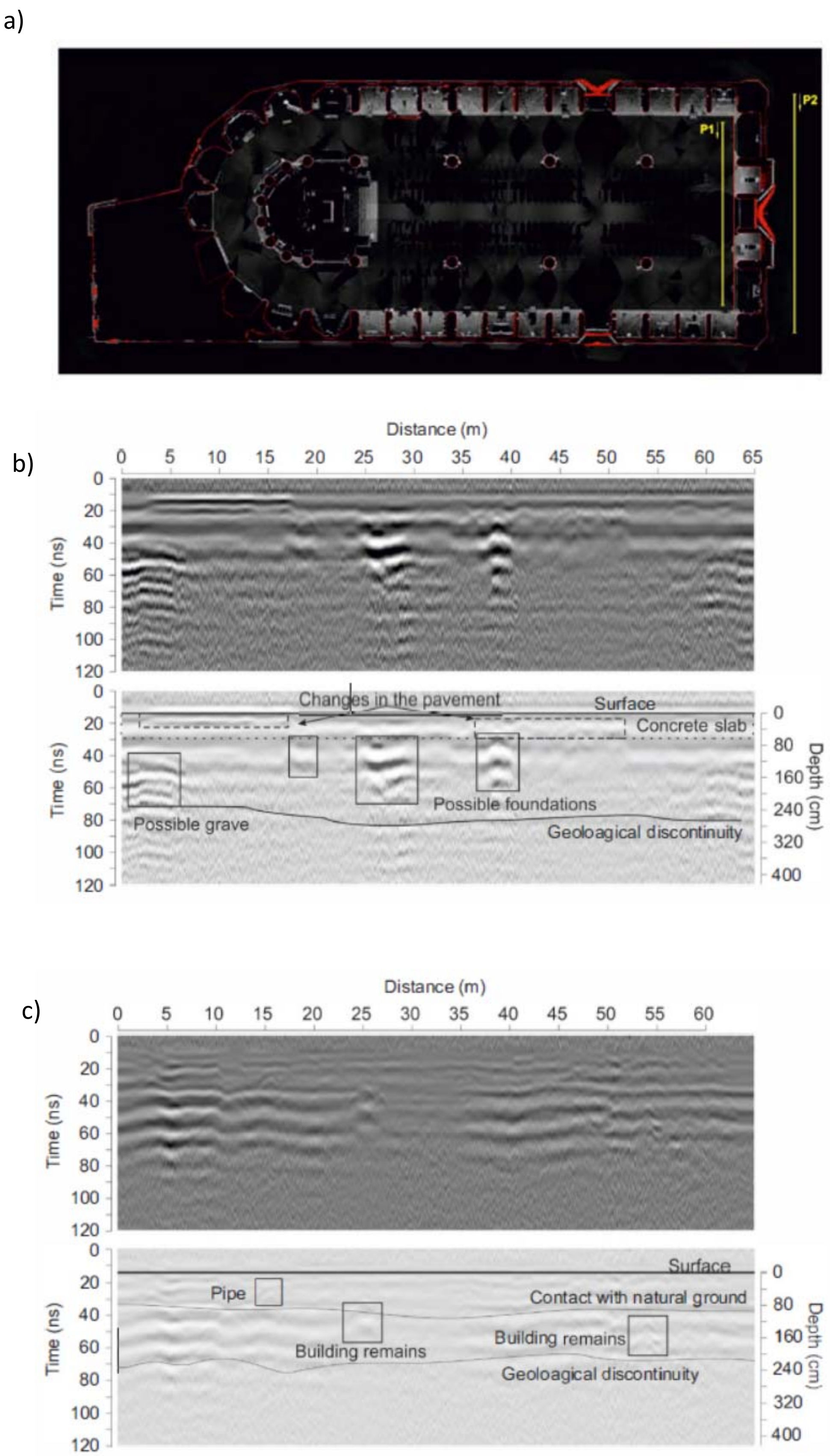


Figure 27. a) Experimental arrangement of GPR paths. b) 2D radargram from P_1 scan and c) 2D radargram from P_2. both with graphic interpretation from test author (Perez-Gracia, et al., 2015).

7.3.2 GPR in transmission method

As it occurs with thermography and sonic pulse velocity test, there is also transmission method for ground penetrating radar test.
For this array minimum two separated antennas are required, one is the wave transmitter and the other is the receiver. They are located one on each side of the element to be evaluated, as it can be seen in figure 27.
As it is with separated antennas in reflection mode, the minimum essential number of workers is three, and that number increase if more receivers are implemented.

