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Preliminary Tests of Millimetric Crack Detection in Ancient Wall Paintings using a Terahertz Radar

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***Abstract*– This work investigates the use of a terahertz radar system for the non-invasive diagnosis of wall paintings at the archaeological site of Pompeii. The imaging system is a frequency-modulated continuous-wave radar with a 27 GHz bandwidth centered at 0.3 THz (wavelength ≈ 1 mm), equipped with a pair of Teflon lenses in a confocal configuration and mounted on a robotic arm for XYZ micromovements. Initial tests targeted visible defects such as cracks and detached paint flakes in order to evaluate system performance. By imaging at multiple focal depths, the radar detected not only surface fractures but also possible subsurface extensions and secondary cracks. Also, THz imaging revealed mold and salt efflorescence with millimeter scale resolution. Although 0.3 THz images do not provide material-specific fingerprints, they clearly reveal dielectric contrasts associated with structural anomalies. Overall, the results demonstrate the potential of THz technology for cultural heritage diagnostics and conservation.**

I. INTRODUCTION

Terahertz (THz) radiation occupies the region of the electromagnetic spectrum between microwaves and infrared light (approximately 0.1–10 THz). In recent years, it has emerged as a powerful tool for non-destructive testing and imaging. Its ability to penetrate non-metallic and non-polar materials, such as paper, paint, and plaster, makes it particularly valuable for applications in cultural heritage and art conservation [1,2]. In artworks, THz imaging can reveal subsurface features including hidden layers, underdrawings, defects, voids, and cracks. Such anomalies typically appear as localized variations in the reflected or transmitted THz signal, arising from changes in dielectric properties or surface morphology [3,4]. Unlike other techniques currently employed, THz imaging is entirely non-invasive, making it especially suitable for the diagnosis of artworks [5]. Other NDT methods that are generally considered non-invasive are not applicable in this case: ultrasound can induce mechanical stress [6], while thermography may impose thermal stress [7]. X-ray imaging, on the other hand, cannot be implemented due to experimental setup constraints. This capability is critical for preserving artworks, as early detection of internal cracks or delamination supports preventive conservation strategies, guides restoration efforts, and contributes to a deeper understanding of the materials and techniques used by artists. In this study, a 300 GHz radar system was employed to map selected wall areas in Pompeii, with the aim of identifying defects such as cracks hidden beneath painted surfaces or mold associated with wall moisture. This approach demonstrates the ability of THz technology to reveal subsurface structures that may remain undetected by conventional imaging methods [8].

II. EXPERIMENTAL SETUP

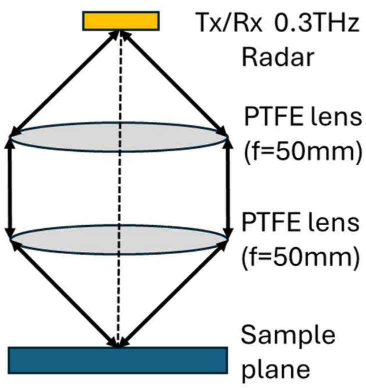

Figure 1 Optical scheme

Our experimental setup, illustrated in Figures 1 and 2, is based on a confocal configuration. It consists of a commercial system incorporating a 300 GHz radar (wavelength ≈ 1 mm, bandwidth 27 GHz) mounted on a robotic arm that enables precise XYZ micromovements of the source (TeraScan Cobot, Lytid SAS, Paris, France). The assembly is secured on a tripod, which provides coarse positioning adjustments. The study site is a room within the Villa of Diomedes in Pompeii. The radar operates at a maximum working distance of 35 mm, determined by the optical design of the mounted Teflon lenses, each with a focal length of 50 mm. The scanned regions are square areas with sides of 50 mm, acquired at a spatial resolution of 0.75 mm.

Figure 2: Experimental setup

III. RESULTS

To evaluate the feasibility of detecting subsurface cracks in the Pompeii wall using this technology, the first analyzed areas were selected for either clearly visible surface cracks or other identifiable defects. For cracks, a visible fracture was examined to detect potential secondary extensions. Similarly, visible defects were chosen to investigate whether affected regions might extend beyond what is apparent to the naked eye. Here, we present two representative cases for each type of wall anomaly.

A: Cracks

The first case is shown in Figure 3A. Radar images were acquired at multiple distances from the wall surface, taking advantage of the system's ability to position the focal plane both at the surface and within the wall. For cracks, this allows observation of potential secondary fractures branching from the visible fracture that are not detectable on the surface. As illustrated in Figure 3B, where the focal plane coincides with the wall surface, the surface crack is clearly visible as a dark blue line. The image acquired at a focal depth of 5 mm within the wall (Figure 3C) is noisier, as expected due to internal imaging, but still reveals a signal corresponding to the crack, identified as a region with higher yellow intensity.

