Unveiling the Historical Significance of Santa Maria d'Àneu: Can Soundscape Studies Illuminate its Role within the Medieval Ecclesiastical Structure?
Odkrivanje zgodovinskega pomena cerkve Santa Maria d'Àneu: ali lahko raziskave zvočne krajine osvetlijo njeno vlogo v srednjeveški cerkveni strukturi?

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Abstract
The church of Santa Maria d'Àneu, located in the Àneu valley of the Catalan Pyrenees, holds significant yet debated historical importance within the ecclesiastical structure of the medieval period. While renowned for its Romanesque paintings, its exact role within the Àneu deanery remains unclear. This article explores whether the church's visibility and the audibility of its bells across the landscape, as a representation of ecclesiastical power, extended across the 22 parishes of the Àneu valley. The study is based on onsite acoustic measurements, virtual sound propagation simulations using the ArcGIS Sound Mapping Tools plugin, and different visibility models built with the QGIS Visibility Analysis toolbox. The findings suggest the existence of a bell aural network among most parishes in the Àneu deanery, positioning Santa Maria d'Àneu as a central church within the district.
Keywords: Medieval soundscapes, archaeoacoustics, sound mapping, aural community, medieval Catalonia

Izvleček
Cerkev Santa Maria d'Àneu v dolini Àneu v katalonskih Pirenejih ima velik, a sporen zgodovinski pomen v cerkveni strukturi srednjeveškega obdobja. Čeprav slovi po svojih romanskih poslikavah, njena natančna vloga v dekanatu Àneu ostaja nejasna. Pričujoči članek raziskuje, ali sta vidnost cerkve in slišnost njenih zvonov v pokrajini kot predstava cerkvene moči veljali tudi za 22 župnij v dolini Àneu. Raziskava temelji na akustičnih meritvah na kraju samem, virtualnih simulacijah širjenja zvoka z uporabo vtičnika ArcGIS Sound Mapping Tools in različnih modelih vidnosti, izdelanih z orodjem QGIS Visibility Analysis. Ugotovitve kažejo na obstoj zvonskega zvočnega omrežja med večino župnij v dekaniji Àneu, ki cerkev Santa Maria d'Àneu postavlja kot osrednjo cerkev v okrožju.
Ključne besede: srednjeveške zvočne krajine, arheoakustika, zvočno kartiranje, zvočna skupnost, srednjeveška Katalonija

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Introduction

In medieval Europe, church bells played a crucial role in daily life. They marked the passage of time, served as alarms during danger, and conveyed news of various events. These auditory messages were broadcast into the surrounding landscape. In addition, bells expressed and shaped contrasting emotions —joy and sorrow— and influenced perceptions of respect, community, and local identity (Corbin 1998; Tullett 2020). The bell, often called the "voice of God," carried significant symbolic and political power across both secular and sacred domains, transmitting auditory messages effectively across the landscape (Castellet i de Ramon 2021, 223–230; Parker and Spennemann 2024).

Church bell sound can be considered an *earcon*, as defined by Blesser and Salter (2007). *Earcon* is a sonic event containing symbolic meaning 'by repeated exposure to a particular event in a corresponding context, which then creates an associating linkage between the sound and its context,' merging religious and philosophical views of the cosmos with life on earth, connecting *here* and *there* (Blesser and Salter 2007, 82). Emotional responses to bell sounds were deeply tied to feelings of attachment to a place, fostering a sense of belonging and connection (Mileson 2016). This strong link between sound, emotion, and place underscores the importance of visualizing how far bell sounds permeated the landscape and how audible they were.

Previous research has suggested that the audibility of bells often coincided with parish boundaries, making them a unique soundmark that contributed to a sense of community (Castellet i de Ramon 2021, 230–241; Mileson 2016). Understanding the inclusivity of soundscapes and the size of acoustic communities enhances our comprehension of the medieval aural environment and the communication networks among neighboring parishes (Mlekuž 2004). That kind of research fits into auditory archaeology, whose main objective is to gather acoustic information that sheds light on the everyday practices of medieval times, including the environment and the relationship between humans, acoustic information, and dwelling places (Mills 2014).

