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Vibroacoustic landscape and defensive network: metrology for the characterization of potential communication systems in Medieval Basilicata until the Longobard-Norman transition

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Abstract – **This study investigates the spatial distribution of medieval fortifications in the Province of Potenza (Italy) to assess whether their placement responded to the need of local defense or to a more general strategic need. A spectral attenuation model for bell sounds was implemented in MATLAB to calculate maximum audible distances under realistic environmental conditions. Combined with a GIS-based analysis of intervisibility, acoustic buffers, and proximity to Roman roads, the results show that very few sites are either visible or acoustically reachable from one another. Instead, most fortifications are located within walkable distances from ancient roads, supporting the hypothesis that they were positioned for local territorial control, rather than interconnection. The study demonstrates how metrological tools from acoustics can be effectively adapted for cultural heritage applications, providing reproducible and quantitative support for archaeological interpretation. The approach contributes to a growing body of vibroacoustic landscape studies, exploring how sound may have shaped the organization of power in medieval southern Italy.**

I. INTRODUCTION

The strategic distribution of medieval fortifications in southern Italy reflects a complex interplay between topography, power, and communication. In the region of Basilicata, characterized by its mountainous terrain and sparse medieval settlement patterns, castles, towers, and monastic structures formed the backbone of territorial control from the Longobard period to the Norman consolidation of power in the 11th century.

While visual line-of-sight networks have long been assumed to underlie this defensive landscape, our research has pointed to the additional role of acoustic signaling, particularly using bells, as a means of long-range communication and coordination.

Previous studies in some areas of Campania and Piedmont regions (Italy) have shown that bell towers, monasteries, and castles were gradually positioned to form vibroacoustic networks, in which distances between nodes were compatible with both direct audibility and coordinated response times [1]. These networks were interpreted as part of a broader strategy of territorial integration, especially in connection with Benedictine expansion and Norman administrative structuring.

This work investigates whether a similar networking strategy, based on an acoustic logic, governed the placement of fortifications in medieval Basilicata prior to or during the Longobard–Norman transition. Thus, the research contributes to the efforts of contributing to the analysis of vibroacoustic heritage, by combining spectral acoustics, geospatial methods, and historical data to reconstruct the intangible dimensions of landscape control in early medieval southern Italy.

By applying a metrological model of bell sound attenuation and combining it with GIS-based visibility analysis and spatial proximity to Roman infrastructure, we test the hypothesis that defensive sites were intentionally located to enable mutual acoustic communication. An alternative hypothesis — that fortifications were placed primarily to oversee local movement along key roads without forming a coordinated network — is also examined.

II. MATERIALS AND METHODS

A. Hypotheses and analytical framework

This study tests two competing hypotheses regarding the spatial logic of fortification placement in medieval Basilicata. In the first hypothesis, fortifications are considered as intentionally placed to ensure mutual communication — either through direct line-of-sight visibility or through the acoustic communications — eventually in coordination with nearby churches or monastic sites. This hypothesis is coherent with previous studies, that showed, both in synchronic and diachronic ways, that visual communications could be substituted with acoustic ones, leading to a gradual territorial integration between defensive and sacred sites [1].

According to the alternative hypothesis, fortifications were located to oversee strategic points of the territory, such as roads or mountain passes, without forming a coherent communicative network. Examples of this approach are found in Longobard fortifications. However, the concession of lands for the construction of monasteries by Longobards, after their conversion to Christianity, also followed similar rules, like in the case of Bobbio monastery [2].

To test these hypotheses, we integrated acoustic modelling and spatial analysis using a combination of algorithms and analytic tools available in MATLAB (release 2024b) and QGIS (v. 3.34.7).

B. Spatial database construction

A dataset of medieval fortifications in the Province of Potenza (Basilicata) was compiled using public documentation available on the “Mondi Medievali” website [3]. Only sites datable to the 11th century or earlier were considered. Each location was manually verified prior to their inclusion using satellite imagery and orthophotos to ensure spatial accuracy.

Additional layers were integrated in QGIS to enrich the territorial analysis. These include: The main hydrography of the region; A vector layer of Roman road traces, georeferenced by Harvard University from historical sources [4]; A high-resolution Digital Elevation Model (DEM) derived from the TINITALY dataset provided under Creative Commons licence by INGV [5].

