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Virtual three-dimensional model of the subsoil of the church of St. Maria Maddalena d'Alga in Palermo, using high-resolution GPR surveys

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***Abstract* – The church of Santa Maria Maddalena d'Alga is located in the historic center of Palermo and belongs to the monumental complex of the military district of San Giacomo, in the ancient western fortified area of the city. Today the area hosts a vast military complex, seat of the Command of the Carabinieri Legion of Sicily. The church is elevated with respect to the current floor. During some maintenance works of the church, for the installation of air conditioners, some georadar surveys were carried out to verify the presence of crypts or tombs under the pavement. The investigations made it possible to reconstruct a 3D georadar model and to identify some anomalies under the pavement. Some of these correspond to rooms that have been opened during maintenance work.**

I. INTRODUCTION

The church of Santa Maria Maddalena d'Alga (fig. 1) is a building located in the historic center of Palermo and belonging to the monumental ensemble of the military district of San Giacomo [1-2]. The church is in the western ancient, fortified area of the city, mentioned by historians with the name Galka or Alga (from the Arabic "al-Halqah", or "the enclosure"). In this area the *Kasr* of the Arabs rose dominant, and later it became the residence of Norman princes and kings and transformed over the centuries, until it took on the shape of today's Royal Palace. In the Galka district from the XVII century a vast military complex was set up, at today the headquarter of the Command of the Sicily Carabinieri Legion, which contains several historic buildings of high artistic interest.

The birth of the church is probably connected to the construction works of the Cathedral of Palermo. In fact, in 1130 there was an older chapel dedicated to Mary Magdalene, built by Elvira of Castile, first wife of Roger II of Sicily [1]. The chapel was contiguous to the south side of the primitive cathedral, dating back to 592. This ancient chapel was demolished in 1187 by Archbishop Walter Ophamil, in order to rebuild it in a nearby site, probably duplicating its shape and using most of the resulting material. The tombs of the Norman princes were temporarily transferred to this new chapel, pending the completion of the construction of the new cathedral, where they would find their definitive location. Some authors [2] believe that it is precisely the Church of Santa Maria Maddalena in Alga, while other authors [3] do not consider this hypothesis valid, arguing that the church does not have in fact the characteristics of the ancient chapel.

Fig. 1. The main façade of the church of Santa Maria Maddalena d'Alga, in Palermo.

In 1382, the church of Santa Maria Maddalena d'Alga was made available to the Congregation of Santa Maria Maddalena for several decades. It later passed to exponents of the fifteenth-century aristocracy. In 1608 the Observant Franciscan Fathers took over and overturned the architectural lines of the Arab-Norman church with an external Renaissance portal (still existing) and internal structural changes, including those of the pointed arches that have become centric and the construction of chapels in the side naves [1].

When the military quarter and the San Giacomo hospital were built in 1622, the church of Santa Maria Maddalena was enclosed within this military complex, together with other religious buildings such as the Church of San Giacomo dei Militari and the Church of San Paolo d 'Alga.

After the unification of Italy in 1860, the church, then almost abandoned, risked being demolished by the military, in order to expand the courtyard of the barracks. Fortunately, in 1891, the church was declared a "national monument" and then restored by the architect Giuseppe Patricolo [2].

Further restorations on the building were carried out in the 40s of the last century, when the church was freed from modern structures, restoring the full legibility of its medieval facies [2]. In 1948 it became a votive temple for the Carabinieri who died heroically in war and in service. In 2019 the church was included in the UNESCO "Arab-Norman Palermo and the Cathedral Churches of Cefalú and Monreale" itinerary.