Over the past few decades, significant efforts have been made to map sound in archaeological contexts using Geographic Information Systems (GIS). In 2004, Mlekuž simulated the propagation of bell sounds in the late medieval soundscape of Polhograjsko hribovje in Slovenia, considering sound attenuation due to distance and topography (Mlekuž 2004). Other studies have mapped the audibility of church bells by tracing public footpaths onsite and noting whether the bells were audible (Mileson 2016). Similarly, sound was mapped at an archaeological site, combining GIS and onsite acoustic measurements of pink noise captured with sound level meters (Scullin 2019). Recent studies of sound propagation in landscapes have utilized SPreAD-GIS, a freely available plugin for ArcGIS. This tool allows complex calculations of sound propagation, including attenuation due to distance, topography, atmospheric absorption, ground cover, wind, and background noise. SPreAD-GIS has been used to test the soundscapes of archaeological sites (Hincks and Johnston 2022; Primeau and Witt 2018; García Atiénzar et al. 2022) and to study the propagation of bell sounds around medieval monasteries (Bertoldi et al. 2022).

This paper examines the case of Santa Maria d'Àneu, a church located in the Àneu valley at the western end of the Catalan Pyrenees. Our focus is on its relationship with other religious centers in the Àneu deanery, a minor administrative division of the Diocese of Urgell that encompassed several nearby parish churches under the authority of a dean. This is a particularly intriguing topic because the historical significance and role of Santa Maria d'Àneu within this ecclesiastical district remain unclear to historians. Based on available sources, it is nearly impossible to confirm the hypothesis that this church, situated in the middle of a plain with no surrounding settlement, served as the center of the deanery. However, our soundscape study aims to

Figure 1: The church Santa Maria d'Àneu in the landscape of Àneu valley, viewed from the road from Esterri d'Àneu village.

explore whether the church bells of Santa Maria d'Àneu, as a symbol of authority, could be heard across the parishes that comprised the district, potentially indicating its central role. In addition, this soundscape study is complemented by a visibility analysis of the site. Our research thus offers new insights that may help to clarify Santa Maria's significance as a potential ecclesiastical center in the Àneu valley.

To achieve this, the paper is structured as follows: First, we explore the current understanding of the ecclesiastical significance of Santa Maria d'Àneu. In the second section, we detail our three-part methodology, which includes onsite acoustic measurements, virtual sound propagation simulations, and visibility analyses. For the acoustic measurements, we simultaneously used a sound level meter to record the bell sounds and background noise and an audio recorder to capture these sound events. Virtual simulations of bell sound propagation were conducted using ESRI ArcGIS Desktop 10.5 and the freely available Sound Mapping Tools (SMT) toolbox, specifically the SPreAD-GIS script (Reed, Boggs, and Mann 2012). For the visibility analysis, we used the QGIS Visibility Analysis plugin (Čučković 2016) to establish the viewshed of Santa Maria d'Àneu, the cumulative viewshed of the entire deanery, and the intervisibility network between its parish churches. In the third section, we present the results of these simulations. Finally, we discuss three key themes that emerged from this study: the limitations of virtual simulations, the challenges of assessing bell audibility over long distances, and how our findings on visibility and audibility contribute to understanding Santa Maria d'Àneu's role within the medieval Àneu deanery.

The Ecclesiastical Significance of Santa Maria d'Àneu

The Santa Maria d'Àneu church is an exceptional case in the ecclesiastical history of the Catalan Pyrenees. Despite the limited documentation that has survived, the importance of this religious center can be argued based on its central position in the Àneu valley, its imposing architecture, and the exceptional Romanesque paintings that decorate its apse (fig. 1). Nevertheless, this church never attained parish status nor generated a surrounding population, and its correct interpretation remains a challenge for historians today.

Very little information is available on the earliest origins of Santa Maria d'Àneu. One of the first Carolingian privileges from the 9th century that refers to the Àneu valley, confirming its attachment to the bishopric of Urgell, already mentions a place under the patronage of Santa Deodata that could be identified as the later church of Santa Maria (Abadal i de Vinyals 1950, 286–288).[1] In a forgery dated 819, whose

1 The same reference also appears in three confirmatory papal bulls of the years 951, 1001, and 1012 (Ordeig Mata 2020, 402–4; Baraut Obiols 1980, 100–101; 1981, 38–40).

actual wording must have been written at the beginning of the 11th century, a church of Santa Maria, 'which was formerly called Santa Deodata,' is mentioned in the valley of Àneu (Ordeig Mata 2020, 759–763).[2] This change of title, combined with the archaism of the first dedication, unknown in the Carolingian period, leads us to believe that Santa Maria d'Àneu is an ancient church, possibly predating the Muslim conquest. Although this has not been archaeologically proven (Cabestany Fort, Matas Blanxart, and Palau Baduell 2005, 192), the mention of this church 'together with all its parishes' has led historians to deduce a certain pre-eminence of Santa Maria over the rest of the churches in the Àneu valley, considering it the center of its ecclesiastical organization (Adell Gisbert and Cases Loscos 1993, 242). Some authors have even suggested it might have been a monastic center (Riu Riu 1992, 214), although none of the surviving sources, whether documentary or archaeological, support that idea (Adell Gisbert and Cases Loscos 1993, 242; Costa-Badia 2019, 358–359).

