Detachments Detection at the 'Grand Stairway' in the Room 38 of the *Domus Aurea* using the PICUS System

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Abstract

The purpose of this research was the diagnosis of the detachments and the analysis of the subsequent stabilization intervention of antique roman plaster in Room 38 of the *Domus Aurea*. We carefully assessed the extent of the detachments in the fresco-decorated plaster before initiating the stabilization intervention. Two methods were implemented: manual auscultation and automatic scanning using the PICUS system. Both produced a map representing the defects prior and after the intervention. The comparison between the map obtained by the auscultation method and the PICUS map shows that they can be superimposed. The map obtained with the PICUS system highlights the most severe defects using a colorimetric scale, which is normally not used in a manual scan. The PICUS system has proven to be a valid support to the classical manual auscultation to prepare the map of the defects of antique, damaged cultural heritage.

Keywords: *Domus Aurea*, Acoustic excitation, Plaster detachment, structural analysis, Inspection systems, Signal processing

1. Introduction

1.1. Description of Room 38, the Great Stairway

The Room 38 of the *Domus Aurea* represents the northern boundary of a portion of the Esquiline wing of the Neronian palatial complex and con-

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stitutes the limit of a complex of rooms gravitating around the so-called Nymphaeum of Polyphemus. The north wall of Room 38 separates the architectural setting from the unexplored spaces, currently still buried under the Colle Oppio (1), as visible in figure 1.a.

The structure, long attributed to Nero's architects as an access to the upper floor of the Domus Aurea, is now re-evaluated in light of recent studies proposing a Flavian age origin[1](2).

This space, inserted between pre-existing architectural elements, underwent several transformations over the course of time until, before the final Trajan's burial, it became a monumental and scenic "Grand Stairway" connecting the rooms on the first floor of the complex with the upper garden level. A wall within the center of the hall, resembling the spine of a stadium, constituted a structure such that, using leveled wooden beams, a step-less staircase was formed. From the western end, bordering Room 39, one accessed to the first ramp, from which two more ramps continued to the outer pavilions of the north terrace of the Domus, as visible in the schematic reconstruction drawing in figure 1.b.

Above the vault of the second ramp, which may have been barrel-shaped or cross-vaulted, lay the access floor to the final ramp. All walls were decorated with fresco paintings. On the south and west sides, the walls were prepared with lime and pozzolana mortar in two or sometimes three stratified layers; the decoration consisted of perspective elements painted in fresco on a bright and intense yellow background. These decorative elements (socles and dadoes) serve as fundamental motifs in the design schemes of various rooms (4; 5).

The transformations of the west wing of the Domus Aurea, in the centuries following Nero's death and in contemporary times, have greatly altered the appearance of Room 38. An arch, probably a Trajanic one but of rather rough workmanship, cuts transversely across the western area of the ramps. The arch rudely intersects the small vault of the second ramp's floor and disrupts the fresco decoration on the south and west sides (6). Trajan's project for the overlying Baths, built on the Oppian Hill using the walls of the Domus Aurea as foundations, involved the construction of a water conduit that passed high above through the rooms adjacent to 38, filling them with

[1] Studies about the consistency with a prolonged use of the pavilion from Nero's death to the obliteration by Trajan are still in progress.

