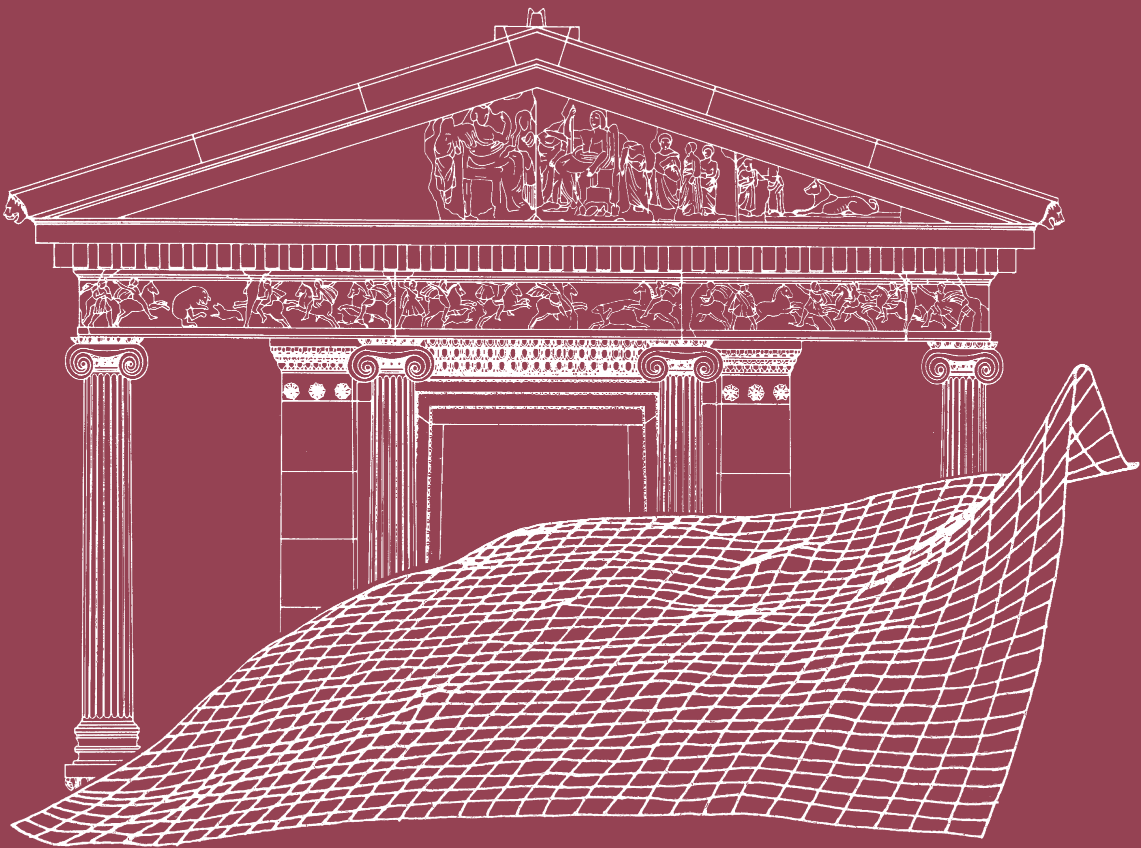

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INDICE

ARCHAEOLOGICAL COMPUTING:
SELECTED PAPERS FROM THE 2020 IMEKO TC-4
METROARCHAEO INTERNATIONAL CONFERENCE

edited by

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NEW DATA ABOUT THE CATHEDRAL OF CATANIA BY GEOPHYSICAL INVESTIGATIONS

1. Introduction

In summer 2015 a multidisciplinary research team began a ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) survey at the Cathedral of Catania (Southern Italy) and its surrounding areas. Part of the survey was aimed at outlining the presence, distribution, burial depth and age of possible buried archaeological remains. Destroyed and rebuilt several times after natural events and accidents, the Cathedral stands on the site of the Roman Achillean Baths and the martyrdom of the patron saint of the city. The current church was built in 1711, on a project by Girolamo Palazzotto. The sumptuous facade in three orders by Giovan Battista Vaccarini is in white Carrara marble, adorned with columns and statues. Noteworthy are the central portal, with 32 finely carved wooden panels, and the three lava apses of Etna, a legacy of the previous Norman Cathedral (Fig. 1).