In the 11th century, during the feudal struggles that affected Catalonia, Santa Maria d'Àneu was usurped by Count Artau I of Pallars Sobirà. This is known from a preserved document in which his son, Artau II, returned the church of Santa Maria d'Àneu to Urgell Cathedral in 1086 in exchange for lifting the excommunication under which his father had died, allowing him to be buried in a sacred place (Baraut Obiols 1984, 145–146).[3] Similarly, shortly afterward, in 1088, a man named Martí Escó also renounced all future claims over the church of Santa Maria d'Àneu, including its tithes and first fruits, before Bishop Bernat of Urgell. This indicates that Escó had also partially appropriated this church (Baraut Obiols 1984, 165–166). In the late 11th and early 12th centuries, Santa Maria d'Àneu also appears as the beneficiary of specific donations in some wills, such as that of the nobleman Tedball Guerlí, who gave it some estates in Esterri (Baraut Obiols 1986, 29–30) and that of Countess Eslonça of Pallars Sobirà, who gave it a man in Unarre (Puig Ferreté 1991, 74). However, none of these documents provide precise information about its historical evolution or juridical nature.

Although the documentation preserved for the Catalan territory became much richer in terms of quality and quantity from the 12th-13th century onwards, the church of Santa Maria d'Àneu remained on the margins of the most relevant sources for understanding the churches and the ecclesiastical reality of the Late Middle Ages. As Josep M. Palau demonstrated in his doctoral thesis, the church of Santa Maria d'Àneu, like the rest of the parishes in its valley, never appears in the episcopal visits made by the bishops of Urgell, at least until the end of the 14th century (Palau Baduell 2015, 90–91). This particularity must be linked to the fact that, at least from the end of the 12th century, the Àneu valley was organized through its own deanery, as evidenced by the election of the priest Arnau Gibert as its dean by Bishop Arnau de Preixens in 1175 (Baraut Obiols 1990, 229). This one had special privileges like other deaneries in the Pyrenean area, as shown in modern period sources. It was ruled with significant autonomy through its own council, comprised of 24 clerics from the valley, with a dean for life who presided over it (Moliné 1982). Therefore, this autonomous character, together with the local clergy's reluctance to allow more significant episcopal interference, could have considerably limited the bishop's capacity for action in the Àneu valley and might explain the systematic exclusion of its deanery

2 Regarding the long debate about the falseness of this diploma and the actual date of its writing, finally fixed around the year 1020, see: Benet Clarà 1983, 137–43; Baraut Obiols 1985, 519–29; Riu Riu 1992, 318–20; Garsaball 1994; Pladevall Font 1998, 21–33; Gascón Chopo and Vergés Pons 2017.

3 It seems that the claims and usurpations of the Counts of Pallars over the church of Santa Maria d'Àneu and the episcopal rights over the Àneu valley did not end with the agreement of 1088, since, almost a century later, in 1164, Count Artau III of Pallars Sobirà once again gave the church of Santa Maria d'Àneu and all the other churches in his county to the Bishop of Urgell, undertaking to preserve its security and properties (Baraut Obiols 1990, 108).