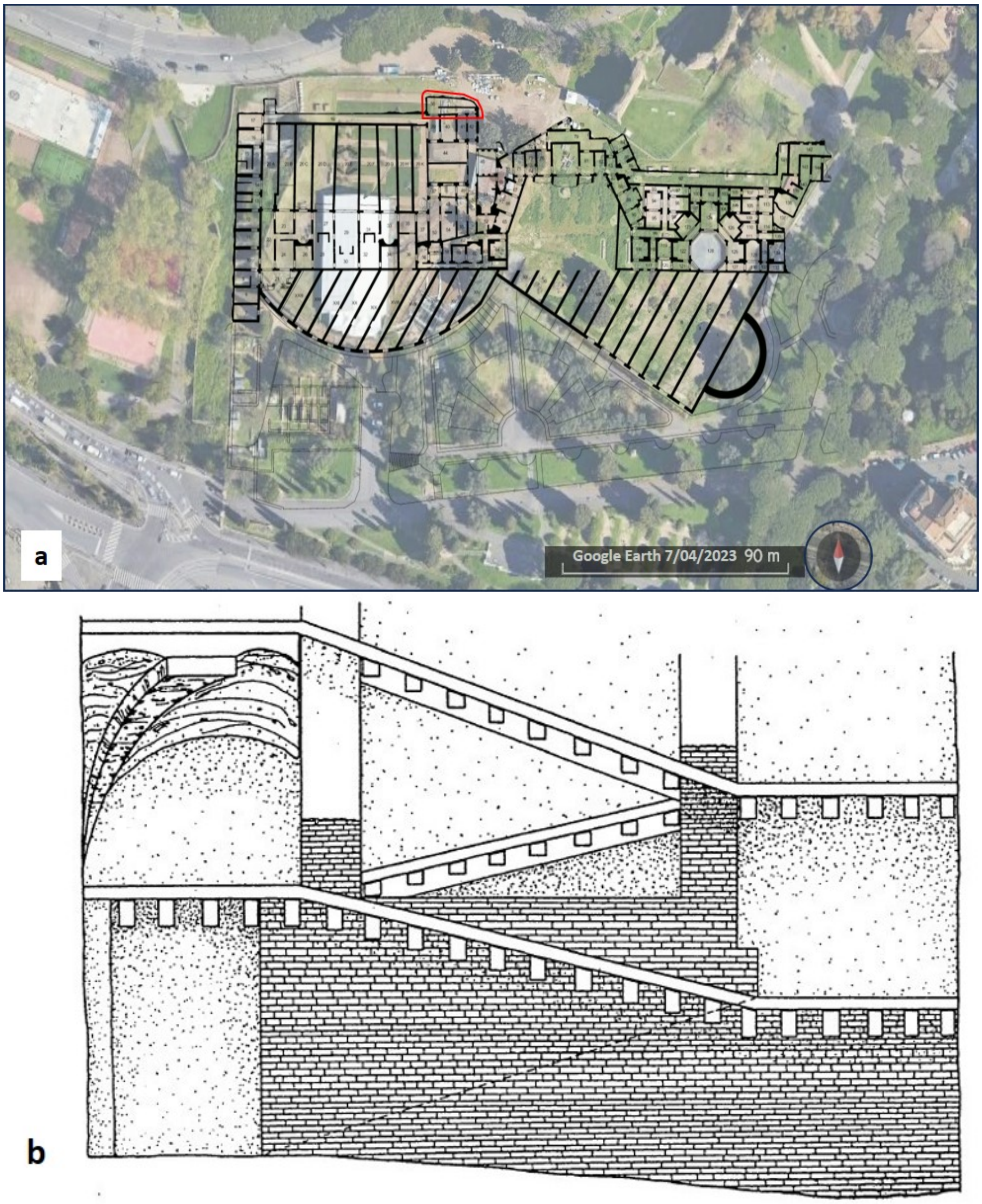

Figure 1: In (a), the currently known plan of the Domus Aurea of the Baths of Trajan and the gardens above. Room 38 at the northern edge of the excavation is highlighted in red. In (b) the schematic elevation drawing of the Stairway 38, north side. Top left: Trajanic arch intersecting the second landing vault. (3).

soil and supporting the conduit on this structure. Room 38 is the only area where the canal was supported by a construction, the aforementioned arch. On the other hand, that the upper landing of the stairs in Room 38 was supported by an added arch suggests that the staircase was not filled in, and it might have still served a purpose in the Trajanic era (5).

1.2. Case of study: the decorated plaster of the second floor

In recent times, but not precisely identified, the lower part of the vault of the second ramp's floor was covered with thick layers of fiberglass-reinforced synthetic material, forming a framework with the purpose of reinforcing the ancient structures and diverting water infiltration from the excavation above[2]. Water, finding its way above the waterproof structure, has continued to seep into the ancient porous structures, trickling along the walls at the interface between the brick facade and the layers of plaster. The plastic layers are exceptionally rigid, impermeable and adhere firmly to old structures, which makes their removal extremely difficult and risky. The almost irreversible presence of this "coat", along with an iron and cement structure serving as the ceiling of the entire room, has significantly altered the micro-climatic, as well as architectural, balance of Room 38.