The interior, with a Latin cross plan, is divided into three naves. The frescoes by the Roman Giovan Battista Corradini stand out in the central apse, with the Coronation of Sant'Agata, while the two columns at the base of the apse arch and the single lancet window are of medieval origin. In the right nave, there is the funeral monument of the musician Vincenzo Bellini, while in the right apse is the sumptuous chapel of Sant'Agata with precious relics. The temple houses the tombs of numerous Norman, Swabian and Aragonese royalty. The use of this site over the centuries makes it challenging to understand the distribution of various features in space and time because the remains of different ages are located at different levels and superimposed on each other. Also, the study area, as well as the largest part of the ancient town of Catania, is highly urbanized today with many nearby buildings from the Nineteenth century making the area fairly 'noisy' for most geophysical data acquisition methods.

Numerous studies have described efficient geophysical methods for archaeological application. Leucci *et al.* (2014) studied the archaeological site of Pisa with the main purpose to test the value of GPR and ERT methods to locate the archaeological stratigraphy. Microgravimetric techniques have been useful in archaeological contexts (Butler 1984; Cuss, Styles 1999; Pasteka *et al.* 2007; Panisova, Pasteka 2009). The applicability of seismic methods for detecting archaeological features has been evaluated by several authors (Woelz, Rabbel 2005; Leucci *et al.* 2007; Forte, Pipan 2008). Magnetic prospection can be successful used on archaeological sites

Fig. 1 – The facade of the Cathedral.

(Ciminale, Loddo 2001; Crew 2002; Linford 2004). Electrical resistivity tomography (ERT) imaging can be used to delineate archaeological features and to locate shallow cavities directly, particularly when cavities are filled with high resistivity contrast material such as voids and more conductive materials (Senos Matias 2003; Leucci 2006; Leucci *et al.* 2007; Scardozzi *et al.* 2020). In the case studied, microgravimetry was very difficult to use because of the many buildings and severe ground vibration due to the heavy traffic. The severe man-made noise made it impossible to use the seismic method. The underground telephone, electricity and water supply networks made it impossible to use magnetic methods. Therefore GPR and ERT were used, which can produce images in three dimensions without being affected by surface obstructions or other features. The GPR and ERT results show that the surveyed area was used also as a burial area over a long period. Other burial features dating from the Roman age (since the third century BC) were discovered.

2. Brief theoretical notes on geophysical methods

2.1 *The GPR method*

GPR method considers that a radar wave, emitted by a transmitting antenna placed directly above the ground surface, propagates in the ground and it is partially reflected by any change in the electrical properties of the subsoil. The reflected energy is then detected by the receiving antenna. Reflection events are produced whenever the energy pulse enters into a material with different dielectrical properties or dielectric permittivity. The strength, or amplitude, of the reflection, is determined by the contrast in the dielectric constants of the crossed materials. This means that a pulse that moves from a material with a low dielectric constant to a material with a high dielectric constant will produce a very strong reflection, while moving from a material with a low difference in constant dielectric will produce a relatively weak reflection. While some of the GPR energy pulses are reflected back to the antenna, energy also keeps travelling through the material until it either dissipates (attenuates) or the GPR control unit has closed its time window. The rate of signal attenuation varies widely and is dependent on the properties of the material through which the pulse is passing.