On the outside, the church has well-defined shapes, characterized by masonry structures obtained using small, well-squared ashlars. The façade (fig. 1), altered from its original appearance, has a sixteenth-century access portal, which originally must have been with pointed arches and retains the medieval bell tower. A staircase leads to the portal of the church whose floor is raised by almost two meters from the external floor. The interior recalls that of the church of San Cataldo in Palermo: with three naves separated by ogival arches resting on four columns. The capitals are a fine example of sculptures of the 12th century, as well as the expedient of shortening the step of the arches proceeding from the façade towards the apse, to create an effect of greater length of the aisles. The latter, covered by a wooden beam ceiling, are concluded by three apses, characterized by the usual columns within corner niches. The aisles are divided by the three-apsed presbytery by a transept above which originally stood a dome, now replaced by a flat ceiling [2].

II. GPR SURVEYS

Ground Penetrating Radar (GPR), commonly called georadar, is today a consolidated method that is widely used for diagnostics and research in archaeological prospecting and in other fields of cultural heritage [4-7]. In this field, the success of GPR is mainly due to its characteristics of high resolution within the first meters of depth [8], high acquisition speed [4], high integrability with other nondestructive methods [9-13] and, finally, high detectability of anthropogenic structures [9, 14].

Many authors discussed the results of GPR investigations to detect ancient foundations and preconstructions under the floor of churches and other monuments, in order to investigate underground environments [15, 13] or verify the presence of underground archaeological remains dating back to phases preceding the current building [10, 16].

In the church of Santa Maria Maddalena d'Alga GPR surveys were carried out using the RIS MF HI-MOD system by IDS, configured with a 200-600 MHz multifrequency antenna, useful to obtain a high resolution in the first meters of underground (using 600 MHz antenna), but at the same time to reach suitable depths of investigation for archaeological purposes (using 200 MHz antenna). Some test profiles were firstly acquired, aiming to optimize the acquisition parameters of the GPR signal (frequency filters, gain, sampling rate).

All profiles were acquired with both frequencies (200 MHz and 600 MHz), using a time range of 60 ns for the 600 MHz antenna and 120 ns for the 200 MHz antenna. To transform the two-way times in depth, it was necessary to estimate the average velocity of the electromagnetic waves in the subsoil. An estimate of about 0.1 m/ns was obtained from the slopes of the branches of hyperbola evident in the profiles. Consequently, the maximum depth of investigation was about 3 meters for the data acquired with a 600 MHz antenna, and about 6 meters for the data acquired with a 200 MHz antenna.

The GPR profiles were processed with ReflexW software [17], trying to eliminate both coherent and inconsistent noise in the unprocessed data. For this purpose, static correction, filtering for background removal, Kirchoff migration and Butterworth type frequency filtering were performed. The Butterworth filter was a 70-1200 MHz bandpass for the 600 MHz data, and a 50-600 MHz bandpass for the 200 MHz data.

In total 14 GPR profiles were acquired, parallel to each other, with a 50 cm spacing. with direction parallel to the aisles. Finally, for each georadar profile the envelope of the radargrams was calculated and the amplitudes were normalized [13, 16].

The processed data was used to build a 3D model of the subsoil, using a code implemented in Matlab for the construction of the data matrix and the Voxler application (Golden Software) for the graphic rendering, by applying for the spatial interpolation the Inverse Distance Weighting algorithm [18], which uses a weighted average based on the distance of the points from the observation point. The first three meters of the 3D model were built using the data matrix related to the 600 MHz antenna, while for the deeper part of the model, down to 6 meters, the data matrix related to the 200 MHz antenna was used.

Figure 2 shows some images, with different perspectives of the 3D model and with different viewing modes (with or without isosurfaces of the normalized amplitude of the electromagnetic field). The 3D model clearly shows some underground anomalies, adjacent to the perimeter walls, 1.5 meters wide and up to 4 meters deep. Their length is equal to that included between the columns of the church. Some of these anomalies correspond to rooms (fig. 3) that were opened during some maintenance work for the installation of air conditioners. These underground rooms are in correspondence with the two side aisles of the church (perhaps three per aisle) and their floor is about 4 m deep from the floor of the church, as is also evident from the depth of the bottom of the anomalies visible in the GPR 3D model. Inside these rooms some skeletons and human remains were found which are currently being investigated. The dating and study of these human remains may perhaps answer some of the questions that remain unanswered today.