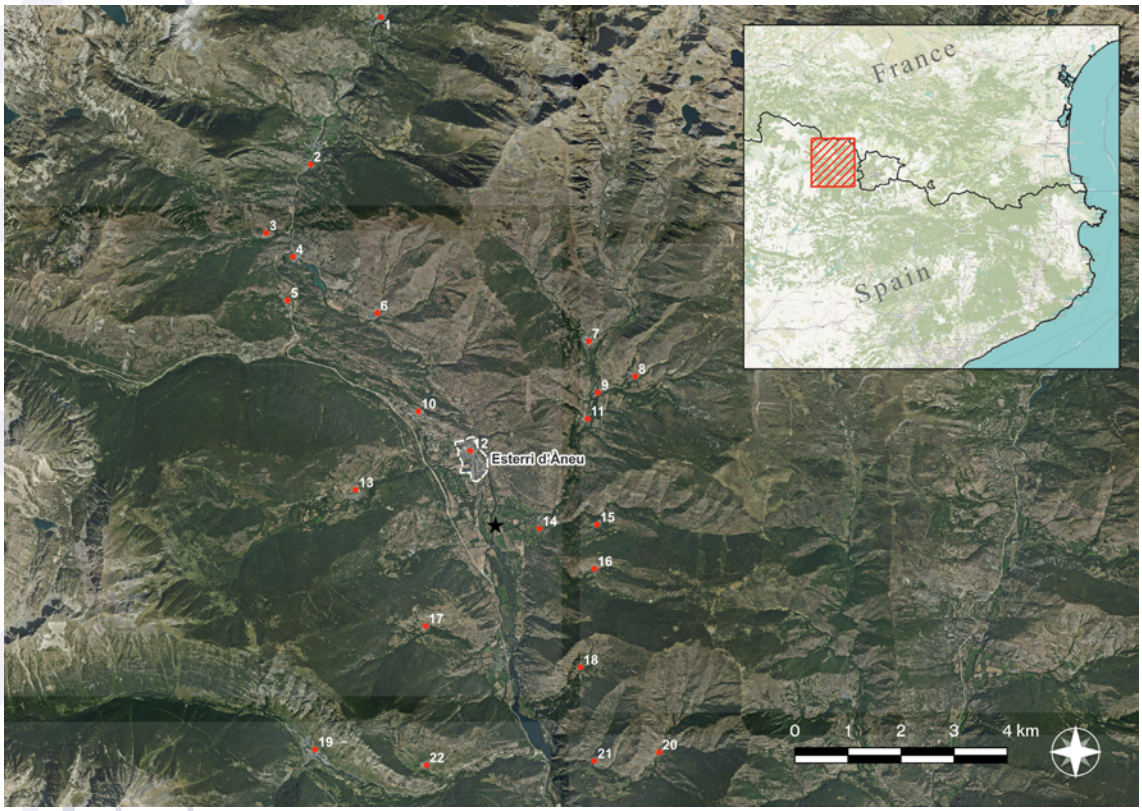

Figure 2. The Location of the Church Santa Maria d'Àneu and the Surrounding Parish Churches belonging to the Deanery of Àneu: (1) Sant Lliser d'Alós, (2) Sant Joan d'Isil, (3) Sant Serni d'Àrreu, (4) Sant Martí de Borén, (5) Sant Pere de Sorpe, (6) Sant Llorenç d'Isavarre, (7) Sant Serni de Cerbi, (8) Sant Esteve de Gavàs, (9) Sant Pere d'Aurós, (10) Sant Andreu de València d'Àneu, (11) Sant Julià d'Unarre, (12) Sant Vicenç d'Esterri d'Àneu, (13) Sant Just i Sant Pastor de Son, (14) Sant Martí d'Escalarre, (15) Sant Joan de Burgo, (16) Sant Miquel de Llavorre, (17) Sant Pere de Jou, 18) Sant Bartomeu de Dorve, (19) Santa Llogaia d'Espot, (20) Sant Quirze de Berrós Sobirà, (21) Sant Jaume de Berrós Jussà, (22) Sant Esteve d'Estais. The parish churches are numbered from north to south, showing that they were positioned all around Santa Maria d'Àneu, with many extending north along the main roads and the river Noguera Pallaresa.

from pastoral visitations (Palau Baduell 2015, 90–91).

The counterpart to this autonomy is the scant information we have about the churches in the territory around Santa Maria d'Àneu. In fact, we do not even know which church would be the center of the deanery of Àneu. Several authors have suggested that Santa Maria might initially have held this role. This would explain why, despite never appearing with the title of a parish church, it has such a unique architectural specificity and pre-eminence (Adell Gisbert and Cases Loscos 1993, 243–244; Cabestany Fort, Matas Blanxart, and Palau Baduell 2005, 194). Additionally, it clarifies why the Counts of Pallars always preferred it, both to promote and appropriate it. Hypothetically, it would also be possible that this church remained in the Late Middle Ages as the ecclesiastical center of the valley and the place of residence of the dean, possibly accompanied by other clerics. Consequently, all the parishes that made up the late medieval Àneu deanery, in total 22 according to Palau's reconstruction (Palau Baduell 2015, 130–131), would have had some relationship of dependence with it (fig. 2).