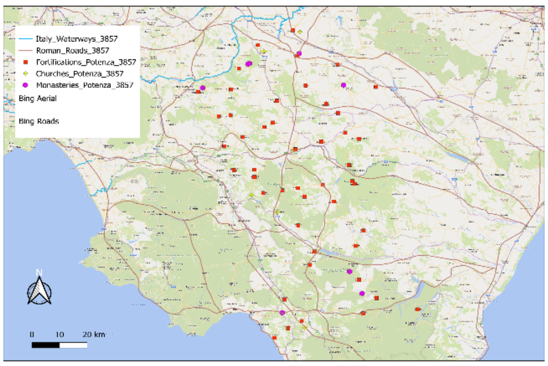

Fig. 1. Position of fortifications (square point), monasteries (hexagonal point) and churches (star point), build until the 11th century in the province of Potenza (Basilicata Region, Italy)

The censed fortifications built until the 11th century, that were included in the database was 48, the monasteries were 8, while the churches were 8. The positions of the sites are shown in Fig. 1.

C. Bell sound acoustic attenuation

Coherently with the results of previous studies [1], we hypothesized the possibility of having communications based on acoustic signalling through the use of bells. However, past studies didn’t model the propagation of bell sounds.

For such a purpose, we employed a spectral attenuation algorithm, implemented in MATLAB R2024b. Starting from the recorded signal of a large bronze bell emitting approximately 110 dB SPL at 10 m, we computed frequency-dependent attenuation as a function of atmospheric absorption, calculated per ISO 9613-1 as [6]:

$$\alpha(f) = 8.686 f^2 \left[a_1 + \frac{a_2}{f_r(f)^2 + f^2} \right] \quad (1)$$

where α is the absorption coefficient, expressed in units of dB/m, dependent on temperature, relative humidity and atmospheric pressure, while $f_r(f)$ are the relaxation frequencies of oxygen and nitrogen. The analysis included three mean meteorological conditions (considering a temperature range from 0°C to 35 °C, a relative humidity range between 55% and 95% and a pressure variability between 1010 hPa and 1018 hPa), covering mean seasonal temperature and humidity variations.

To evaluate the acoustic reach of bell signals under real environmental conditions, we implemented a spectral attenuation algorithm in MATLAB R2024b. The input sound was the recorded signal of a 13th-century bell currently mounted in the bell tower of Salerno Cathedral. The bell strike was captured using a UMIK-1 measurement microphone with a linear frequency response, sampling rate of 44,100 Hz, and stored in *uncompressed .wav format to preserve full spectral content.

For each frequency peak extracted from the bell spectrum, the distance at which the signal would fall below a subjective hearing threshold (e.g. 30 dB SPL) was calculated.

D. GIS-based visibility and acoustic network analysis

In QGIS, visibility between sites was assessed using the “Create Viewpoints” and “Viewshed Analysis” tools applied to the database of fortified points, in integration with the DEM raster layer.

Sound audibility zones were modelled using vector buffer operations centred on each acoustically active site (including fortifications, monasteries, and churches, treated as potential signal stations). The radius, derived from the mean spectral attenuation calculations, was fixed to 3 km.

To evaluate the alternative hypothesis, a Python script was developed within QGIS to compute the shortest distances and mean distance between each fortification and the pre-existing Roman road network. These distances were statistically analysed the plausibility of the hypothesis, which considers the fortifications to be placed in relation to key routes, independently from a pre-fixed inter-visibility or acoustic connectivity among fortifications.

III. RESULTS AND DISCUSSION

A. Results

The visibility analysis showed that only 14 fortifications could be connected thanks to a mutual line-of-sight (Fig. 2).