Materials with a high dielectric will attenuate the electromagnetic wave and it will not be able to penetrate as far. These materials will attenuate the electromagnetic signal rapidly. An example of a very high dielectric constant is the materials with high water content. Metals are considered to be complete reflector and do not allow any amount of signal to pass through. Radar energy is not emitted from the antenna in a straight line. It is emitted in a cone shape. This defines the horizontal resolution of the method. The vertical resolution instead is related only to electromagnetic wave velocity in the materials and the frequency of the transmitter antenna. As the antenna is moved over a target, the distance between the two decreases until the antenna is over the target and increases as the antenna is moved away. It is for this reason that a single target will appear in the data as a hyperbola. The target is actually at the peak amplitude of the positive wavelet (for more see Leucci 2019, 2020).

2.2 *The ERT method*

ERT is an advanced geophysical method used to determine the subsurface's resistivity distribution by making measurements on the ground surface. ERT data are rapidly collected with an automated multi-electrode resistivity meter. ERT profiles consist of a modelled cross-sectional (2-D) plot of resistivity (Ω·m) versus depth. Resistivity, measured in Ω·m, is the mathematical inverse of conductivity. It is a bulk physical property of materials that describes how difficult it is to pass an electrical current through the material. Two electrodes are used as current (they inject current into the material). The other two electrodes are used to measure the potential difference in a certain point under the surface. In this way measurement of all possible combinations of electrodes in the profile is carried out automatically while the function of individual electrodes changes as emitting and measuring functions alternate.

This measuring algorithm, called dipole-dipole, is the most commonly used in archaeological applications at present (Leucci 2015). Its application is especially recommended in the research of vertical structures (e.g. tombs,

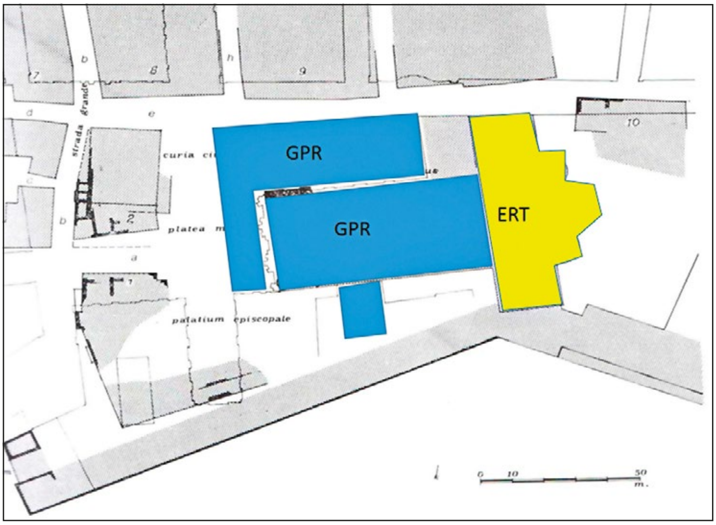

Fig. 2 – The surveyed areas: blue indicates GPR survey; yellow indicates ERT survey.

walls, etc.). Absolute maximal depth in which one can measure electric resistivity is theoretically given by maximum spacing of emitting electrodes (for more see Leucci 2019, 2020).

3. GPR data acquisition and analysis

The GPR surveyed areas are shows in Fig. 2. The GPR survey was carried out with a Ris Hi-mod georadar using the 200-600MHz (centre frequency) dual-band antenna. The frequency was chosen to optimize both the penetration depth and resolution, considering that the targets of the survey were supposedly located between 0.5 m and 5 m below the surface level. Survey profiles were parallel and spaced at 0.25 m. Each reflection profile was processed by standard two-dimensional processing techniques and transformed into pseudo-three-dimensional amplitude maps using GPR-slice Version 7.0 software (Goodman 2013).