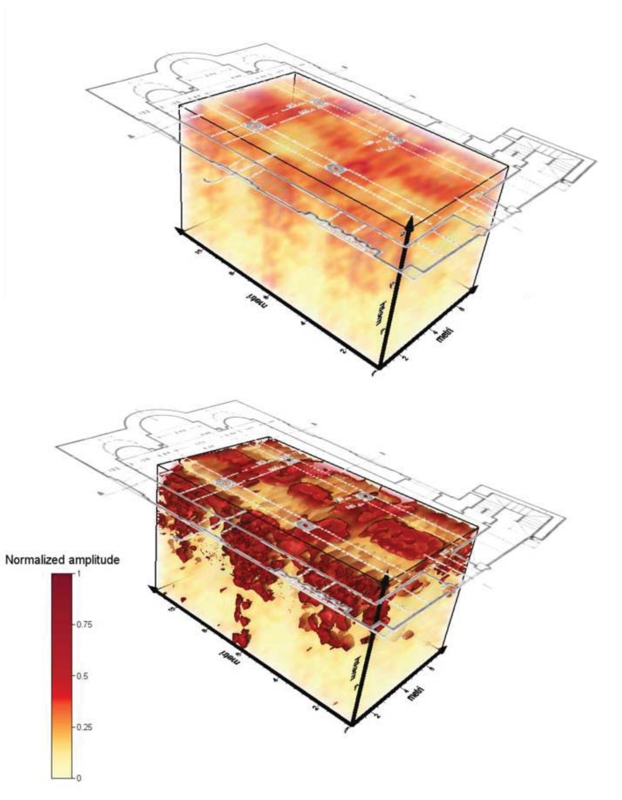

Fig. 2. 3D electromagnetic model of the subsoil of the church of Santa Maria Maddalena in Alga, obtained from GPR surveys, with (bottom) or without (top) isosurfaces of the normalized amplitude of the electromagnetic field.

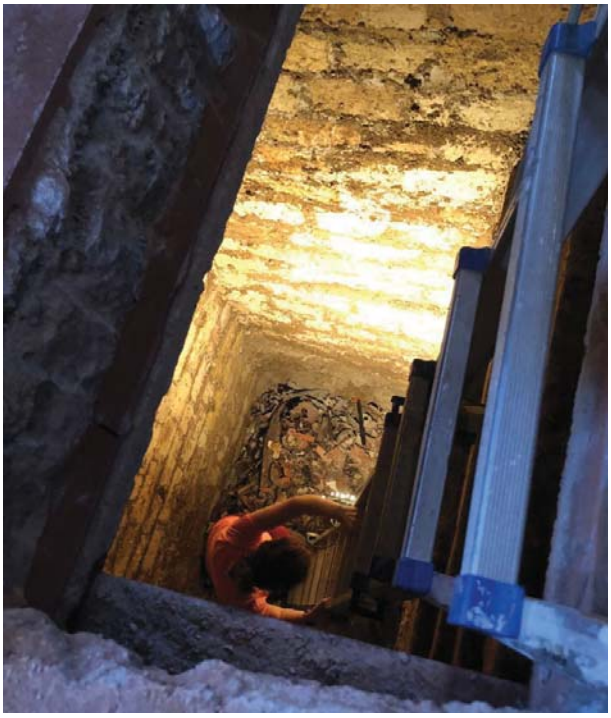

Fig. 3. One of the underground rooms discovered during some maintenance works of the Church of Santa Maria Maddalena d'Alga, in Palermo.