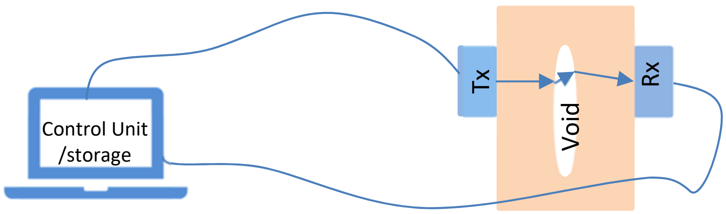


Figure 28. Scheme setup of GPR in transmission method.

In this case, the time-of-travel of the wave is just the time of one way, but in order to reduce the angle of distortion the respecting position between both antennas is needed. Thus, the distance calculation is the fundamental relation of:

$$d_i = v \cdot t_i$$

Equation 7. Depth calculation for GPR transmission method.

Where d is the depth at certain location, v is the known wave speed and t the one-way time-of-travel.
If the phase speed is not known, it is sufficient to know the distance between both antennas and the travel time. Thus the phase speed can be calculated.
This method is mostly recommended for moisture detection (ONSITEFOR MASONRY, 2004); the high wave attenuation because of the presence of water, does not permit sometimes the two-way travel of the wave in reflection mode. Thus, direct path between transmitter and receiver is reachable under high humidity for certain waves.
In transmission mode, the approximate frequencies recommended for historic masonries are in the range of 100 MHz – 500 MHz (RILEM, April 2001).

No matter the method, reflexion or transmission, the graphical result of linear scans is usually a 2D radargram. It is the compilation of all the processed EM reflection traces in an image. That image represents the length of the scanned path by the GPR, the time-of-flight of the wave and the depth of investigation. Also, the intensity of received signal (wave amplitude) can be characterized by colour or brightness in the image (figure 28).

In figure 29, the image is an example of a test carried out by Binda et al. (1998) at a wall of the Castle of Malpaga (Italy). The scan was performed in transmission mode along a vertical path of 1,5 m long at a masonry wall. It was able to show the presence of different layers, but the signal was clearly affected by the dampness of the bottom part of the wall. The radargrams represent in spatial and time scale the founded inhomogeneities, which allows to locate accurately on-site discovered defects.

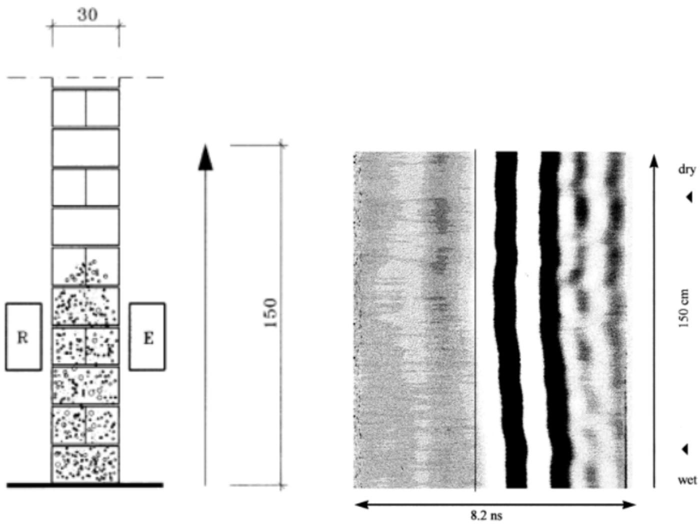


Figure 29. Experimental procedure and resulting 2D radargram (Binda, et al., 1998)

7.3.3 GPR tomography

Ground Penetrating Radar tomography is another type of transmission method. The concept is the same as in tomography with sonic pulse velocity. Tomographic radargrams are the result of a specific set-up array tested in transmission method. The transmitter generates electromagnetic waves and several antennas receive the signal and process it. Afterwards, the not fixed antenna receiver is moved to next testing point and repeats the process. Hence, the application of tomographic method requires much more antennas than reflection and simple transmission modes (Binda, et al., 2003) (Topczewski, et al., 2007) . (See figure 29)