The following data processing was performed (Leucci 2020): 1) background removal, whereby the filter is a simple arithmetic process that sums all the amplitudes of reflections that were recorded at the same time along with a profile and divide by the number of traces summed – the resulting composite digital wave, which is an average of all background noise, is then subtracted from the data set; 2) Kirchhoff two-dimensional velocity migration, which is a time migration of a two-dimensional profile

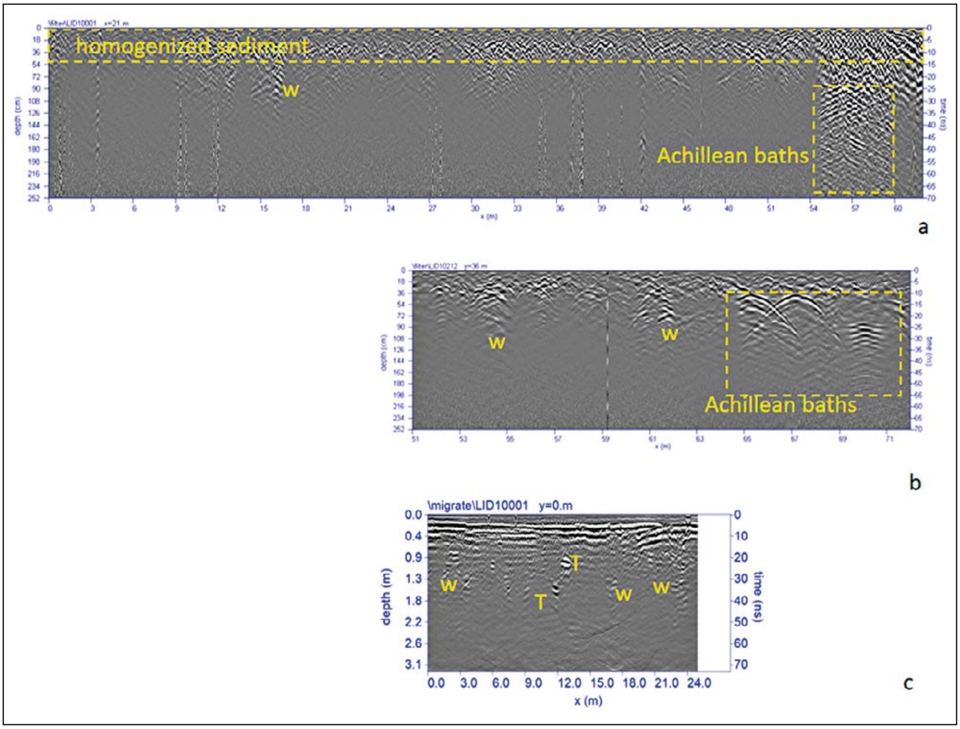

Fig. 3 – Processed GPR radar sections related to the 600MHz antenna.

based on a two-dimensional velocity distribution, is performed. The goal of the migration is to trace back the reflection and diffraction energy to their 'source'. The Kirchhoff two-dimensional velocity migration is done in the x-t range; this means that a weighted summation for each point of the profile over a calculated hyperbola of pre-set bandwidth is performed. The bandwidth means the number of traces (parameter summation width) over which summation takes place.

Each profile was gained manually and the background was removed. This was performed in different time ranges by subtracting a 'local' average noise trace, which is estimated from suitably selected time-distance windows with low signal content. This local-subtraction procedure was necessary to avoid artefacts created by the usual subtraction of a 'global' average trace estimated from the entire section, which is due to the presence of zones with very high amplitude reflections. Estimation of electromagnetic wave velocity was undertaken by hyperbola fitting (resulting in an average velocity of 0.075 m/ns) and reflections were migrated utilizing the Kirchhoff method using this value.