Other anomalies have not been verified through excavations in order to not destroy the valuable flooring of the church. The 3D model also shows a clear anomaly measuring 2 m x 2 m and about 3 meters deep, in front of the altar (fig. 4). Although there is a circular hatch in the pavement corresponding to this anomaly, it was not possible to remove it. Also, in the central part of the church, in the central nave, there could be a compartment, corresponding to a georadar anomaly. There are also some superficial anomalies in the central part of the nave which could be some tombs in shape and size. Finally, the model seems to show an oblique anomaly with respect to the orientation and the perimeter walls of the church, which passes roughly under the columns near the entrance.

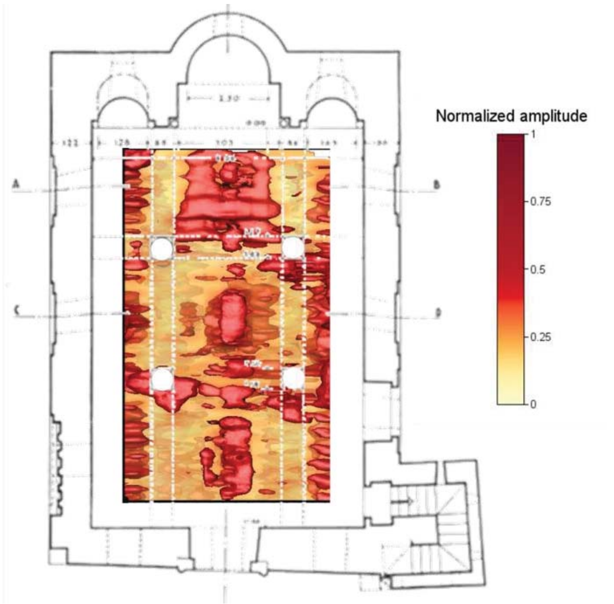

Fig. 4. Plan of the church of Santa Maria Maddalena d'Alga, in Palermo, with the top view of the GPR 3D model superimposed.

III. DISCUSSION AND CONCLUSIONS

The analysis of the georadar data acquired with 600 and 200 MHz antennas made it possible to reconstruct a 3D model of the subsoil, detailed in the superficial part and up to an adequate depth. Some of the anomalies found correspond to buried rooms that are narrow and long and deep up to about 4 meters, as also highlighted by the 3D model. Unfortunately it was not possible to verify all the anomalies of the 3D model with direct investigations. Some of these are probably only tombs under the pavement, but others could correspond to larger rooms. The purpose of these rooms has not been identified, although some human remains have been found inside, but insufficient to interpret them as ossuaries. Finally, the oblique anomaly with respect to the orientation and the perimeter walls of the church certainly deserves to be investigated further.

The 3D model obtained under the church of Santa Maria Maddalena d'Alga, in Palermo, may play an important role in future archaeological investigations as they provided a synthetic view of the location and dimensions of the underground structures of the church.

REFERENCES

[1] Palermo G. (1816) Guida istruttiva per potersi conoscere ... tutte le magnificenze ... della Città di Palermo, vol. 4, Reale Stamperia, Palermo.

[2] Guiotto M. (1949) La chiesa di S. Maria Maddalena in Palermo, *Bollettino d'Arte*, ed. Ministero dei Beni e delle Attività Culturali e del Turismo, Roma, vol.34, No.4, pp. 361-367.

[3] Bellafiore G. (1967) Edifici di età islamica e normanna presso la Cattedrale di Palermo, *Bollettino d'Arte*, ed. Ministero dei Beni e delle Attività Culturali e del Turismo, Roma, vol.52, No.5, pp. 178-195.

