# High-Resolution GPR Surveys at Tyndaris and Gioiosa Guardia: preliminary non-invasive investigations for future archaeological research

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This paper presents preliminary results from non-invasive geophysical surveys conducted in the urban area of Tyndaris and at the archaeological site of Gioiosa Guardia. The primary goal was to collect data guiding future archaeological investigations and to verify the continuity of known structures. A 500 MHz Ground Penetrating Radar (GPR), specially designed for high-resolution surveys in archaeological contexts, was used to detect buried features at depths of approximately two meters. Following a pseudo-grid survey design, data were processed (time-zero correction, background removal, band-pass filtering, diffraction-stack migration) to generate vertical radargrams as well as 2D and 3D maps.


Fig. 1 -Overview map of Sicily highlighting the two study sites discussed in this article.

This brief contribution presents the preliminary outcomes of non-invasive investigations carried out in the urban area of Tyndaris and at the site of Gioiosa Guardia (Fig. 1). These investigations employed geophysical tools, chiefly a 500 MHz Ground Penetrating Radar (GPR) specially tailored for high-resolution work in archaeological settings[1].

GPR operates by emitting high-frequency electromagnetic waves that penetrate the ground, allowing users to locate buried objects at varying depths and to gather insights into the nature and location of subsurface structures. Its principle hinges on measuring the travel time of emitted waves as they move through the ground and bounce back to the surface. By recording these data, it is possible to distinguish between different materials and densities, thereby identifying buildings or objects buried in archaeological contexts.

The collected data can be displayed as vertical sections (radargrams) or converted into raster intensity maps. Dedicated software also supports 3D visualization of the data. In archaeology, a 500 MHz frequency typically enables exploration to depths of about two meters, detecting anthropogenic anomalies such as negative features (ditches, pits) or positive features (masonry structures) at intervals of about 0.5 $m^2$.

This study targeted specific areas at both the urban site of Tyndaris (Tyndaris) and at Gioiosa Guardia. At Tyndaris, an overall area of 1,400 $m^2$ was surveyed, including part of Via Monsignor Pullano in the small village bordering the fenced archaeological area, as well as two sectors located west and east of the so-called Basilica[3]. At Gioiosa Guardia, roughly 400 $m^2$ were explored just south of an archaeological zone excavated decades ago (Fig. 2)[4].

## OBJECTIVES

The principal aim was to obtain preliminary data supporting future archaeological interventions and to validate the presence of buried structures, in addition to confirming the continuity of known remains. In both locations, GPR surveys have uncovered subsurface features suggestive of buried structures. This paper thus emphasizes the potential for further investigations at both sites, reinforcing their significance as areas of considerable archaeological interest.

## TYNDARIS: AN OVERVIEW

The archaeological site of Tyndaris (38°08’37.62”N – 15°02’35.98”E, 266 m a.s.l.) is located in Sicily, roughly 45 km southwest of Messina by direct line, lying between Capo Milazzo and Capo d’Orlando. It occupies a promontory towering above the sea at the northern end of a ridge extending from the Peloritani and Nebrodi mountains, parallel to the Tyrrhenian coastline. The surrounding terrain features hilly and mountainous zones with steep inclines and short, seasonal watercourses (fiumare). The only sizable flat area is the Milazzo plain. The geological substrate of the promontory—where Dionysius I of Syracuse founded the city in 396 BCE—consists mostly of metamorphic rocks and limestones[5].

Archaeological work began in 1866–1867, when the then “Commissione di Antichità e Belle Arti” conducted initial excavations and restorations. Further efforts followed in 1866 and 1867, but it was only in the 1880s that more focused studies of the major monuments began. Systematic excavations took place in the early 1900s, then again in the 1930s through the 1960s. A resurgence occurred in 1987, when four excavation campaigns were initiated after several properties had been expropriated. The most recent published excavations date from 1993 to 2007[6]. There is no documented history of non-invasive surveys at Tyndaris prior to this study.