Significant detachment phenomena (7) have occurred because of the leaking, with large portions of the mortar separating from the wall support. In result, the plasters on the south and west sides of the second ramp's floor showed only a few isolated sections of adherence to the wall support. An area of about six square meters of plaster was only held in place along the upper edge by the fiberglass vault itself, resembling large mortar slabs ready to give way by their own weight, as in figure 1. Thanks to the composition of the original mortars, based on pozzolana, plasters have retained their mechanical characteristics, still cohesive and "stiffly elastic". The detachment from the wall support appears to have acted as a protective barrier, isolating the layers and mitigating the degradation effects.

Recently, a stabilization work campaign prepared the upper basin in the

[2]Since the 1960s, many attempts have been made to improve or stabilize the internal environmental conditions of the Domus Aurea, some with discontinuous results. In 2010, the Great Conservation Project of the Domus Aurea began. The preservation of the structures and decorated surfaces is conducted on a multidisciplinary scientific basis. The project also includes the creation of a new garden above the Domus, with technological solutions to mitigate and progressively eliminate water infiltration.

Figure 2: Detached plaster on the south wall

gardens above the Domus Aurea for restoration with a technological roofing package [3]. Although the overall saturation level is expected to stabilize over time, occasional instances of infiltration and dripping may still occur before the system reaches equilibrium. In order to minimize the stress on the plaster and promote its re-bonding to the substrate, a stabilization intervention project was designed. It included curbs to support the weight and grouting to ensure localized but stable reattachment of the mortar to the wall, while creating drainage pathways. This would allow water to percolate along the walls, behind the plaster and across the curbs, preventing the formation of dangerous stagnant water at the base of the reinforced vaults and reducing the risk of leaks above the painted surfaces.

1.3. The PICUS System in Room 38 analysis

The case of the south wall, second floor of the monumental ramp of Stairway 38, was well-suited for examination with the PICUS System (8; 9). The PICUS System is an non-destructive and non-invasive tool [4] , (that includes

[3]This intervention was planned in 2022 by the Archaeological Park of the Colosseum, Rome, as part of a broader program aimed at securing the monument, recovering, conserving, and enhancing its structures and decorative elements. The work was supervised by M. Bartoli and S. Borghini, with scientific oversight by F. Guarneri.

[4]On-site non-destructive and non-invasive techniques do not cause any alterations to the decoration or its structural support, although they may involve electromagnetic or mechanical interactions.

a probe and a signal processing procedure) that serves as an effective qualitative screening method for detecting and mapping defects in the adhesion, addressing situations where more sophisticated and quantitative evaluation techniques face limitations (10; 11). Some of these techniques are contactless, such as Doppler laser scanner vibrometry (11), infrared thermography (IRT) (12), and electronic speckle pattern interferometry (13). Others require controlled contact (14), including micro-seismic sonic techniques (15; 16), acoustic tracing and tap-testing (17), high-resolution ground-penetrating radar (GPR)(18; 19; 20).

For the intervention in Room 38, several of these methods proved unsuitable. Specifically, contactless optic equipments were incompatible with the operational conditions. Radar techniques required prolonged surface contact, which was impractical, and due to the temperature consistent around 16°C, infrared imaging would necessitate artificial thermal perturbation (21), potentially harmful to conservation efforts. PICUS is an acoustic system inspired by the auscultation performed by conservators when assessing the presence of detachments. It involves contact, with a set of impulse-like mechanical solicitation of the surface, at a calibrated force and the sampling and processing of the acoustic response, as described in Section 3.3.

2. Research aim

The primary aim of this research was to diagnose the severe detachment scenario in the south wall of Room 38, in such an illustrious and simultaneously extreme environment as the Domus Aurea, and analyze the stabilization intervention through the application of the PICUS system. A thorough assessment of the plaster's conservation state and comprehensive documentation were essential to designing effective intervention methods and ensuring their successful implementation. The research aimed to test the PICUS System, which had benefited from advancements in the preceding two years of research (22; 23), for its feasibility in challenging conditions, such as a microclimate environment, biological contamination, and the limited access caused by scaffolding.

Additionally, the study aimed to compare the pre-intervention maps produced by the manual auscultation technique—a well-established method performed by professional conservators—and those produced by the PICUS system, to evaluate their accuracy and potential improvements.