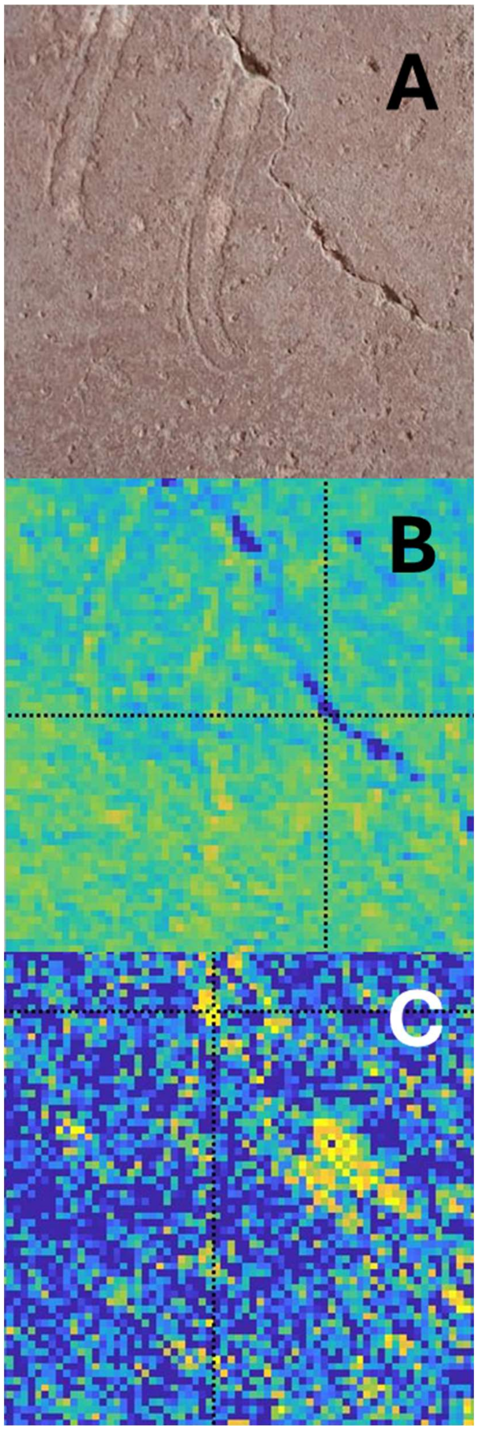

Figure 3: Different views of the same Crack. (A) Visible image. (B) THz image with the focal plane coincident with the wall surface. (C) THz image with the focal plane set 5 mm inside the wall

Figure 4 presents a second crack case, acquired with the focal plane at the wall surface. The visible image (Figure 4A) shows a relatively large crack, along with areas of differing wall height, highlighted by a black ellipse. In the corresponding THz image (Figure 4B), the main crack is clearly visible running diagonally, accompanied by secondary features. The first, indicated by the black ellipse, corresponds to the height variation observed in the visible image. The second, highlighted by the red ellipse, has no visible counterpart, suggesting a subsurface crack beneath the painted surface.

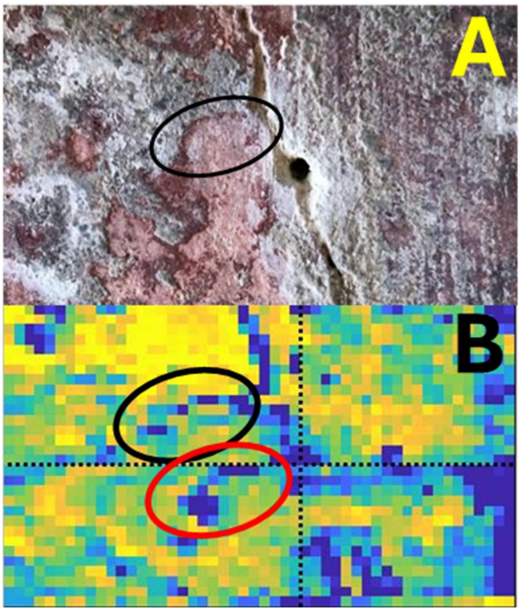

Figure 4: (A) Visible picture of a crack. (B) THz image of a crack.

B: Defects

For material defects, we first present a slightly lifted paint flake (Figure 5). The visible image (Figure 5A) highlights the area of interest with a light blue rectangle, showing slight delamination of the fresco. Beneath this portion, white material is visible, likely mold or salt efflorescence. In the corresponding THz image (Figure 5B), the height difference is traced by a dark blue line: regions above this line correspond to the lifted flake, exhibiting non-uniform intensity that reflects both the height gradient and the possible presence of underlying material. The observed intensity variations suggest additional material beneath the flake rather than solely partial detachment.