Verifying whether Santa Maria d'Àneu served as the center of the Àneu deanery through existing historical records is challenging. However, our soundscape analysis offers a novel perspective by assessing whether this church had the auditory capacity to initiate the deanery's aural network, transmitting auditory messages throughout the Àneu parishes via its bell ringing. Thus, our findings introduce fresh evidence that may help to resolve the debate regarding the central ecclesiastical role of Santa Maria in the Àneu valley.

Methodology of Archaeoacoustic Study

The methodology of this archaeoacoustic study consists of three main parts: 1) field acoustic measurements, 2) virtual sound propagation simulations, and 3) visibility analysis.

Field Acoustic Measurements

In March 2024, we conducted outdoor acoustic measurements at the site of Santa Maria d'Àneu. The church features a bell gable on the west-facing entrance wall, slightly offset towards the south. A medium-sized bell within the bell gable (fig. 3) is manually rung by pulling a rope from the interior church gallery. We recorded acoustic data using the Sound level meter Cesva 202 connected to a ZoomH4n recorder. This setup provided acoustic data in an Excel file as the sound level meter output and a corresponding audio file in WAV format from the recorder. The sonometer was mounted on a tripod at a height of 1.5 m, approximating ear height.

As shown in fig. 4, we recorded background noise and bell ringing for two receiver points: in front of the church and approximately 70m

Figure 3: The Location of the Bell Gable with the Microphone/Sonometer Set at the Receiver Point R1 in Front (left) and a Close-up of the Bell (right).

Figure 4: Map Showing the Bell's Location (white dot) and Two Receiver Points (red dots)—R1 in Front of the Bell Gable and R2 Approximately 70 m Down the Road.

down the road from the bell. For each acoustic measurement, the bell was rung three times to ensure a reliable and consistent record of the sound level.

Virtual Sound Propagation Simulations

The second part of our research involved simulating bell sound propagation in the surrounding landscape using GIS. We used the ESRI ArcGIS Desktop 10.5 software and the Sound Mapping Tools (SMT) toolbox, specifically the SPreAD-GIS script, developed by Reed and colleagues (Reed, Boggs, and Mann 2012). This script simulates sound propagation in natural environments, adapted from the SPreAD - System for the Prediction of Acoustic Detectability (Harrison, Clark, and Stankey 1980). Ideally, sound propagates spherically, diminishing as the square of the distance from the source increases. The SPreAD-GIS script also incorporates the effects of atmospheric conditions, vegetation, wind, and terrain. These factors collectively contribute to sound level attenuation, as detailed in tab. 1. The script aligns with ISO 9613-2 standards for outdoor sound attenuation (Keyel et al. 2017). It tracks the propagation of various frequencies, allowing us to determine the dominant pitch in different areas. Moreover, the map design was carried out using the software QGIS Desktop 3.38.0.

For the simulation, we defined the study area and overlaid a digital elevation model (DEM) as a cartographic base obtained from the website of the Centro Nacional de Información Geográfica (n.d.). We used the National Land Cover Data (NLCD) provided by the European Space Agency (n.d.) for vegetation cover data. The land cover data were reclassified into seven categories:

Table 1. Environmental Sound Propagation Factors that are Included in the SPreAD-GIS Calculation Process

Environmental sound propagation factors	Declining the sound level due to...
Spherical Spreading Loss	Distance
Atmospheric Absorption Loss	Atmospheric absorption which depends on temperature, humidity and elevation
Foliage and Ground Cover Loss	Absorption by the ground and scattering by vegetation
Downwind and Upwind Loss	Wind direction, wind speed, seasonal conditions
Terrain Effects	Barrier effects from hills or ridgelines
Predicted Noise Propagation	The difference between introduced and background levels

barren land, coniferous forest, herbaceous/grassland, deciduous forest, scrubland, urban/developed land, and water. DEM and NLCD were set at the same resolution of 10x10 meters, the highest available resolution for the NLCD in this Catalan region. We also introduced data related to the sound source, including the location of the Àneu bell and a frequency table with measured sound levels in the one-third octave frequency bands from 400–2000 Hz, recorded at a distance of 11 m (tab. 2).