3. Materials and methods

3.1. Stabilization of the detached plaster

The stabilization intervention for the painted plaster on the south side of the second floor of the ramp adopted a gradual approach. The process began by supporting the lower profile of the plaster layers, ensuring that the hanging slabs remained uncompressed. After several trials, a handcrafted mortar based on natural hydraulic lime and pozzolana, with filling and adhesive characteristics, was prepared. This mortar was used to create a support curb to make the edges of the plaster solid with the wall surface. To ensure water drainage, restorers inserted aluminum tubes with an 18 mm diameter into the fresh mortar to create passage channels crossing the curb. These tubes ascend into the gap between the plaster and the wall for a height of approximately 60 cm. The second step involved filling a portion of the void between the remaining plaster, the still adherent portions, and the curb. Injections of mortar with very low specific weight formulated for consolidation and re-adhesion was performed. During this phase, the tubes in the gap were left on place to ensure that the channels remain open. When the grouting mortar was set, the tubes have been carefully removed, leaving water pathways.

3.2. The assessment of detached plaster with the auscultation technique

The restorers engaged in investigations of detachments rely on the well-established auscultation procedure. The method entails gently tapping the surface with the fingers or knuckles of one hand, placing the palm of the other hand next to them. The percussion is calibrated on the potential solicitation bearable by the layer under examination. Despite involving a form of contact with the surface, the method can be considered non-invasive and certainly non-destructive. Depending on the conservator's sensitivity, the 'detachment system' produces a response detected as an acoustic wave and vibration (10). Conservators selected a solid and well-adhered point based on this result to serve as a reference (PICUS REF, also for the subsequent PICUS measurement procedure). The resulting map using the traditional auscultation method is shown in figure 3.

3.3. The PICUS system

PICUS is an automatic system to detect and measure the detachments, and more in general non visible defects (11; 8). In the traditional auscultation method, the analysis, the transfer of data into a map and the interpretation of

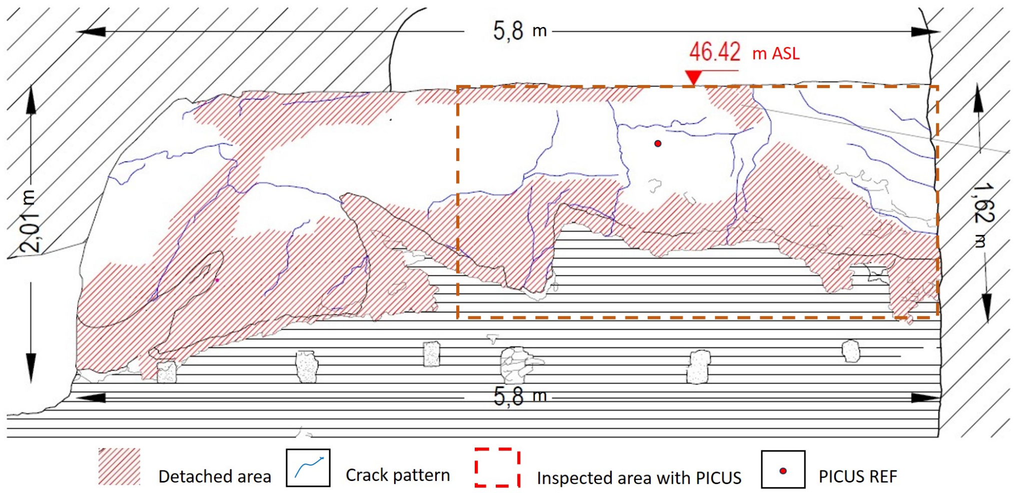

Figure 3: Conservation status: evaluation of detachment status prior to stabilization procedures with traditional auscultation method. The figure shows the detached areas (red hatching), crack patterns (blue lines), the area inspected with the PICUS system (dashed red outline), and the reference point for the PICUS system (red dot).

the results heavily rely on the sensitivity and perception of the practitioners[5]. For this purpose, we have developed a handheld tester (9), easy to use, safe for the delicate structures to be examined, ensuring the repeatability of the measurement to monitor the evolution of the conservative scenario. The proposed technique allows measuring entire surfaces, using a correlation method between an acoustic "snap" of the point of interest and an acoustic "reference snap" of a point certainly known (the PICUS REF of figure 3). The conservators, based on their experience, establish the reference point: with respect to this point all the other points will be compared and cross-correlate between them. The proposed method was implemented on an easy-to-use and inexpensive portable version of PICUS probe (22) making the new system suitable for "in situ" operation.