## GIOIOSA GUARDIA: AN OVERVIEW

The archaeological site of Gioiosa Guardia (38°08’56.39”N – 14°56’00.23”E, 748 m a.s.l.),


Fig. 2 - Panoramic view of the survey areas at Tyndaris and Gioiosa Guardia, highlighting the locations of the archaeological sites and the sectors examined with GPR.

administratively incorporated within the Tyndaris Archaeological Park, is located in the Nebrodi region of northern Sicily, about 10 km northwest of Tyndaris in a straight line. It spans a plateau of around five hectares on the eastern slopes of Monte di Gioiosa (813 m a.s.l.), at elevations ranging from 720 m to 760 m, overlooking the Gulf of Patti with geology similar to that of nearby Tyndaris.Steep slopes and challenging access points played a critical role in this ancient site's strategic—but isolated—location, offering sweeping views over both the coast and the interior.

Discovered in the 1980s, Gioiosa Guardia is considered a classic case of a Hellenized indigenous settlement. Its earliest village consisted of circular huts dating to the Protohistoric period (13th–12th centuries BCE), a typical hilltop settlement form in Sicily during the Protohistoric and Archaic eras. From the 7th century BCE onward, under the influence of nearby Greek colonies (such as Zancle, modern Messina), this settlement underwent a marked urban shift. The circular huts were replaced by multi-room rectangular houses arranged east to west along the slope and grouped in blocks separated by narrow stone-paved lanes with terracotta roof tiles. Archaeological excavations revealed approximately 2,500 m² (likely around 5%) of this settlement, comprising 10–15 houses joined by roads of various widths, some up to 3.5 m. High-quality ceramics, not exclusively Greek, were among the finds[7].

By the late 5th century BCE, the site suffered abrupt destruction, possibly linked to the founding of Tyndaris and the Syracusans' expulsion of the Carthaginians. Nevertheless, it was not entirely deserted: in the 4th century BCE, burials were introduced among the ruined dwellings, signifying the presence of a residual community. For centuries thereafter, Gioiosa Guardia remained largely abandoned until the medieval era. In the 11th century, it passed into the hands of the Benedictine Convent of Patti, and in the 18th century, the Church of San Francesco and its convent—whose ruins are still visible—were built. A separate settlement arose in the 14th century atop Monte di Gioiosa, presumably on the ancient acropolis, but this medieval town was eventually deserted by the late 18th century, when its inhabitants relocated closer to the coast, founding Gioiosa Marea[8]. Nowadays, the archaeological area is in disrepair and urgently needs maintenance and restoration for its preservation.

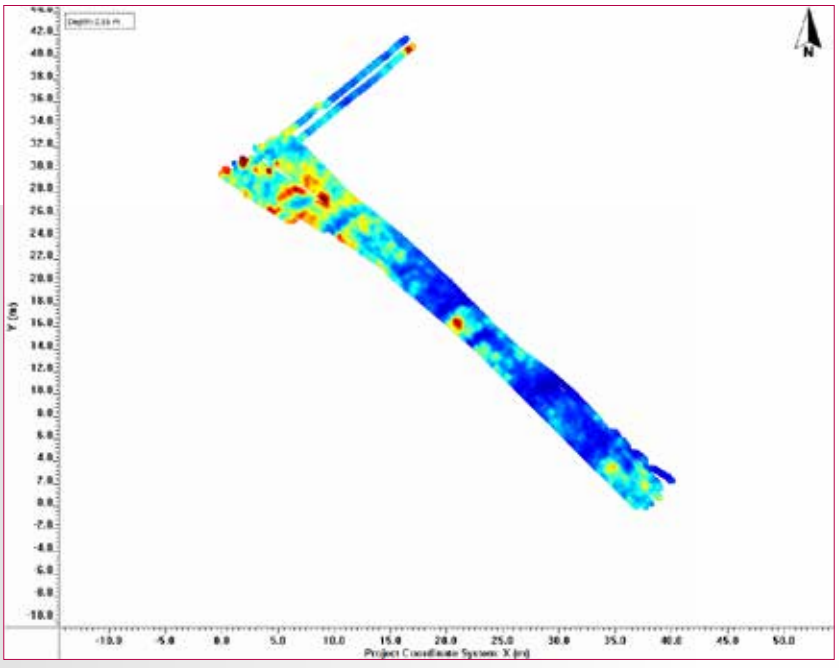

Fig. 3 - Radargram of the Via Monsignor Pullano section at Tyndaris, showing significant anomalies attributed to known masonry structures.

