

# **GEOPHYSICAL SURVEY ON THE VAULT OF SCARSELLA OF THE S. GIOVANNI BAPTISTERY IN FLORENCE**

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## **SUMMARY**

Electric tomography, seismic tomography and ground probing radar surveys were carried out on the *scarsella* vault of the Baptistery of S. Giovanni in Florence in order to supply structural information for the restoration of the monument. 3D rendering of the results allowed to reconstruct the pattern of the measured physical parameters in the vault structure.

## **1. INTRODUCTION**

A geophysical study was performed within the framework of studies that were carried out on behalf of the *Opera of Santa Maria del Fiore* in Florence on the Baptistery of S. Giovanni, to increase knowledge on the structural characteristics of the *scarsella* vault. The non invasive investigation, carried out with methods normally used in earth prospecting, offers useful information on the construction characteristics of the vault which can be used by the restorers. *Scarsella* is the high altar in Saint John's Baptistery in Florence, the roof of which is a cross-vault completely covered with precious mosaics of the medieval age. The vault is about 10m long, 5m large and shows a variable thickness from a maximum of about 5m to a minimum of 2.5m. There are small fractures on the internal surface, that cross in both main directions. In order to know the trend of these fractures as well as to define the structural characteristics of the vault itself, three different geophysical techniques were carried out, i.e. electrical tomography, to obtain electrical resistivity imaging; seismic transmission tomography, to

obtain elastic wave velocity distribution and GPR surveying, that was performed using 400, 900 and 1500MHz antennas, to obtain different resolution degrees. The data processing involved both 2D elaboration of electrical tomography and radar sections, 3D inversion of seismic tomography and 3D rendering of electrical tomography and radar images. The final interpretation, obtained from a comparison of the results of the different methodologies led to further detailed knowledge of the internal structure.

## 2. MATERIALS AND METHODS

Great care was taken in the data acquisition so as to obtain high resolution imaging of the internal structure and to prevent any possible damage to the mosaic. As the aforementioned techniques are usually employed in the field to survey for physical and geometrical characteristics of large areas, it was necessary to carry out some changes in the data acquisition procedure because of the small-scale of the monument and the fragility of the mosaics. Electrical data were acquired by using slim 2.5cm long silver needle-shaped electrodes, coated in silver chloride, which were carefully placed in joints between the tessera of the mosaic. Seismic tomography sensors were attached to the mosaic with medical tape, using silicone; silicone was also placed on the edges of the sensors to prevent weakening of the signal. The GPR survey radar antenna were wound with bands to prevent scratching the mosaics.

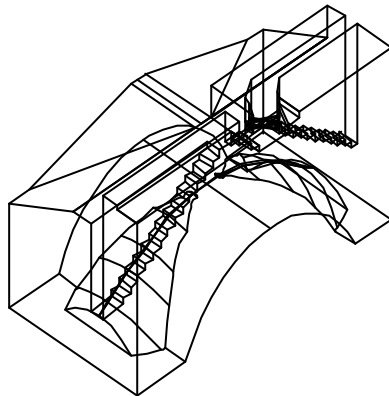


Figure 1: perspective view of the internal vault and the roof coverage

A high precision topographic survey of the vault was necessary to process the data (Fig.1), especially for the seismic tomography where the precise location of the sensors and shot points is crucial. The Electrical Resistivity Tomography (ERT) was carried out along 7 profiles located on the internal surface of the vault; the survey resulted in about 2500 apparent resistivity measurements. The data processing involved a forward solution based on the finite-element method. Meshes of generic triangular elements were used to follow the complex topographic surface of the Scarsella vault. The forward solution numerically solves for the electrical potential for three-dimensional (3-D) sources in a two-dimensional (2-D) model (Fig. 2). The inversion was carried out using Occam's inversion approach. This method allows the

estimation of the smoothest possible model that fits the data to an “a priori” defined statistical parameter [ 1 ].

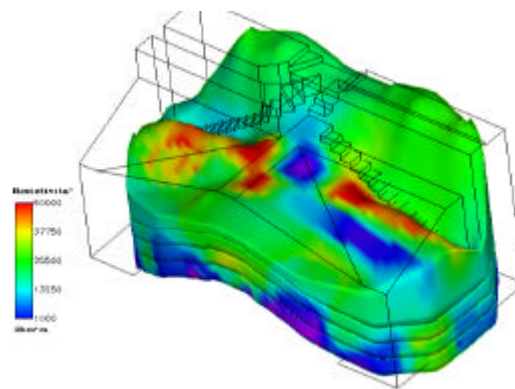


Figure 2: 3D rendering of the resistivity distribution inside the vault.