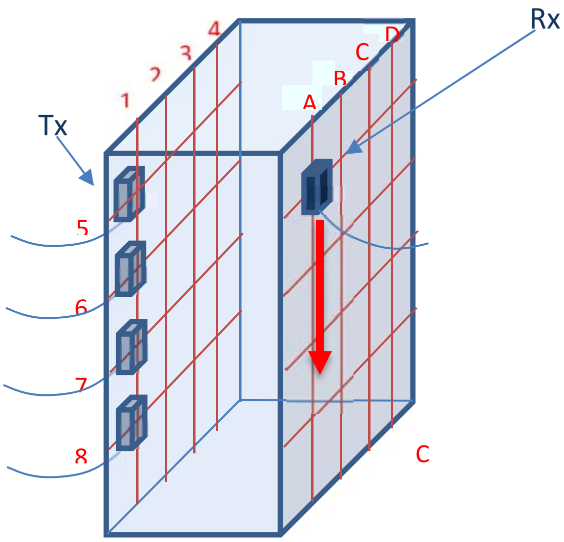


Figure 31. Example scheme of a possible GPR tomography set-up at a wall

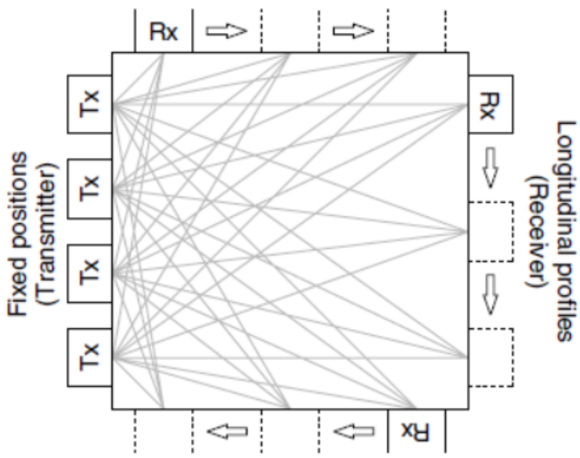


Figure 30. Scheme of GPR tomography set-up at a column (Topczewski, et al., 2007)

The outcome of this methodology is a map of velocities, representing the wave velocity inside the analysed element (figure 32). The wave propagation velocity for each ray path can be calculated directly with the known distance between Tx and Rx antennas' locations and with the time travel of the signal since it is emitted until it is detected.

The image below is the result of a GPR tomography method applied to a pier of the Cathedral of Noto. This is a map of velocities inside the pier. Each point at certain height and depth inside the pier is related to a specific wave speed during the test.
From the image, the high presence of water into the structure can be determined by the severe reduction of velocity at the bottom of the graphic.

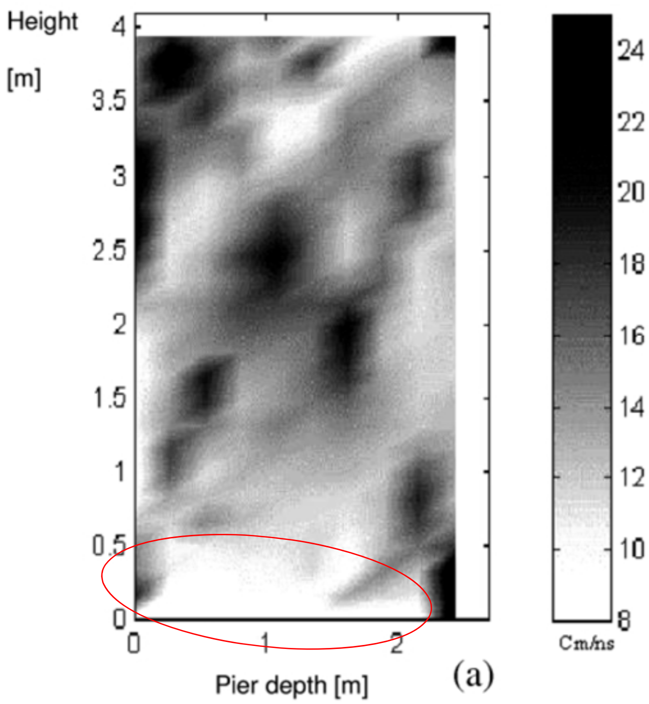


Figure 32. Example of ground penetrating radar tomography of a column of the Cathedral of Noto, Italy (Binda, et al., 2003).

Despite it is also a transmission methodology, this preparation is indicated to examine more decays than simple transmission arrangement, usually related to contrasting materials, and more reliable when water is involved, (ONSITEFOR MASONRY, 2004) (Binda, et al., 2003) namely:

- Multiple leaves detection and their thickness
- Masonry inhomogeneities
- Inner voids
- Material characterization
- Moistures

On the contrary to the multiple explained benefits of this methodology, simpler techniques are preferred as first option to detect flaws, because of significant amount of work to perform tomographic GPR test. This procedure is commonly used to assess fine targets after other previous examinations were not accurate enough.