## METHODOLOGY, INSTRUMENTATION, AND DATA ACQUISITION/PROCESSING

The investigations in both Tyndaris and Gioiosa Guardia utilized a GPR system from Sensors & Software (Canada) with dual 500 MHz antennas (transmitter and receiver)[9]. Survey velocities ranged from 0.14 to 0.10 m/ns, calculated based on soil type and the heightened moisture content resulting from rainfall during the survey period[10]; the maximum depth reached was 2 metres.

Topographical correlation of the GPR data was facilitated by a Leica GS18 RTK GNSS receiver, ensuring precise georeferencing of each survey line. Data were collected following a pseudo-grid design, with parallel lines oriented north-south and east-west, overlapping by about 25% in a zigzag pattern to maximize coverage[11]. Each area was divided into two pro-

jects corresponding to the two primary orientations, and the resulting datasets were later merged in final processing.
Both at Tyndaris and Gioiosa Guardia, geophysical surveys were complemented by photogrammetric flights carried out with a DJI Mavic 2 drone. This integrated approach allowed the identification of previously unknown archaeological traces and clarified the continuity of known remains. The combination of parallel profiling and pseudo-3D GPR mapping proved effective for a preliminary characterization of the archaeological environment in both settings, minimizing site disturbance and providing crucial information for strategically planned excavations.

## DATA PROCESSING

Raw GPR data were processed with specialized software, yielding radar sections that highlight stratigraphic and structural anomalies. The typical workflow included time-zero correction, background removal, band-pass filtering, and diffraction-stack migration to generate horizontal slices, capturing features at depths of up to two meters. These steps, combined with time-to-depth conversion, facilitate the recognition and classification of key anomalies even in the presence of obscuring elements (e.g., large stones or roots).

## RESULTS TYNDARIS

In the surveyed portion of Via Monsignor Pullano, data revealed various utilities within the upper 0.50 m. At deeper levels, notably near the western edge of the roadway, significant anomalies correlate with known masonry structures (Fig. 3).
Near the so-called Basilica, the surveys revealed multiple linear anomalies likely attributable to walls, suggesting the presence of previously undocumented structures possibly linked to the agora (Figs. 4-5).

## RESULTS GIOIOSA GUARDIA

In the 400 m² area south of the previously excavated sectors, GPR imaging suggests a continuity of the known habitation pattern (Fig. 6). Several quadrangular subsurface features were detected, along with a prominent rectilinear anomaly (Fig. 7) extending northwest-southeast through the entire area at depths of approximately 0,40 m. This feature may represent a roadway or a wall integral to the ancient urban layout.

## DISCUSSION

These preliminary outcomes demonstrate the effectiveness of geophysical methods for investigating complex archaeological settings like Tyndaris and Gioiosa Guardia. In Tyndaris, the surveys facilitated a detailed mapping of both contemporary and ancient structures, whereas at Gioiosa Guardia, newly revealed features expand our understanding of the settlement's spatial extent.