[4] Conyers LB, Leckebusch J (2010) Geophysical Archaeology Research Agendas for the Future: Some Ground penetrating Radar Examples. *Archaeological Prospection*, **17**(2), 117-123. https://doi.org/10.1002/arp.379

[5] Goodman D, Piro S (2013) GPR Remote Sensing in Archaeology. Springer, 9. https://doi.org/10.1007/978-3-642-31857-3

[6] Deiana R, Leucci G, Martorana R (2018) New Perspectives on Geophysics for Archaeology: A Special Issue. *Surveys in Geophysics*, **39**(6), 1035–1038. https://doi.org/10.1007/s10712-018-9500-4

[7] Martorana R., Capizzi P. (2022) Joint investigation with Ground Penetrating Radar and Infrared Thermography as a Diagnostic Support for the Restoration of Two Wall Mosaics in the Church of St. Mary of the Admiral in Palermo, Italy. *Heritage*, **5**(3), 2298-2314. https://doi.org/10.3390/heritage5030120

[8] Daniels DJ (2004) Ground Penetrating Radar, second ed. The Institution of Electrical Engineers, ISBN 0 86341360 9. https://doi.org/10.1002/0471654507.eme152

[9] Forte E, Pipan M (2008) Integrated seismic tomography and ground-penetrating radar (GPR) for the high resolution study of burial mounds (tumuli). *Journal of Archaeological Science*, **35**(9), 2614–2623. https://doi.org/10.1016/j.jas.2008.04.024

[10] Casas A, Cosentino PL, Fiandaca G, Himi M, Macias JM, Martorana R, Muñoz A, Rivero L, Sala R, Teixell I (2018) Non-invasive Geophysical Surveys in Search of the Roman Temple of Augustus Under the Cathedral of Tarragona (Catalonia, Spain): A Case Study. *Surveys in Geophysics*, **39**(6), 1107–1124. https://doi.org/10.1007/s10712-018-9470-6

[11] Obrocki L, Eder B, Gehrke H, Lang F, Vött A, Willershäuser T, Rusch K, 829 Wilken D, Hatzi-Spiliopoulou G, Kolia E, Vikatou O (2019) Detection and localization of chamber tombs in the environs of ancient Olympia, Peloponnese, Greece, based on a combination of archaeological survey and geophysical prospection. *Geoarchaeology*, **34**(6), 648–660. https://doi.org/10.1002/gea.21724

[12] Martorana R, Capizzi P. (2020) Seismic and non-invasive geophysical surveys for the renovation project of Branciforte Palace in Palermo. *Archaeological Prospection*. 1–14. https://doi.org/10.1002/arp.1781

[13] Bottari C., Capizzi P., Martorana R., Azzaro R.,

Branca S., Civico R., Fucile M., Pecora E. (2022) Diagnostic Multidisciplinary Investigations for Cultural Heritage at Etna Volcano: A Case Study from the 1669 Eruption in the Mother Church at the Old Settlement of Misterbianco. *Remote Sensing* **14**(10), 2388. https://doi.org/10.3390/rs14102388

[14] Verdonck L, Launaro A, Vermeulen F, Millett M (2020) Ground-penetrating radar survey at Falerii Novi: a new approach to the study of Roman cities. *Antiquity*, **94**(375), 705–723. https://doi.org/10.15184/aqy.2020.82

[15] Cozzolino, M., Di Giovanni, E., Gentile, V., Mauriello, P., Pizzano, N. (2020) Ground-Penetrating Radar Survey for the Study of the Church of Saint Cosma in Helerito (Tagliacozzo, L'Aquila, Italy). *Geosciences*, **10**(6), 244. https://doi.org/10.3390/geosciences10060244

[16] Capizzi P., Marrone M., Aleo Nero C., Bonfardeci A., Canzoneri A., Carollo A., Martorana R, Romano F. (2021) Georadar investigations in the Church of San Paolo (San Giacomo dei Militari, Palermo). Near Surface Geoscience 2021 – Bordeaux, France, 29 August – 2 September 2021, 1-5, https://doi.org/10.3997/2214-4609.202120203

[17] Sandmeier, K.J. (2016) ReflexW Version 8.1. Program for Processing of Seismic, Acoustic or Electromagnetic Reflection, Refraction and Transmission Data. Software Manual, Karlsruhe, Germany.

[18] Shepard, D. (1968) A two-dimensional interpolation function for irregularly-spaced data. Proc. 23rd National Conference ACM, ACM, 517-524.