7.4 GPR Test Standards

Ground penetrating radar technology is being used for several fields such as military defence, medicine, archaeology, aerospace industry, architecture and civil engineer among others. Hence, many standards were and are being developed in relation to GPR application.
In the fields of historic building conservation, GPR is relatively a young method. Many scientific papers show different cases where this system can be applied and prove or discard its use for certain targets, but still there are not so many official norms to standardize the application procedure for historical structures or buildings.
The main available standards regulate general aspects in relation to the topic such as terminology, general working principles, fundamental electromagnetic concepts and calculations, equipment requirements and the minimum content that the final report should contain. But mostly differ in the detail of explanation and their real applicability on site.
The most interesting standards and guidelines nowadays for ground penetrating radar application are:

- EN 302066 - ETSI HARMONISED EUROPEAN STANDARD Short-Range Devices (SRD); Ground- and Wall- Probing Radar applications (GPR/WPR) imaging systems
- ASTM D6432−11: Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation
- ASTM D4748−10: Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar
- ASTM D6087−08: Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar
- RILEM Recommendation TC 127-MS-D.3 – *Radar investigation for masonry*

7.4.1 Standard ETSI EN 302066

European Telecommunications Standards Institute has elaborated this precise norm that complies the EU standards. It is not applicable for communication purposes. The exact target of application is the explicit use of Ground- and Wall Penetrating Radars, radiating with frequencies in between 30 MHz and 12,4GHz, in close proximity the element of study. This element is clearly specified as a building material structure or the ground.

Because of its explicit narrow scope, in order to assure the officiality of a test in historic buildings or structures to a competent organization, the strict following of this norm should ensure the quality of the test procedure. On the contrary, the sections of this standard are mostly empty of content or refer to another European document, EN 303 883, which summarizes all the available information for general application of Ultra-Wide Band measurement techniques. That is not helpful in order to apply GPR onsite to historic buildings.

Technically, the standard relies the application methodology on the guideline delivered by the GPR manufacturer. The only section which explain a proper procedure is the *Calibrated setup*. It consists on the calibration testing the GPR device over a sand pit box of 50 cm deep. This calibration is mentioned is most of the procedures which involve radar techniques but due to the logistic that it requires, it is meaningless to carry it out of the laboratory.

Interferences are one of the main issues with GPR devices mentioned in the document. It does not give as much importance to the external waves that can interfere and affect the results of the test. The standard remarks the possible negative effect of emitted GPR electromagnetic radiation on other devices and living beings. Some recommendations are keeping off the device until it is going to be used or avoid sensitive places like hospitals or airports.
To avoid the external signal that might interfere to the test, the standard simply relies on manufacturer's

quality and recommendations.

The annex B named *Application form for testing* is a very helpful formulary to document professionally the GPR testing procedure. It can be taken as guideline and the minimum information required is as it is shown in figure

a) GENERAL INFORMATION

Type of Equipment

- Stand-alone
- Combined Equipment (Equipment where the radio part is fully integrated within another type of equipment)
- Plug-in radio device (Equipment intended for a variety of host systems)
- Other……….

The nominal voltages of the equipment or test jig in case of plug-in devices:

- Supply Voltage:
- type of power source (internal power supply, external power supply, battery…)

b) SIGNAL RELATED INFORMATION

General description

Operational bandwidth(s) of the equipment

The worst case mode for each of the following tests

c) RX TEST INFORMATION

General description

Performance criterion

- Accuracy, sensitivity…

Level of performance in %

Interfering signals

- Frequency [MHz]
- Power [dBm]
- Type of signal

d) ADDITIONAL ITEMS / SUPPORTING EQUIPMENT

- Spare batteries
- Chargers
- Technical documentation

Figure 33. Suggested data for application formulary for GPR testing.

7.4.2 ASTM D6432 - Standard Guide for using the Surface Ground Penetrating Radar Method for Subsurface Investigation

The American society of testing and materials has developed this standard as a guide for general application of GPR methodology. Although it is neither focused on preservation of historical building, its approach is more appealing to be used on-site, due to the applicability of its information: calculation formulas, practical recommendations, etc.

As most of the standards, it has a structure that includes terminology related to the topic. Besides the definitions, the fundaments of ground penetrating radar technology and the required equipment are explained. It explains in more detail that the European norm the steps for GPR procedure. The general scheme of the steps which are described in the norm for the GPR application including the final report is shown in figure 34.

Planning of investigation
- Targets
- Depth of penetration
- Desired resolution

↓

Selection of the GPR method
- Reflection
- Transmission
- Tomography

↓

Test design
- Required a priori data
- Plan of GPR line paths
- Access to element of investigation
- Dimensions of the element

↓

On-site implementation and check-up
- Possible modifications

↓

Calibration

↓

Data Calculation and Interpretation
- General equation: $V = d/t$
- Transformation of time-travel into depth
- Recommended verification of material strength with additional techniques
- Contour maps (mostly for direct method)

↓

Report
- Scope and aim of the test
- Description of tested element
- Boundaries of test
- Hypothesis
- Description of GPR characteristics
- Locate on site maps the set-up arrangement and scan lines
- Measured results
- Processing method and used software
- Results representation
- Interpreted results and description

Figure 34. Scheme for general application of GPR test.