To validate the simulation, we first recreated the weather conditions present during the field measurements (tab. 4, weather scenario A.1). Then, we generated the sound propagation map, showing sound levels at the receiver points (fig. 5). Tab. 3 compares the measured and simulated sound levels, showing a deviation of 3 to 4 dBA, an acceptable range for validation. This validation allowed us to proceed with further testing under different weather conditions.

Anticipating that the simulations would reveal the extremes of sound propagation under different weather conditions, we conducted simulations for both extreme winter and summer days (B and C, tab. 4). Meteorological data were sourced from Servei Meteorològic de Catalunya (n.d.), including data from nearby stations. Wind data were obtained from Tírvia, extreme temperature data from the last 50 years were taken from Tremp, and humidity data were collected from La Pobla de Segur. Given that wind significantly influences sound propagation, we also tested conditions with the most favorable wind direction, blowing from SSE towards Esterri d'Àneu (tab. 4, A.2.).

Table 2. The Frequency Table Used to Characterize the Sound Source for the SPreAD-GIS Simulation, Including Sound Pressure Levels (dBA) in the One-third Octave Frequency Bands from 400–2000 Hz, Recorded at 11 m from the Source.

Frequency (Hz)	400	500	630	800	1000	1250	1600	2000
Sound Pressure Level (dBA)	47	73	69	70	81	80	76	80

Table 3. Measured vs. Simulated Values of Sound Pressure Levels for Two Receiver Points on the Site of Santa Maria d'Àneu

Receiver ID	Receiver location	Measured values (L AF; dBA)			Simulated values (dBA)
		1st toll	2nd toll	3rd toll	
1	In front of the church and bell gable	81.7	80.3	90.7	85
2	On the earthen road behind the church	60.2	53.3	56.2	64

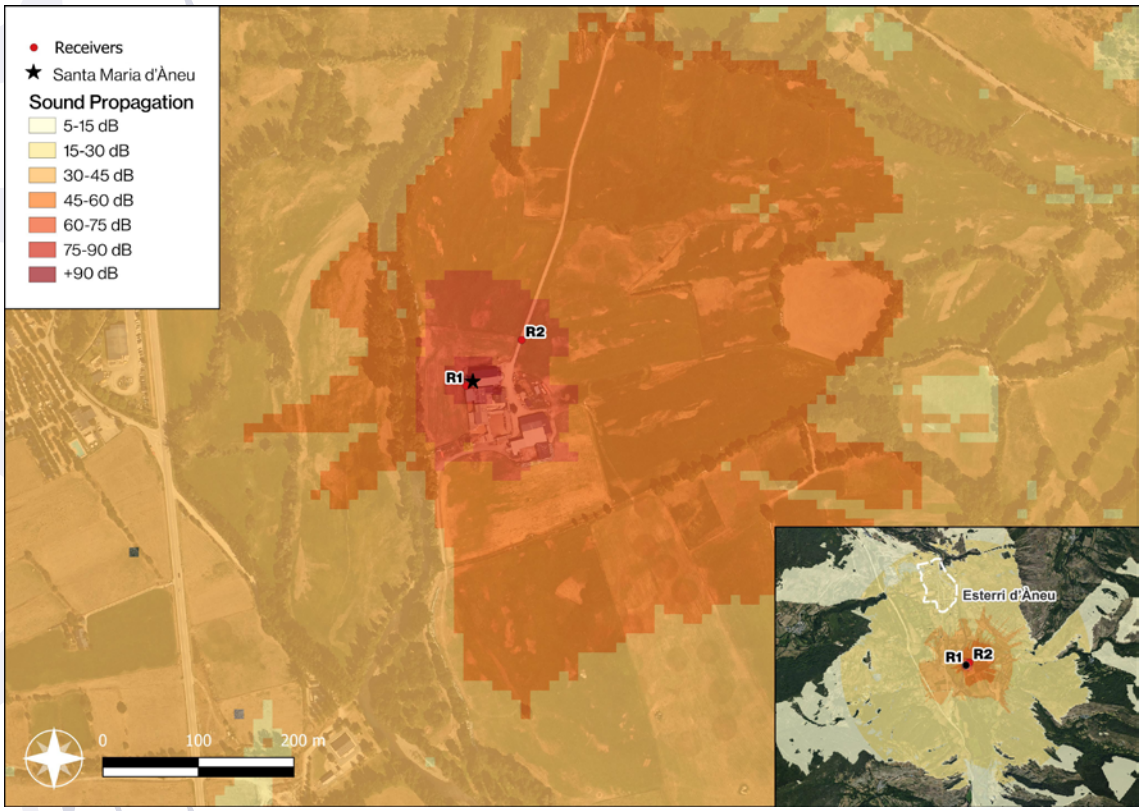

Figure 5: Bell Sound Propagation Map Simulating the Weather Conditions during the Onsite Acoustic Measurements. The values obtained for two receiver points – R1 and R2 – were used to validate the SpreAD-GIS script (see tab. 3).