## CONCLUSIONS AND FUTURE PERSPECTIVES

The geophysical surveys at Tyndaris and Gioiosa Guardia

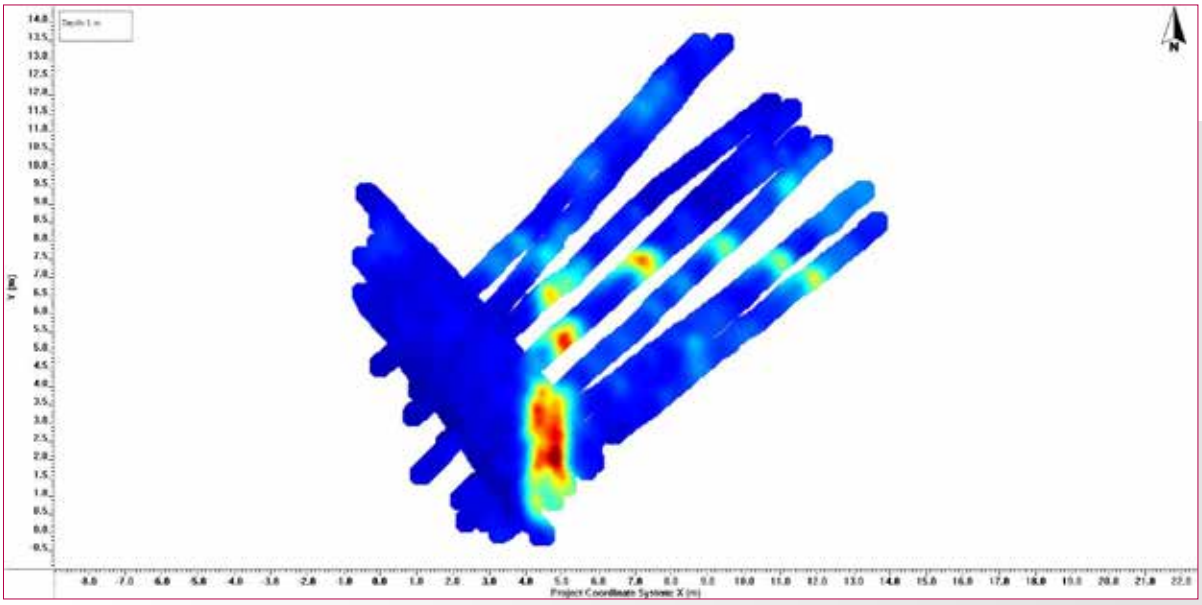

Fig. 4 - GPR image of the area adjacent to the so-called Basilica at Tyndaris, revealing linear anomalies potentially linked to undocumented walls.

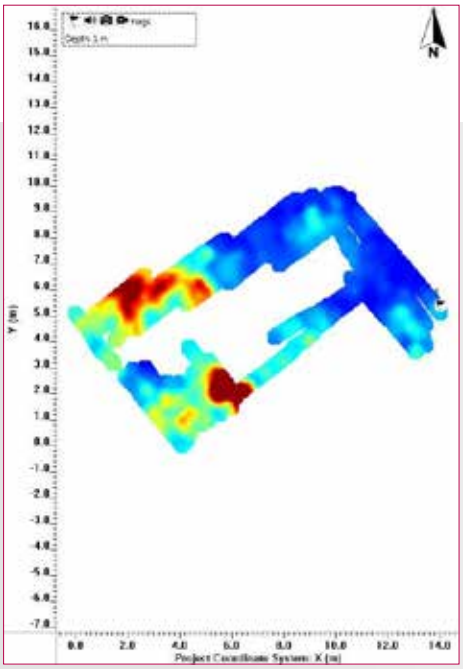

Fig. 5 - 2D map generated with GPR near the Basilica at Tyndaris, suggesting the presence of structures associated with the ancient agora.