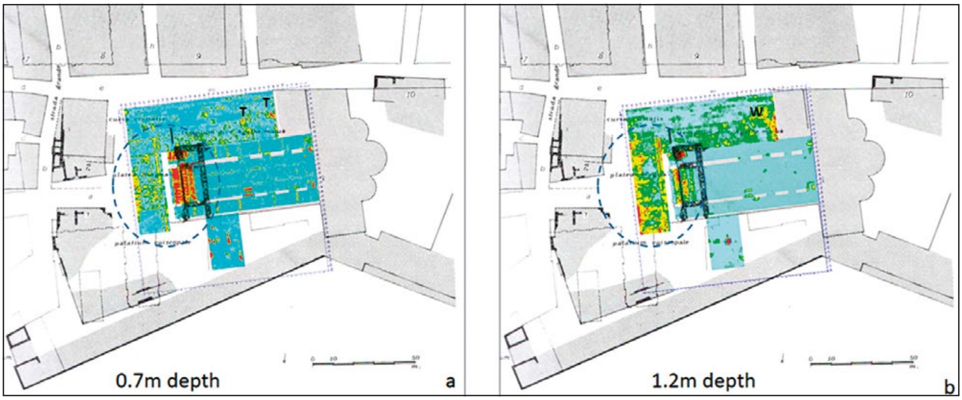

Fig. 4 – Time slices.

Migrated reflections were also visualized as a pseudo-three-dimensional volume in isosurfaces, also using GPR-slice software. The GPR profiles showed jumbled areas with many point-source reflections are probably areas where homogenized sediment was used to fill the base of the church surface (Fig. 3a). Very high amplitude reflection features are visible at the end of the profile (Fig. 3a). These reflection events are related to the well-known Achillean baths. Interesting is the shallow high amplitude reflections evidenced inside the dashed yellow rectangular in Fig. 3b. They are probably related to the top of an unknown extension of the Achillean baths. The reflection profile (Fig. 3c) shows a shallow high-amplitude reflection (T) related to the tomb. Other high-amplitude reflections (labelled W) are also visible. They could be related to the presence of buried walls.

The GPR reflections were also visualized in horizontal amplitude maps. These were constructed by taking an average of the amplitudes over the 5 ns two-way time window, which was squared to produce positive values. The slices shown in Fig. 3 are overlapped to the planimetry of surveyed areas. They visualize the more significant subsurface features between 0.7 m (Fig. 4a) and 1.2 m (Fig. 4b). There is a strong correspondence between the location of the Achillean baths. This evidence of the unknown extension of the baths. High-amplitude reflections (labelled 'T' in Fig. 4a), were interpreted as tombs. In the deeper slice (Fig. 4b) the evidence of the walls (W) is visible.

The spatial relationships between reflections can be visualized in the pseudo-three-dimensional isosurfaces produced from the two-dimensional profiles (Fig. 5). These were produced after Kirchhoff migration and the application of the Hilbert transform, which created a positive-valued envelope of the amplitude of radar reflections. As asserted in Leucci (2019), the selection

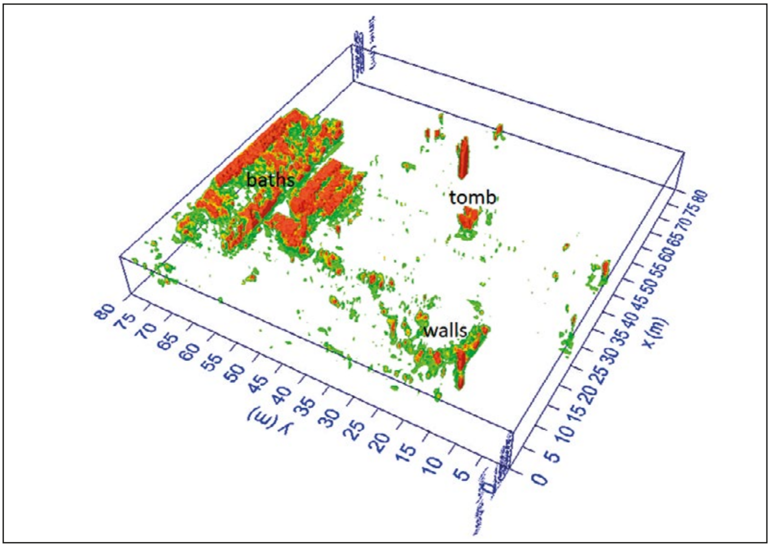

Fig. 5 – Isosurface visualization of the envelope of the processed data.

of a proper amplitude threshold is crucial in the iso-surface method because lowering the threshold value increases the visibility of the main anomaly and smaller objects, but also heterogeneity noise.