Methodology for the Visibility Analysis

While the primary aim of this paper is to identify and study the aural network of Santa Maria d'Àneu, we also complemented our findings with a virtual visibility simulation to assess the church's visual influence over the deanery of Àneu. This study was conducted using the Visibility Analysis plugin developed by Zoran Čučković for the open-source software QGIS (Čučković 2016).

We employed three different types of visibility analysis. First, we defined the individual viewshed of Santa Maria d'Àneu, calculating the entire area visible from this observation point

Table 4. Weather Scenarios that Are Used in Testing the Sound Propagation

#	General description	Temperature (°C)	Wind (direction, m/s)	Relative Humidity (%)
A.1.	As measured onsite (no wind)	18	No wind	30
A.2.	As measured onsite, but with the most favorable wind conditions	18	SSE 3.75	30
B.1.	Extremely cold and calm winter day	-8	No wind	74
B.2.	Extremely cold and windy winter day	-8	NNE 6.25	74
C.1.	Extremely hot and calm summer day	36	No wind	53
C.2.	Extremely hot and windy summer day	36	WSW 3.75	53

based on the region's digital elevation model (DEM). Second, we generated the cumulative viewshed of all the parishes in the Àneu deanery to determine whether Santa Maria was situated in a more or less visible area compared to the surrounding churches. Finally, we constructed a network of intervisibility between these religious centers, establishing which churches were visible to each other and which were not.

To build these models, we used the same coordinates file and 10x10 meters DEM for the sound propagation simulations. However, visibility analysis requires converting the original points into 'viewpoints,' which necessitates establishing the height above ground for both the observers and the target objects. For the individual viewshed of Santa Maria d'Àneu, we assumed the observation would be from ground level, as the church has only a small modern bell gable. Therefore, we set the observer height to the average height of a person: 1.60 meters. The same value was applied for the cumulative viewshed of the Àneu valley and the intervisibility network between its parishes, as our interest lies in views of daily life, not those from the tops of steeples.

Determining the height of the target objects—the medieval parish churches—was more challenging. These churches undoubtedly stood above ground level, but most have been extensively rebuilt in modern times, making it difficult to determine their original height in the Middle Ages. To address this uncertainty, we set the target height at 7.50 m for the two viewshed analyses, a reasonable estimate for medieval churches (for example, Santa Maria d'Àneu rises to 11 m). For the intervisibility network, in order to avoid misleading results, we conducted three different simulations: one assuming all buildings were approximately 7.50 m tall, another considering the maximum current height of the buildings (including their modern bell towers), and a third assuming both the observer and target points were at the top of the respective steeples.[4] As we will discuss below, the differences between these simulations are minimal for Santa Maria d'Àneu but provide some thought-provoking insights.

Finally, all procedures accounted for the earth's curvature and atmospheric refraction, set at 0.13000. However, all simulations assumed optimal visibility conditions without considering adverse weather effects, such as fog, which could significantly impact visibility.

Results of the Simulation of Sound Propagation

The sound propagation is simulated for six weather scenarios: without wind (A.1., B.1., C.1.) and with wind (A.2., B.2., C.2.). Fig. 6 displays the sound propagation maps for these scenarios, using different colors to indicate seven ranges of sound levels (5-15 dB, 15-30 dB, 30-45 dB, and so on).

Scenario A.1. represents the most common mild weather conditions without wind. In this case, the total area coverage is the largest, about 16.5 km² (tab. 5). However, bell ringing reaches half of this area with less than 15 dB. Whether this low sound level could have been heard depended on several factors, primarily if the background noise (such as river or traffic) was sufficiently quiet. Our acoustic measurements of background noise at the site Santa Maria d'Àneu range from an $L_{Aeq,\,2min}$ of 30 to 45 dB. However, given that no motor vehicles existed in the medieval period, the background noise was undoubtedly lower than today.