Seismic tomography involves the reconstruction of the seismic wave velocity distribution within the structure using traveltimes measurements of the seismic waves travelling through the structure. The methodology is based on traveltimes measurements obtained from a series of seismic sources and sensors located on the boundary surface of the investigated structure. In structure analysis the distribution of seismic velocity is useful to investigate the type of materials and to detect voids or fractures. In the specific case the data acquisition and processing were optimised to elaborate a three-dimensional tomographic image of the vault. This process involved acquisition using 46 sensors and 42 shot points. A pre-processing of the data was performed to identify and eliminate all those ray-paths that travelled in the air or were unrealistic because of noise; this step reduced the useful ray-paths for the inversion to 630. Taking into account the Fresnel ray theory [2] the vault was divided into 365 voxels with dimensions of  $1 \times 1 \times 0.55 \text{m}^3$ . The LSQR algorithm was used to invert the measured data set. This algorithm is suitable to invert ill conditioned systems. It is more robust than other commonly adopted algorithms and the convergence of the iteration process is more efficient than the conjugate gradient [3]. Two damping factors were included in the inversion procedure: the first led to the optimum trade-off between data misfit and solution instability; the second was used to obtain the condition of minimum heterogeneity, minimising the differences between the slowness of the neighbouring voxels with respect to the considered one. The covariance matrix was calculated to evaluate the degree of amplification of the noise in each voxel and the correlation degree of each voxel with respect to each other (Fig.3).

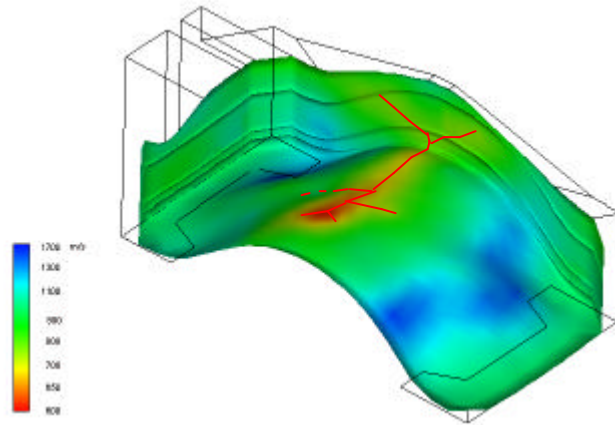


Figure 3: three dimensional image of the seismic tomography results; the spatial distribution of the seismic velocity is represented with different colours.; internal view from below, where the spatial locations of fractures are pointed out.

The GPR survey was performed along 9 profiles (longitudinal) and 10 profiles perpendicular to the previous ones, on the internal surface of the vault. The data were acquired in a common-offset single reflection acquisition mode. Variable offset profiles were also acquired to estimate the average velocity of the electromagnetic wave propagation in the first 30-40 cm of the internal structures. Due to the favourable site condition, the investigation depth at the different frequencies was about 0.6-0.7 meters at 1500 MHz, 1.5 meters using the 900 MHz antenna and 2-2.5 meters at the frequency of 400 MHz. The data processing (see [4]) aimed to enhance the presence of near surface fractures and to investigate the distribution of the materials inside the structure (bricks, stones etc.). The processing involved: trace editing and removal, horizontal normalisation and frequency filtering, static corrections to consider the curvature of the vault. Finally, complex attributes were calculated to enhance the response of the main anomalies. The processing of the CDP data permitted to estimate an average velocity of the near surface layers of about 0.12 m/ns; this corresponds to a wavelength of 0.10-0.12 m in the frequency band close to 1500 MHz and a theoretical spatial resolution of 0.05 meters. A deconvolution analysis was performed on some radar sections to estimate the lateral continuity of the main reflections due to the contact between the first layer of the mortar and the bricks and between the bricks and the overlaying materials. A three-dimensional rendering of the results was carried out, starting from the two-dimensional data processing of the complex attribute calculation. The first step was to generate the time-slices of the instantaneous amplitude values. Then these were spatially correlated to reproduce the iso-surface volumes: each iso-surface represented the "volume" characterised by instantaneous reflection amplitudes greater than or equal to a selected limit value. The selection of the limit value is a subjective procedure that can substantially modify the volume and the shape of the evidenced body. However, the 3D visualisation may help detect the presence of heterogeneity of a structure even though the exact dimension and shape of the elements cannot be determined (Figure 4).

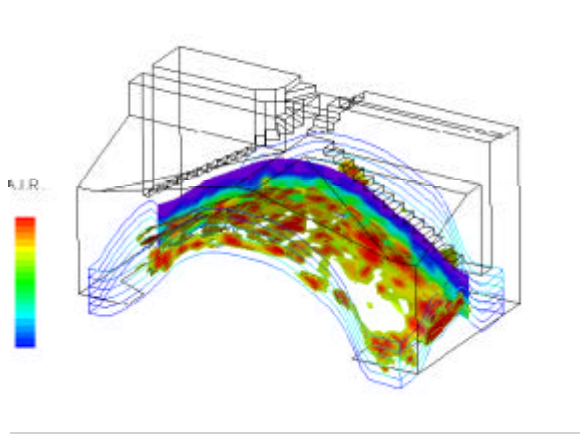


Figure 4: three dimensional rendering of the amplitude of the reflection (AIR) of the radar data acquired at 1500 MHz; the discontinuity of the response is correlated to the strong heterogeneity of the materials in the first 30-40 cm.