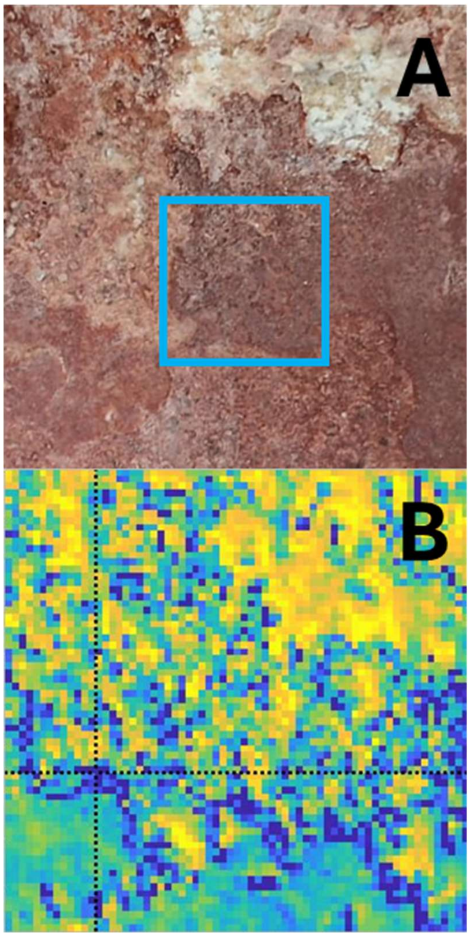

Figure 5: Case study of a defect. (A) Visible picture with a blue box highlighting the area studied with THz imaging. (B) THz image

A second defect case involves raised white material, likely salt efflorescence (Figure 6). The visible image (Figure 6A) also shows areas where the fresco layer is missing. Two THz images of the same surface, acquired at different focal planes along the z-axis, highlight complementary information. Figure 6B emphasizes height differences, clearly revealing the raised white material and areas of missing fresco, while Figure 6C highlights contrast within the fresco, likely associated with variations in wall moisture content.

Overall, THz radiation emerges as a promising tool for diagnosing specific issues affecting artworks. It should be noted that defects do not exhibit unique spectral fingerprints in this context; rather, they appear as contrast features within the images. Consequently, while this method does not determine the nature of a defect, it can indicate the presence of multiple types of anomalies within the analyzed area.

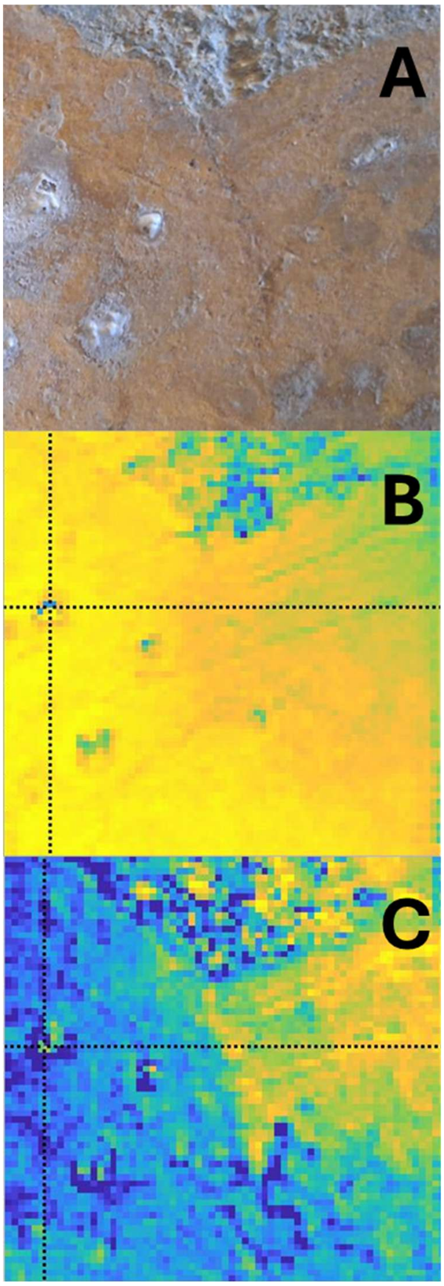

Figure 6: Case study of a defect. (A) Visible picture. (B) & (C) XY planes at different z of the THz image

IV. CONCLUSION

Terahertz (THz) imaging at 300 GHz has shown promising capabilities for non-invasive diagnostics of wall paintings in Pompeii. By analyzing both visible cracks and lifted paint flakes, the system demonstrated its ability to detect subsurface features and structural anomalies. Although THz images do not reveal the exact nature of defects, they provide contrast variations that can indicate the presence of multiple defect types. Further analysis, including techniques such as principal component analysis (PCA), is ongoing to improve defect classification and interpretation. These results highlight the potential of THz imaging as a complementary tool for preventive conservation, enabling early detection of hidden damage, guiding restoration strategies, and contributing to a better understanding of the materials and construction techniques used in historic artworks. Future developments may focus on enhancing spatial resolution, improving imaging speed, and integrating spectral analysis to provide more detailed material information.

V. REFERENCE

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