Isosurface renders are displays of surfaces of equal amplitude in a three-dimensional volume. It is possible to display any surface between 0 and 100% of maximum amplitudes in the volume. The 100% surface represents the strongest surface in the volume and 0% isosurface represents the weakest reflector. As the amplitude of the reflections, which could be related to features of archaeological interest, assumed different values, to visualize the maximum amplitude events, three isoamplitude volumes were created. This representation allows visualization of the strongest amplitude reflections. Here is possible to see the 3D extension of the Achillean baths, walls and tombs.

4. ERT data acquisition and analysis

ERT surveyed area is shows in Fig. 2. This part was inaccessible to the GPR. To investigate the area below the Cathedral non-standard ERT arrays were used. The electrodes were distributed in such a way as to cover the back of the Cathedral (Chavez *et al.* 2011; Argote-Espino *et al.* 2013; Tejero-Andrade *et al.* 2015; Leucci *et al.* 2017; Leucci 2019, 2020). A dipole-dipole axial array was used. A roll-along acquisition mode considering several L shape profiles was used. The spacing between the current electrode pair, C2-C1, is

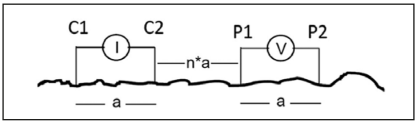

Fig. 6 – Dipole-dipole array scheme.

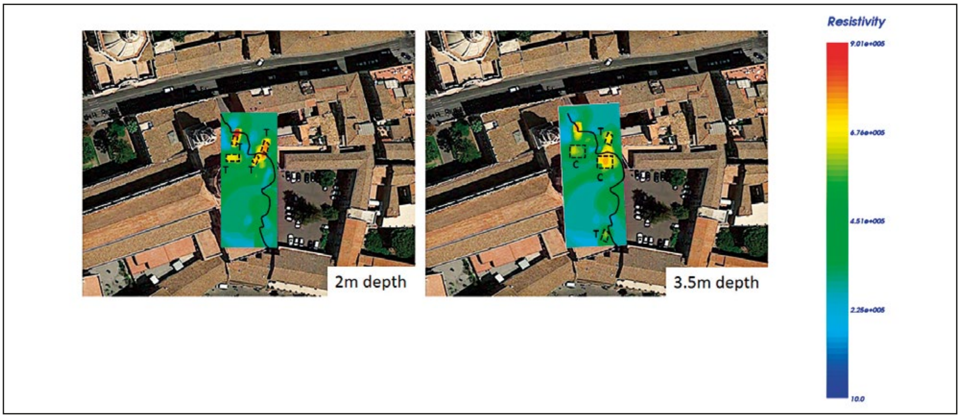

Fig. 7 – Electrical Resistivity Tomography (ERT) resistivity depth slices.

given as 'a' which is the same as the distance between the potential electrode pair P1-P2. This array has another factor marked as 'n' in Fig. 6.

This is the *ratio* of the distance between C1 and P1 electrodes to C2-C1 (or P1-P2) dipole separation 'a'. In this array, the 'a' spacing is initially kept fixed, and the 'n' factor is increased from 1 to 2 to 3 up to about 6 to increase the depth of investigation. The measurements usually start with a spacing of 1a between C1 and C2 (electrodes of current) and also between P1 and P2 (electrodes of potential). The first sequence of measurements is made with a value of 1 for n factor, followed by n = 2, while keeping the C1-C2 dipole pair spacing fixed at 1a. For successive measurements, the n spacing factor is increased to a maximum value of about 6. To increase the depth of investigation, the spacing C1-C2 and P1-P2 is increased to 2a and another series of measurements with different values of n is made.