### 3. DISCUSSION AND CONCLUSION

The electrical tomography highlighted a spatial distribution of the resistivity values mainly in the range between  $10^3$  and  $10^5$  Ohm·m. A preliminary analysis of the electrical tomography allows one to point out a shallow electrical layer characterised by strong heterogeneity of the materials, probably because of the presence of an inner brick vault. The internal structure is characterised by resistivity values in the range between  $10^4$  –  $10^5$  Ohm·m, referring to the presence of stony materials. The tomography delineates some zones where resistivity values locally exceed  $10^5$  Ohm·m. The interpretation of these anomalies could be affected by some ambiguity, as these high resistivity values can be either correlated to the presence of voids and cavities inside the materials, or to the presence of fractures in the stone materials. However, ERT ambiguity can be resolved when the results are compared with the results of the seismic tomography.

As far as the interpretation of the seismic tomography is concerned, it is noteworthy that, from the elastic properties point of view, the monument may be divided into three main zones. With reference to figure 3 the lower central zone, where the lowest Pwaves velocities (600-800m/s) were detected, corresponds to the area where mechanic discontinuities are visible to the naked eye. These discontinuities seem to spread into the inner side of the vault where a second zone characterised by velocity ranging from 800m/ to 1000m/s is located. Finally, a third zone that is characterised by a velocity ranging from 1000-1700m/s was detected in the peripheral sides of the vault. These high values of velocity can be ascribed to the stress concentration in the vault near the boundary wall of the Baptistery that increases the stiffness of the structure and consequently rises the velocity values. Furthermore, observing the structure from transverse sections, it could be highlighted that the inner zones of the vault show better elastic characteristics than the outer sides. This is probably because the outer side of the vault was built in different period using different techniques and materials. Another reason for the different velocity values could be ascribed to the fact that the inner side of the Baptistery

vault is subjected to the load of the main dome which increases the stiffness of the structure and consequently increases the P wave velocity.

The main results achieved with the georadar survey can be summarised as follows: the detection of a main reflection corresponding to a two-way traveltime of 0.8-1 ns, pointed out by the deconvolution analysis performed on data acquired at the frequency of 1500 MHz; the evidence of a second main reflection at the two-way traveltime of 4 ns, which was depicted in several profiles acquired using the 900 MHz antenna; the presence of several scattering phenomena for two-way traveltimes above 4 ns, which could be related to heterogeneity of the internal structure due to the presence of unconsolidated filling material between the internal vault and the external roof.

The final interpretation of the survey is the compliance of the single data elaboration to obtain a realistic model of the internal structure. Obviously, each methodology offers a different perspective on the physical behaviour of the investigated area: electric and radar investigation are sensitive to lateral changes of the electromagnetic properties of materials (electrical conductivity and permittivity), which are greatly affected not only by the nature of the materials but also by the presence of humidity and moisture in the pores or fractures within the material. Voids and microcavities may provide a good contrast of electromagnetic properties; in this case electrical resistivity tomography might not be as sensitive as GPR or seismic measurements, especially when the investigated body is characterised by high resistivity values because of the presence of building stones and other electrically insulating materials. On the other hand, the seismic velocity distribution permits an estimation of the quality of the structure from a mechanical point of view and offers some useful information on the presence of a weak zone, potentially correlated to an intensely fractured portion of the vault. In such a context three dimensional seismic tomography is certainly an efficient and realistic way of describing the internal structure behaviour, even though the physical resolution of the results is limited by the size of the voxels used in the tomographic reconstruction process. A better resolution is achieved from the georadar survey, but in many cases great care must be taken in the interpretation process to avoid mistakes due to the presence of "ghosts" or artifacts in the radar images. Therefore only a refined comparison of results from different methodologies allows one to estimate the presence of discontinuities with an appropriate accuracy.

#### **4. ACKNOWLEDGEMENTS**

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#### **5. REFERENCES**

- [1] La Breque D.J., Miletto M., Daily W., Ramirez A., and Owen E., 1996, The effects of noise on Occam's inversion of resistivity tomography data. *Geophysics*, 61, 538-548.
- [2] Cerveny V. Soares J.E.P. 1992 Fresnel volume ray tracing *Geophysics*, 57, 902-915.
- [3] Van der Sluis A. and Van der Vorst H.A., 1987. Numerical solutions of large sparse algebraic systems arising from tomographic problems. In *Seismic Tomography* (ed G. Nolet), 49-83. D.Reidel Publishing Company.
- [4] Goodman, D., 1994, Ground-penetrating radar simulation in engineering and archaeology. *Geophysics*, 59, 224-232.