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# Non-contact intrawall penetrating radar for heritage survey: the search of the 'Battle of Anghiari' by Leonardo da Vinci

M. Pieraccini[a,*], D. Mecatti[a], G. Luzi[a], M. Seracini[b], G. Pinelli[c], C. Atzeni[a]

[a]Department of Electronics and Telecommunications, University of Florence, via Santa Marta 3, 50139 Firenze, Italy
[b]EDITECH, Editech srl, via dei Bardi, 28 50125 Firenze, Italy
[c]IDS SpA, Via Livornese, 1019 56010 Pisa (loc. San Piero a Grado), Italy

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**Abstract**

In this paper a high-frequency large-bandwidth synthetic aperture penetrating radar intended for the inspection of masonry walls, and its application to intrawall investigation of an important Heritage structure in Florence, Italy, are described. The radar system has been conceived and designed for non-contact operation, in particular for allowing walls covered by paintings to be inspected avoiding damages to the surface artworks. The radar signal was a Continuous-Wave Step-Frequency (CW-SF) waveform, sampling a 4 GHz bandwidth at 10 GHz center frequency, thus providing relatively high resolution images of the investigated structures. Cross-range resolution is provided by applying a synthetic aperture approach, obtained by mechanically moving the radar antenna along a 2 m length aperture. In order to assess the radar performances and its detection capability, laboratory tests on masonry facilities were preliminarily performed. Finally, an extensive measurement campaign was carried out on a famous 16th century structure: the 'Hall of 500', in Palazzo Vecchio (Old Palace), in Florence (Italy). This investigation was aimed at finding evidence of possible discontinuities in the masonry walls, where fragments of the famous fresco the 'Battle of Anghiari' by Leonardo da Vinci could be hidden.


*Keywords:* Cultural heritage; Masonry; Microwave; Penetrating radar; Synthetic aperture radar (SAR)

## 1. Introduction

Penetrating radar imagery offers an unique non-invasive means for retrieving information on the internal structure of masonry and on the localization and size of reinforcement bars, voids and defects [1,2]. Penetrating radar is used increasingly in the field of Heritage investigation, diagnostics and restoration [3–6].

This paper describes a novel non-contact penetrating radar system, first experimented in a search campaign aimed at detecting hollow spaces or embedded discontinuities in historic painted walls of the 'Hall of 500' in Palazzo Vecchio in Florence. This investigation represents hopefully a contribution to the detection of possible remainings of the legendary lost fresco of Leonardo da Vinci the 'Battle of Anghiari', which a number of historians and scholars are convinced lies behind a wall in the Hall of 500. The history of the Battle of Anghiari began in 1504 when Leonardo da Vinci accepted a commission from the chief magistrate of the new Republic of Florence to paint a large fresco on the walls of Palazzo Vecchio's Sala Grande (Great Hall), commonly referred to as Hall of 500 from the number of persons it could contain. It would commemorate the historic Battle of Anghiari, in which the Florentine army defeated the Milanese in 1440. The mural was to be Leonardo's largest and most substantial work—about three times the size of the famous 'Last Supper' fresco he painted in Milano in 1495. Work began on June 1505, but like so many of Leonardo's works, the Battle of Anghiari would unfortunately never be completed. The unfinished fresco remained in the Sala Grande until 1563, when the painter and architect Giorgio Vasari undertook renovation of the space. The ceiling and the walls were raised, and the space was restructured by building new walls. Finally, Vasari himself

* Corresponding author. Tel.: +39 554 796 273; fax: +39 55 494 569.
*E-mail addresses:* pieraccini@det.unifi.it (M. Pieraccini), seracini@editech.it (M. Seracini), g.pinelli@ids-spa.it (G. Pinelli).

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covered the new walls with his own frescoes, which are visible today. All traces of the Battle of Anghiari were lost. Nevertheless, some scholars believe that Vasari was far too big a fan of Leonardo to have destroyed the artwork. Furthermore, they argue that it would have been a simple enough matter for him to have built a new wall over the work of Leonardo—as was commonly done then—rather than knock it down. Thus, scholars and technicians have spent decades searching for evidence of whether the Battle of Anghiari was preserved by Vasari behind one of the extant walls.