The number of audio samples is set in such a way which is a good compromise between the memory occupation and the fidelity of the recorded signal

[5]Notably, operating condition over time may not be consistent, application of force during the examination may vary. Another specific feature is the precision of the information transfer into a map.

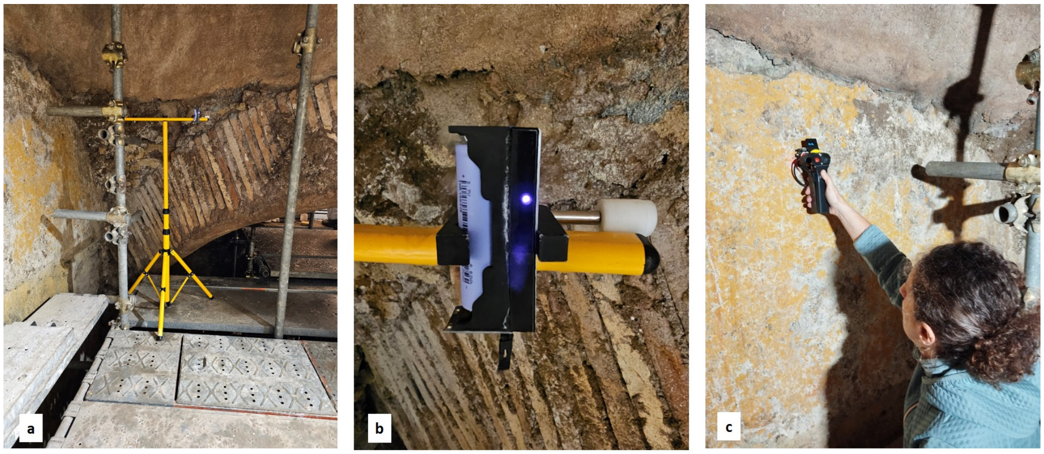

Figure 4: In (a) a view of the small space available for the operator; in (b) a detail of the infrared source, used for tracking the PICUS; in (c) a PICUS measurement session.

(22). The calculation of the cross-correlation vector, the maximum of which represents the index of cross-correlation measured by the instrument, was implemented using a procedure in time domain. The procedure produces a similarity index ranging from 0 to 1, which compares the response of the examined point to that of the reference point. A cross-correlation index close to 1 indicates a high similarity between the sounds recorded at the two points, while an index near 0 signifies significant dissimilarity. Data are stored in the SD-card on board of the PICUS probe. At the end of the measurement's session, it is possible to plot a contour line map[6].

3.4. The mapping system and its implementation

The PICUS tester has available a position tracking system based on the use of a new and low-cost infra-red (IR) camera which implements a real-time object tracking. The IR camera return a couple of coordinates for the bright IR spot, an IR LED source, depicted in figure 4.b. The IR LED source was placed on a stand, adjusting to the limited space available in situ (figure 4.a). The dimension of the IR camera frame was dictated by the Trajan substructures that cut obliquely through the available space. The maximum

[6]Mapping tools available at https://www.generic-mapping-tools.org/

distance available was 235 cm to tighten to about 130 cm in some areas[7]. This has led to some difficulties in framing a significant area, with the IR target very close to the PICUS probe and little maneuvering space for the operator (figure 4.c). For this reason, it was necessary to move the IR target along the perimeter of the scaffold and then acquire six separate measurements in six different framing, which are then overlaid on the photographic reference, as shown in figure 5.a and 5.b.

4. Discussion

The primary goal was to stabilize the detached plaster and prevent it from losing material or falling, therefore, it was necessary to carefully assess the entity of detachments before intervention. Both methods, auscultation and PICUS scan, were implemented and produced a map representing the defects; in figure 5.a, the map of detachments obtained before the intervention, using the PICUS system. The PICUS System map highlights the most severe issues using a colorimetric scale[8]. This is achieved by setting a threshold of cross-correlation values less than or equal to 0.64, instead of the typical value of 1, to ensure clarity in representation. By setting the maximum cross-correlation value in the representation to a lower threshold (0.64 in this case), the focus is shifted toward highlighting defects that deviate from the reference point (indicating no detachment). This approach avoids displaying all contour levels and emphasizes areas with significant differences, making the defects specific to the object under examination more prominent. The threshold is indicative, tailored to the needs of this case, and informed by the professional experience of the conservators. It can be considered a marker for detachments that require prompt action, while higher cross-correlation values are intentionally omitted from the representation. The comparison between the map obtained through the auscultation method and the PICUS map demonstrates that they can be superimposed, as both provide a qualitative

[7] The camera can work properly up to a distance of about 3 meters from the IR target, and considering the viewing angles of both the camera and the IR LED source, this specification translates into the ability to map an area of more than 8 meters on a side; in this case, the maximum side length was about 150 cm.