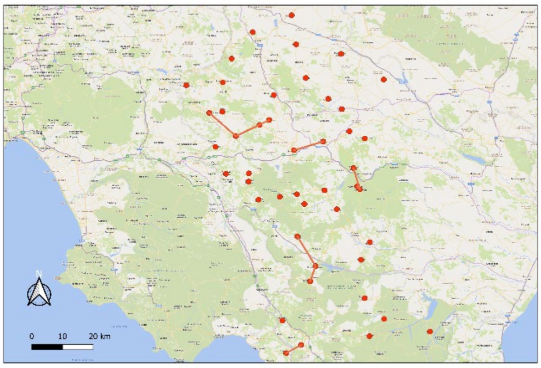

Fig. 2. Inter-visibility (red line) among medieval fortifications, built until the 11th century in the province of Potenza (Basilicata Region, Italy)

Using the bell sound attenuation model, and assuming open-field, humid conditions with a bell source emitting 110 dB SPL, the maximum distance of audibility was estimated between 2.6 and 3 km—a result consistent with experimental literature on bell propagation in rural areas.

Extending the network to include churches and monastic sites as potential acoustic relays, the number of acoustically reachable points increases to 11 couples of points (Fig. 3).

However, even within this theoretical range, very few points fall within each other's acoustic buffer zones. This suggests that a coordinated network of audible communication between sites couldn't be feasible, contrary to what was previously observed for the Campania Region (provinces of Salerno and Avellino) and the Susa Valley (Piemonte Region, in Northern Italy).

To test the alternative hypothesis — namely, that fortifications were placed to control routes, rather than communicate visually or acoustically to improve the civil and military life integration coordination within the area — each site's distance to the pre-existing ancient Roman road network was calculated.

Fig. 4 represents the 48 fortifications (red square points) and the Roman road network (brown lines) in the area of interest for this study.

The analysis revealed a mean distance of 5477.18 meters from each site to the nearest Roman route. This is compatible with an average walking time of under two hours, supporting the idea that fortifications were distributed to oversee the movements along ancient transport arteries in locally strategic points, rather than to form a coherent communication mesh.

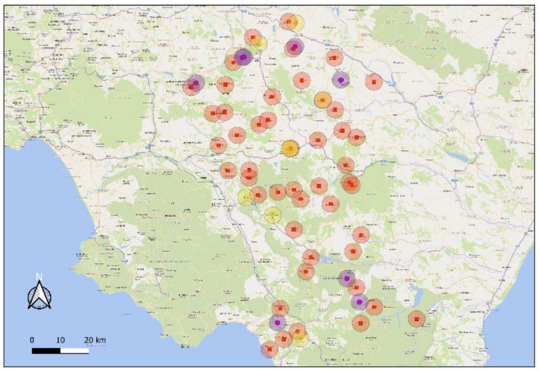

Fig. 3. Potential acoustic communication among fortifications, monasteries and churches built until the 11th century in the province of Potenza (Basilicata Region, Italy)

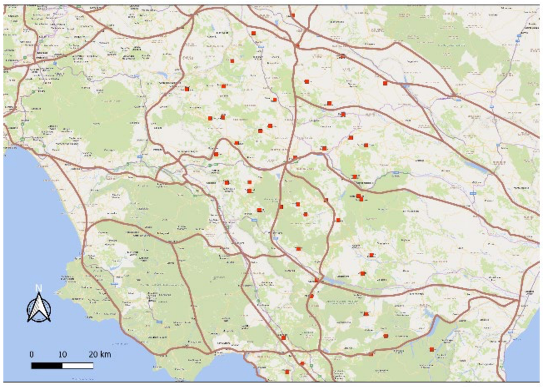

Fig. 4. Fortifications (red square points) built until the 11th century in the province of Potenza (Basilicata Region, Italy) and Roman roads network (brown lines).

B. Discussion

The results of our studies, compared with previous studies to characterize the territorial coordination in other areas in Southern Italy during the Longobard-Norman transition, indicate that the logic behind the positioning changed, reflecting also different ways of manifesting and integrating the existing territorial powers, including that of the Church. The settlements in the studied area, for the period included in this study, reflect a defensive logic, driven by geographical and orographic factors. However, historical and political conditions appear to become dominant in a second phase of consolidation of Norman power, starting from the Campania region. Consequently, the results obtained in this work point to a previous phase of territorial organization, compared to that of Salerno and

Avellino during the 11th century, after the Norman conquest, when the Benedictine monasticism and Norman governance converged to structure an integrated large-scale coordination network [1]. In other words, the territorial integration appeared after a historical and political integration between the Normans and the Benedictine order. Instead, in the studied area, monastic sites were sparse, coherently with what is observed for Basilian monastic sites of Greek rite, and no large-scale coordination between religious and political power were observed.