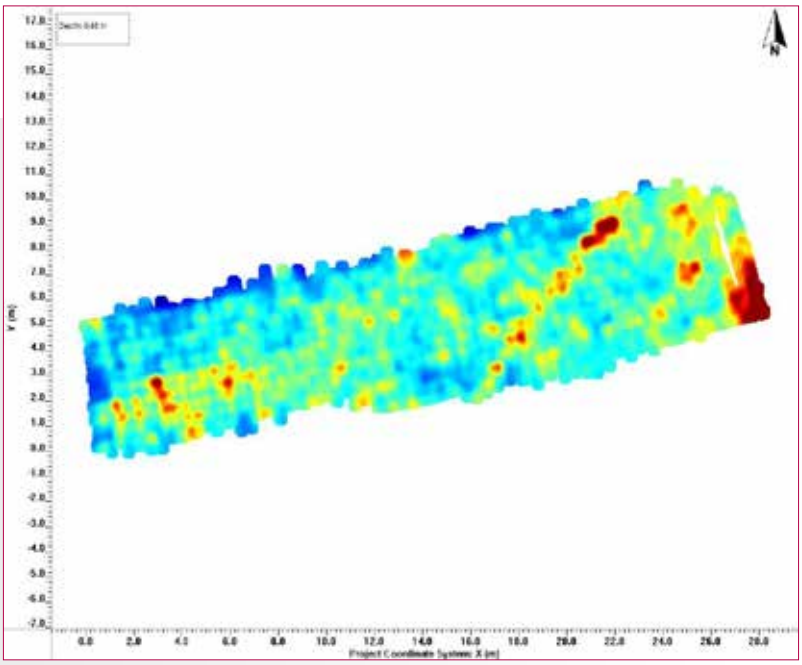

Fig. 6 - Radargram of the portion of Gioiosa Guardia south of the excavated areas, highlighting buried quadrangular structures.

have provided promising initial findings, emphasizing the need for more in-depth studies. At Tyndaris, the investigations covered areas of both the modern settlement and the adjacent archaeological zone, previously unexplored through non-invasive means. At Gioiosa Guardia, GPR prospections clarified the southern expansion of the ancient habitation and offered fresh insights into potential architectural or infrastructural elements.

These results form a solid basis for future research that will integrate geophysical techniques, topographic mapping, and traditional archaeological analyses to yield a more comprehensive picture of settlement history and urban development. Planned directions include applying multiple GPR frequencies and other methods—such as magnetometry and expanded photogrammetry—to provide a thorough perspective of the stratigraphy and evolution of both sites.

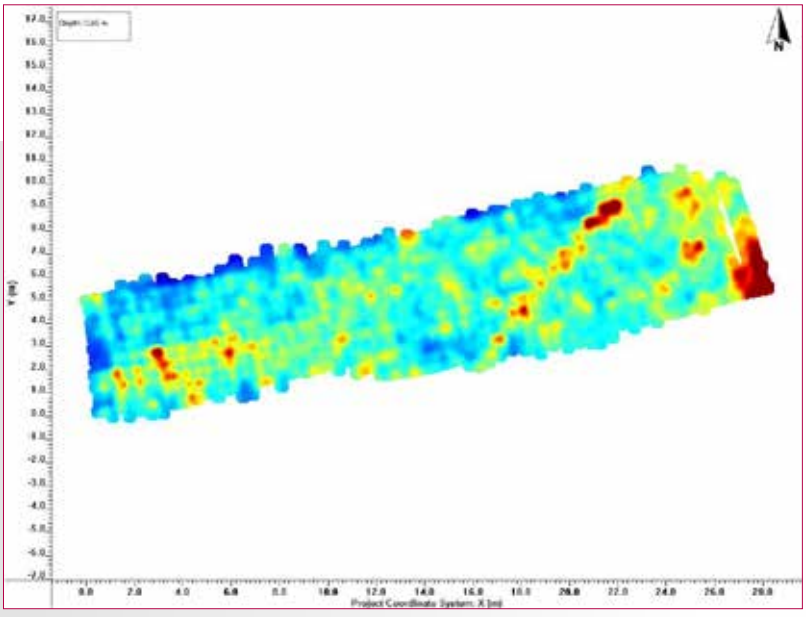

Fig. 7 - GPR image of the prominent rectilinear anomaly identified at Gioiosa Guardia, interpreted as a roadway or wall integral to the ancient urban layout.


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## Note

1 Goodman, Piro 2013, 26-27; Leucci et al. 2016, 295-296; Leucci, Giannino 2022, 126-129.
2 Boschi 2020, 106-113.
3 Bernabò Brea 1966.
4 Tigano, Coppolino. Martinelli 2008.
5 Fasolo 2013, I.
6 Fasolo 2013, 48-54.
7 Tigano, Coppolino. Martinelli 2008.
8 Minutoli, Lumini 2018 2580-2581.
9 Verdonck et al. 2013, 239-252.
10 The velocity for the Tyndaris site, was calibrated based on the findings outlined in a geological report commissioned by the Soprintendenza per i Beni Culturali ed Ambientali of Messina in 2019. This report followed "the execution of two continuous-core geognostic boreholes, during which samples were collected for subsequent laboratory geotechnical analyses, as well as an SPT (Standard Penetration Test)." These investigations determined that the soil is predominantly composed of metamorphic terrains, with a sandy composition up to a depth of 2.45 meters, along with smaller proportions of silt, clay, and minimal amounts of gravel (Relazione Geo-Service 2019, pp. 4-17).
11 Each stripe covers an approximate 0.25m amount of ground.