The dipole-dipole array is very sensitive to horizontal changes in resistivity, and it is effective to map vertical structures as archaeological remains (Loke 2002). Initially, a 2D survey is conducted along each perpendicular line or transect. In the next step, the current electrodes remain at the end of one line, while the potential electrodes are moved, along the line. Then, the current electrodes are moved by one electrode position and the potential electrodes are moved as previously described. The process is repeated until the current and potential electrodes cover the L geometry. This sequence of observations produces a series of apparent resistivity observations towards and beneath the central portion of the array.

Resistivity data were acquired with two reels of 55 m long, the selected distance 'a' between the electrodes was 1 m. After the data acquisition process was performed, the apparent resistivity data were analysed to identify abnormal measurements with a high standard deviation. The investigated volume was computed using the software ErtLab (http://www.geostudiastier.it) which makes use of the Finite Elements algorithm. Fig. 7 shows the slices from 2.0 m in depth to 3.5 m in depth. First, it is possible to note the presence of a heterogeneous subsurface with resistivity values ranging from $2{\times}10^5$ to $9{\times}10^5$ ohm m. Furthermore, it is possible to note the presence of some anomalous zone labelled T that correspond to tombs. Other anomalies are visible. In particular, high resistivity values are linked to the buried rooms (C).

5. Conclusions

In this paper, the results of a GPR and ERT survey performed in the Cathedral of Catania were presented. The aims of the survey were the assessment of the shallower under floor layers in the church and possibly the identification of the tombs and other structures of archaeological interest. The survey was performed both inside and around the Cathedral. The GPR images below the Cathedral show the presence and distribution of features with shapes, sizes and burial depths that suggest they are of Roman and possibly earlier age. Most of them are interpreted as an unknown extension of the Achillean baths. Other archaeological features are tombs, rooms and walls.

A variety of three-dimensional visualization tools were used to establish a connection between the information of the GPR and ERT data obtained in the surveyed areas and the archaeological features, to find relationships and possible interpretations. High to moderate-amplitude GPR anomalies were identified as tombs in the shallow subsurface, placed just under the external areas of the Cathedral, while in the deeper subsoil anomalies of regular shape were found. These could be interpreted as other possible archaeological structures, probably an unknown crypt.

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ABSTRACT

The town of Catania, located in the southern part of the Sicily region, Italy, holds the remains of an ancient settlement in the city centre. One of the most important buildings is the Cathedral and the buried Achillean Baths. The Cathedral was repeatedly destroyed and rebuilt after the earthquakes and volcanic eruptions that occurred over time. The first building dates back to the period 1078-1093 and was built on the ruins of the Roman Achillean Baths, on the initiative of Count Roger, acquiring all the characteristics of an equipped (i.e. fortified) ecclesia. Already in 1169, a catastrophic earthquake demolished it almost completely, leaving intact only the apse. In 1194 a fire created considerable damage and finally in 1693 the earthquake that hit the Val di Noto destroyed it almost completely. The area around the Cathedral is today highly urbanized, but it was the locus of social and political life over the centuries for people of different cultures who have inhabited the area since the 8th century BC. Therefore, this area contains stratigraphically complex layers of buildings and other remains, which can help understand the use of this area of the town over many centuries. A ground-penetrating radar and electrical resistivity tomography surveys were performed inside and outside the Cathedral of Catania. Data were visualized in three-dimensions using a standard amplitude slice technique as well as the construction of isosurface images of amplitudes. These images reveal the position of architectural features whose shape, size and burial depth suggest they are Roman and earlier in age. The features mapped overlap the development of the Achillean Baths and the presence of some tombs and unknown rooms.

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