[8] i.e, characterized by a sampled acoustic response corresponding to a low cross-correlation index, indicating significant detachment areas that are structurally compromised and at a higher risk of material loss.

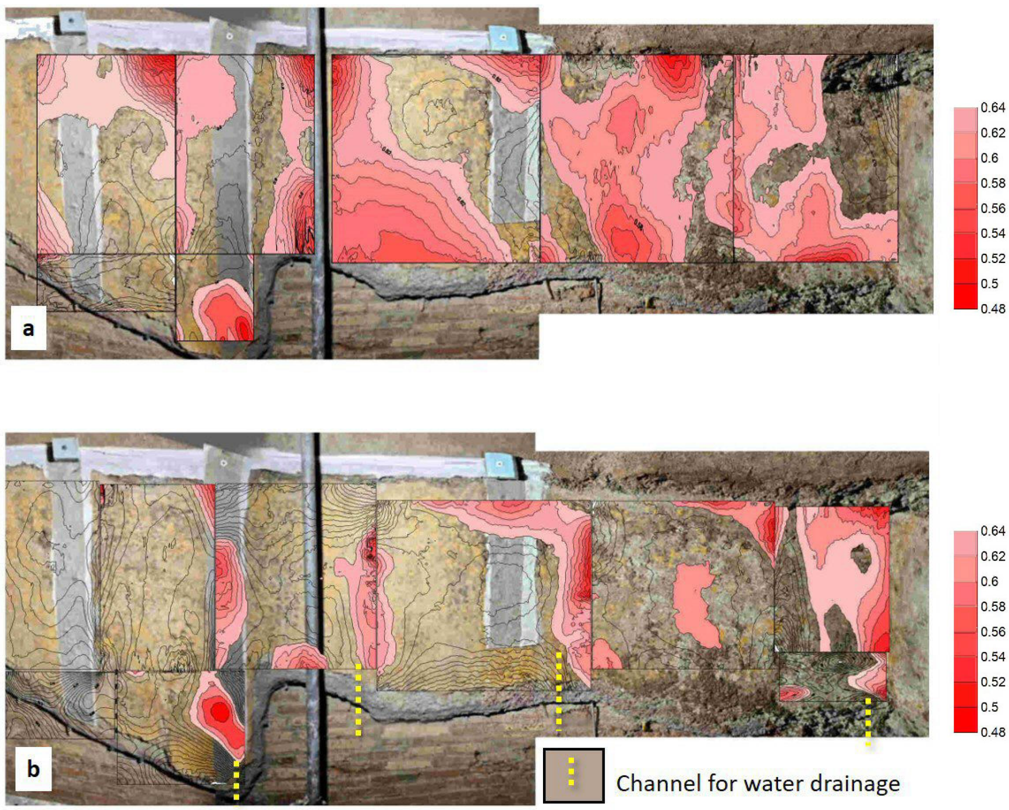

Figure 5: Maps of detachments obtained: in (a) before the intervention, in (b) after the intervention

distribution of detachments. This alignment is particularly important, as it confirms that the indications traditionally perceived through human auscultation are consistent with those detected by the PICUS system, validating its reliability. Through direct contact with the surface, the auscultation technique helps restorers engage with the problem, while the PICUS map offers a more detailed visualization of the detachment areas. Both helped to focus on the entity of the operations and also on the localization of the pathways to leave open for water drainage and air circulation.

5. Conclusions

The PICUS system provided effective non-destructive qualitative analysis for the hanging plaster detachments of the southwest ramp of Room 38 in the Domus Aurea. Other survey methods have proven to be more limited, such as thermographic prospecting without irradiation, because of the stable temperature in the environment and, like the auscultation method, prone to human interpretation. The PICUS system is stable under in situ operating conditions and the measurement can be repeated, e.g. before and after stabilization interventions. To repeat the procedure in situ, some limitations are experienced in positioning the IR LED source to frame the same area of the test object, but this can be overcome by means of aims used also in photogrammetry.

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