The limited presence of acoustic or visual connectivity between fortifications in the case of Potenza area, in Basilicata Region, reinforces the interpretation that these defensive settlements were still treated as local strongholds, rather than components of an integrated communication system used to coordinate the political power over a larger area. In Basilicata, the evidence rather reflects a defensive and reactive logic during periods of political instability, prior to the full consolidation of Norman power.

The presence, in the same territory, of Basilian monastic sites and hermitages further supports the idea of fragmented spatial logics, prior to the emergence of Norman–Benedictine integration seen elsewhere [7,8]. These structures, characteristic of the Greek rite monasticism, had expanded across southern Italy during the Byzantine reconquest and were sustained through local Greek-speaking populations, especially in Calabria and the Salento. However, by the mid-eleventh century, this monastic tradition was entering a period of decline.

The turning point was marked by a series of geopolitical and ecclesiastical realignments. After the Battle of Civitate (1053) and the Treaty of Melfi (1059), in which Robert Guiscard swore fealty to Pope Nicholas II, the Normans became formal protectors of the Roman Church. As part of this oath, Robert agreed to place all churches in his domains under Roman jurisdiction. This arrangement laid the foundations for a process of Latinisation, wherein the Greek rite and monastic structures—which had until then enjoyed a degree of autonomy—were gradually replaced by the Latin rite and Benedictine monasticism [9].

This shift was not only liturgical, but deeply political. In Campania Region, as shown in prior studies, the Normans employed this religious-political alliance to weave together fortifications, monastic centres, and churches into acoustically and visually coherent territorial system [1]. This territorial consolidation, in the previously studied case of Campania Region, relied on the choice of Normans to support the Benedictine order, since the time of Mt. Saint Michel abbey reconstruction, in France, after its destruction by the Viking warlord and Norman ancestor Rollo. Again, the Treaty of Melfi (1059) marked a strategic realignment. The Papacy, under Nicholas II, and through the efforts of Archdeacon Hildebrand of Soana (later, pope Gregory VII), recognized Norman legitimacy in exchange for fealty and the defence of the *terra sancti Petri*. In this context, Abbot Desiderius of Montecassino (later, pope Victor III), initially tied to anti-Norman factions, decisively aligned with the reformist Papacy and sought protection from Norman rulers such as Richard of Capua and Robert of Hauteville [10].

This study not only contributes to the verification of an archaeological research hypothesis, with specific focus on understanding of territorial logic in pre-Norman Basilicata, providing also a robust methodological framework for applying a physical metrology to the context of landscape archaeology. The combination of spectral attenuation modelling, calibrated acoustic thresholds, and spatial analysis demonstrates how quantitative tools from physical acoustics can support the reconstruction of intangible cultural dynamics, such as long-distance communication.

In particular, this approach exemplifies how vibroacoustic metrics — traditionally used in architectural and environmental acoustics — can be extended to support historical hypotheses about power, infrastructure, and governance. The replicability of the method and its sensitivity to real-world conditions make it a valuable model for future interdisciplinary research in cultural heritage metrology

IV. CONCLUSIONS

This study applied a metrological framework to investigate the spatial organization of early medieval fortifications in the Province of Potenza, focusing on their potential for acoustic and visual communication. By combining digital terrain modelling, spectral sound attenuation analysis, and GIS-based proximity studies, we quantitatively tested the hypothesis that these sites formed a coordinated vibroacoustic network during the Longobard–Norman transition.

The results indicate that neither line-of-sight visibility nor acoustic reachability explains the positioning of most fortifications, even when extended to include churches and monasteries. Instead, spatial correlation with the Roman road network suggests a logic of territorial oversight and strategic access control rather than inter-site communication.

From a metrological standpoint, this work exemplifies how methods traditionally reserved for acoustic engineering—such as calibrated attenuation modelling and frequency-resolved propagation thresholds—can be successfully adapted to the study of historical landscapes. The approach strengthens the interpretive power of digital archaeology and supports reproducible, parameter-driven hypotheses in cultural heritage research.

Future applications may expand this methodology to assess historical soundscapes across broader territories, offering new perspectives on how intangible dimensions such as sound contributed to the construction and control of power in pre-modern societies.

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