## Bibliografia

Bernabò Brea (1966) Tindari. *Restauro della "Basilica"*, in BdA, LI, pp. 114-116.
F. Boschi (2020), Archeologia senza scavo. *Geofisica e indagini non invasive*, Bologna. Bononia University Press.
M. Fasolo (2013), *Tyndaris e il suo territorio I*, *Introduzione alla carta archeologica del territorio di Tindari*, Roma (mediaGEO).
M. Fasolo (2014), *Tyndaris e il suo territorio II*, *Carta archeologica del territorio di Tindari e materiali*, Roma (mediaGEO).
F. Giannino, G. Leucci, Electromagnetic Methods in Geophysics Applications in GeoRadar, FDEM, TDEM, and AEM. Hoboken, USA, (John Wiley & Sons, Inc.), 2022.
D. Goodman, S. Piro, GPR Remote Sensing in Archaeology. (Springer), 2013.
Leucci et al. = G Leucci, L. De Giorgi, G. Di Giacomo, I. Ditaranto, I. Miccoli, G. Scardozzi, HYPERLINK "https://www.sciencedirect.com/science/article/pii/S2352409X16301791"3D GPR survey for the archaeological characterization of the ancient Messapian necropolis in Lecce, South Italy, in J. Archaeol. Sci. Rep., 2016, 290-302.
G. Minutoli, A. Lumini (2018) Gioiosa Guardia: prime indagini per un progetto di valorizzazione e restauro attraverso metodologia HBIM in F. Minutoli (ed.) ReUSO, *L'intreccio dei saperi per rispettare il passato interpretare il presente ,salvaguardare il futuro*, Roma, Cangemi Editore SpA International, 2580-2581.
G. Tigano, P, Coppolino, M.C. Martinelli (2008), *Gioiosa Guardia l'Antiquarium e il sito archeologico*, Catanzaro, Rubettino editrice.
Verdonck et al. 2013 = L. Verdonck, F. Vermeulen, R. Docter, C Meyer, R. Kniess. 2D and 3D ground-penetrating radar surveys with a modular system: data processing strategies and results from archaeological field tests, in Near Surface Geophysics, vol. 11, 239-252. https://doi.org/10.3997/1873-0604.2013007.

## Abstract

*This paper presents preliminary results from non-invasive geophysical surveys conducted in the urban area of Tyndaris and at the archaeological site of Gioiosa Guardia. The primary goal was to collect data guiding future archaeological investigations and to verify the continuity of known structures. A 500 MHz Ground Penetrating Radar (GPR), specially designed for high-resolution surveys in archaeological contexts, was used to detect buried features at depths of approximately two meters. Following a pseudo-grid survey design, data were processed (time-zero correction, background removal, band-pass filtering, diffraction-stack migration) to generate vertical radargrams as well as 2D and 3D maps.*
*At Tyndaris, investigations revealed significant anomalies associated with modern infrastructure and new architectural evidence near the so-called Basilica, possibly related to the ancient agora. At Gioiosa Guardia, newly discovered quadrangular features and a large rectilinear anomaly suggest an extension of the ancient settlement beyond previously excavated areas. These findings underscore the importance of integrating geophysical methods, topographic surveys, and traditional archaeological analyses to build a comprehensive picture of settlement dynamics. Future research will focus on expanding surveys with multiple GPR frequencies, magnetometry, and photogrammetric data for a more complete understanding of subsurface stratigraphy and site development.*

## Parole Chiave

Tecnologia; valorizzazione; beni culturali; fruizione; accessibilità; virtual tour; digital twin; fotogrammetria; Lidar; beacon; modelli 3D; GPR; Magnetometry; Geophysics

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