In 1976, a first investigation was carried out by Travers Newton, an American restorer, and John Asmus, a physicist from the University of California at San Diego; they attempted to determine whether or not Leonardo's mural was behind one of the walls, using a variety of introspection methods. Unfortunately, the research was unsuccessful and halted in 1977. Anyway, an invasive introspection was attempted by making a carving at a lateral zone of the Vasari's fresco in the left panel of the western wall. The assay showed a 15 cm large masonry wall leaning against an older stone one, and no hollow space between them.

In 2002, one of the authors (Maurizio Saracini) promoted a new campaign, in cooperation with the University of Florence, based on a number of technologies: infrared camera, ultrasound transducer and penetrating radar. In this paper the results of the extensive measurement campaign carried out in the Hall of 500 through an especially developed non-contact penetrating radar are reported. The employed radar, though not completely new with regard to working principle, has been specifically designed for this kind of applications and presents performances in terms of operative frequency and bandwidth not achievable with other radars.

## 2. The radar system

The center frequency of the penetrating radar system was chosen as 10 GHz, allowing to obtain a very large 4 GHz bandwidth using low cost and reliable microwave components. The expected drawback of high-frequency operation is obviously a high attenuation of the signal propagating inside the investigated medium, since the attenuation coefficient of a great part of ground and masonry materials depends linearly on frequency [7]. Dry masonry, however, typically has a low attenuation also at high frequency [8], and furthermore small discontinuities inside the investigated medium exhibit a larger cross section at higher frequency [7]. Therefore, the selected band appears a reasonable choice in order to investigate small discontinuities in a dry masonry up to about 1 m depth.

The block scheme of the radar is sketched in Fig. 1. The radiated signal is a Continuous-Wave Step-Frequency (CW-SF) waveform, generated by an external synthesizer, that the samples required bandwidth in programmable frequency steps [9,10]. The receiving section of the apparatus is based on the classical homodyne architecture. The synthesizer feeds the antenna and provides a reference signal for the mixer of the receiver that detects the in-phase component of the echo signal. Transmitting and receiving antennas, separated in order to minimize CW coupling, consist of two exponential horns with 20° half-power beam-width at 10 GHz frequency. The demodulated signal is amplified and digitized by a specifically designed acquisition board.

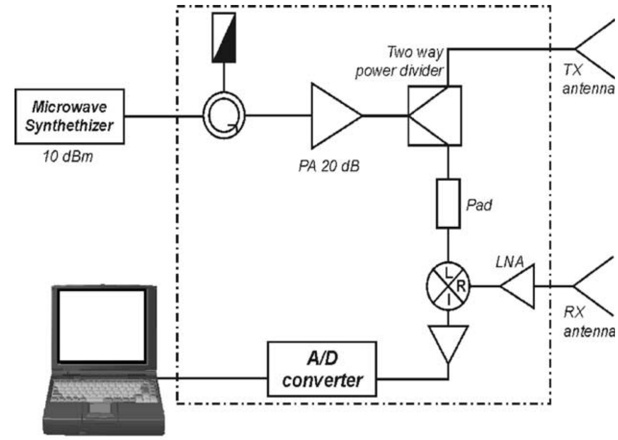


Fig. 1. Architecture of the radar system.

The radar is mounted on a 2 m length mechanical guide in order to synthesize a large aperture by moving the transmitting/receiving antennas and coherently adding and processing the signals received at different antenna positions in order to implement a Synthetic Aperture Focusing Technique (SAFT) [11–13]. Non-contact operation of the system requires some additional processing in order to take into account that the electromagnetic signal propagates through two different media, from air to wall.

Generally speaking, the air–wall interface causes the following effects:

(1) the path is changed by reflection (Snell's law);
(2) the speed along the path is changed according to the relative dielectric constant;
(3) part of the power impinging on the wall is back-reflected because of reflectivity of the interface (Fresnel's law);
(4) the wave propagating inside the masonry is exponentially attenuated according to a coefficient approximately depending linearly on frequency. This attenuation, if not compensated, acts on the image as a filter mismatch [14].

In order to take into account all the above points relative to the non-contact operation several specific SAFT are available in literature [12,13], in this paper we propose a ray tracing approach.

Let us consider a point $n$ inside the wall at a depth where focalization is desired, and a bundle of $N_r$ rays, comprised