7.4.3 ASTM D4748-10 - Standard test method for determining the thickness of bound pavement layers using short-pulse radar

Although this standard is very specific for the testing of pavement layers, the procedure can be highly useful to apply GPR to determine thickness of layer of historic structures.
In contrast to the mentioned norm ASTM D6432, which is an overall guide of use with general recommendations, the ASTM D4748-10 is a practical method.
The apparatus that is required for testing bounded pavements is different. Thus, the planned frequency, between 1 and 2,6 GHz, can be reduced to be used on building elements.
The procedure description is much shorter but more precise pointing at the important steps and calculation as it is shown in figure 35.

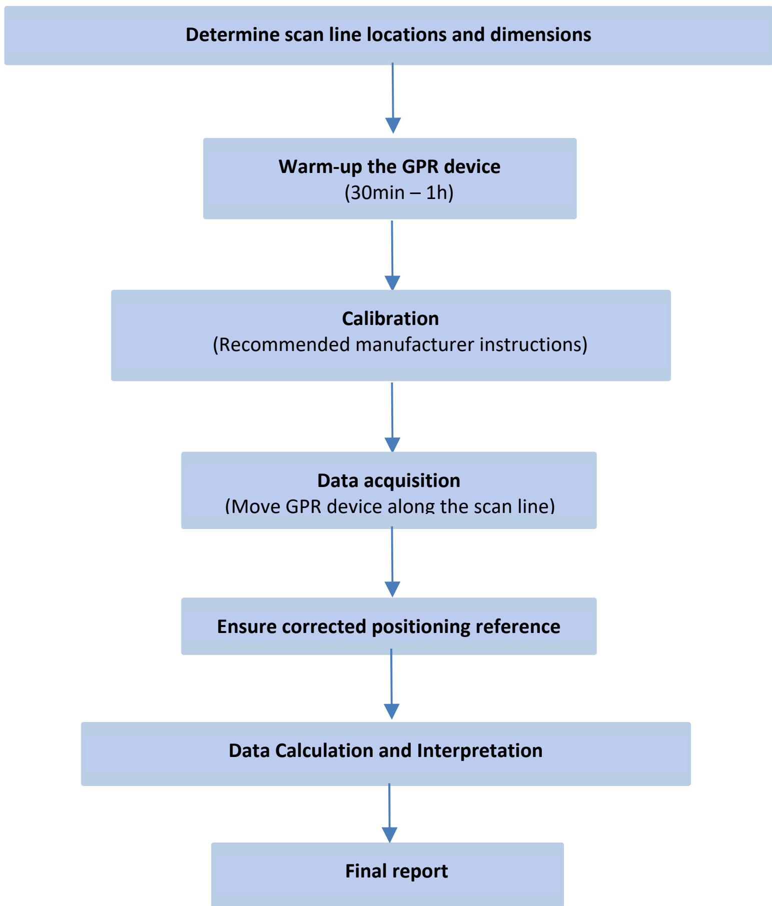


Figure 35. Procedure scheme of ASTM D4748-10

8. Conclusion

The technical development of the devices allows to save time in manual calibration, optimization of the set-up and numerical corrections. Standards need to be more specific in terms of the target testing problem for what they are planned. For the investigation planning and interpretation of results from NDT the expertise of the user is still a determining factor. In order to rely less on the practice experience with these techniques and to ease the selection of intervention areas, the importance of the preliminary investigation of the building is high.
For some techniques like ground penetrating radar, the preliminary assessment is mandatory but for active thermography, the standards do not consider any previous inspection before the test. The experience of the professionals is the opposite. By experience it is demonstrated that integrating at least a preliminary inspection before the planification of the test improve the efficiency of the tests. Thus, the integration of initial analysis of the building, before any NDT is selected, should be mandatory and documented as part of the protocol by official normative. With it, the selection of the most suitable diagnostic technology should be easier and more accurate.

Another important conclusion is about the recommendation of combining testing techniques, often joining non-destructive with minor destructive techniques. They are needed for mechanical characterization of materials. For further analysis, comparison in a table format of the efficiency of these combinations could be useful.

In relation with the existing standards, their strict application out of the laboratory is essentially insignificant. This should be signal for the official organisations to rethink the real influence of their standardization.

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