Observing the maps in the left column of fig. 6, we notice a more extensive coverage area than the maps on the right. This is because the maps on the left show scenarios without wind, allowing the sound of the bell to propagate further into the landscape. According to the simulations, the sound of the bell reaches the churches Sant Vicenç d'Esterri d'Àneu and Sant Martí d'Escalarre (numbers 12 and 14 on the map, re-

4 The height of the different buildings has been obtained thanks to an inventory of all the bells and steeples in the Àneu valley (Dalmau Argemir and Orriols Sendra 2001).

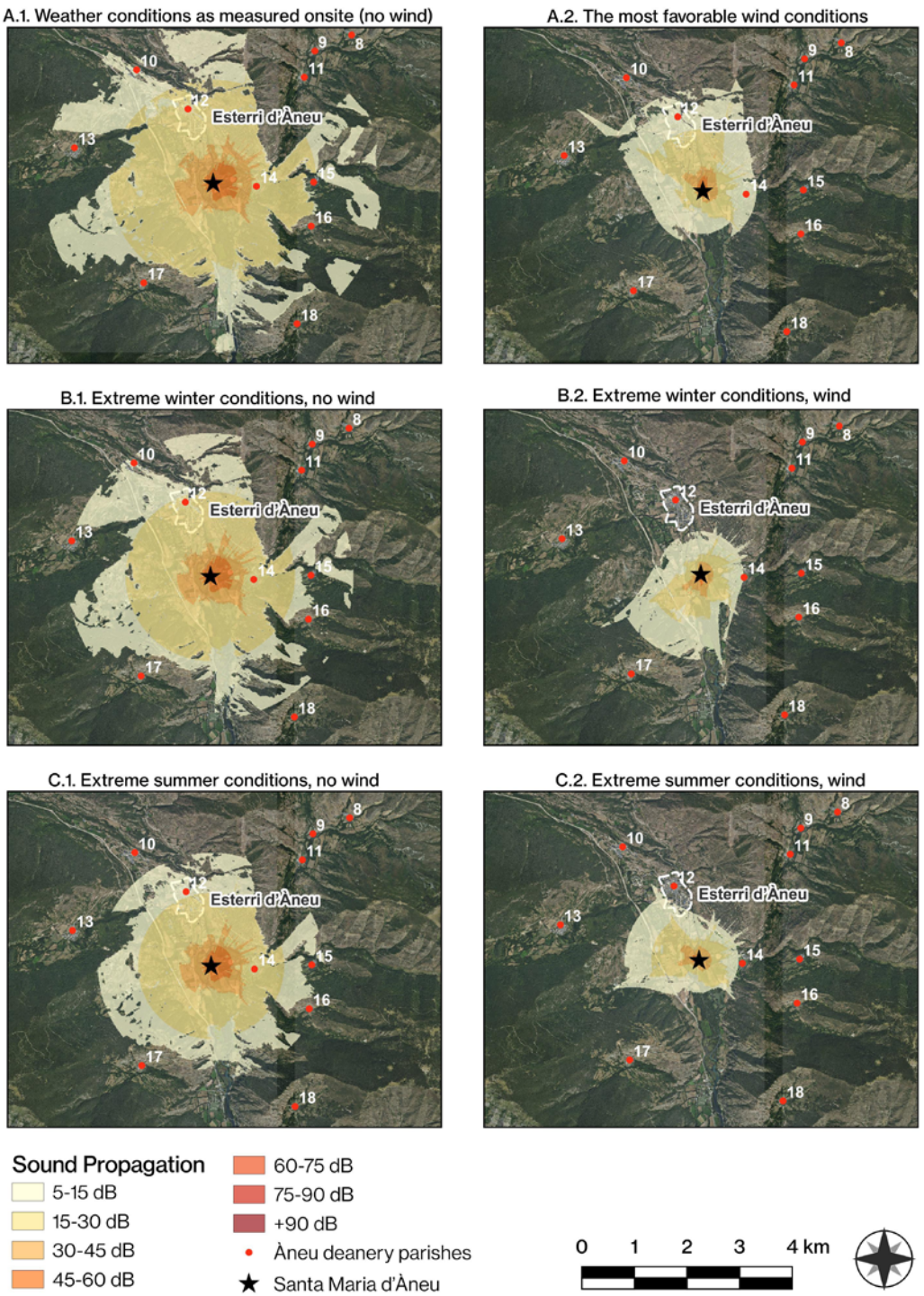

Figure 6: Sound Propagation Maps for Six Weather Scenarios, Showing the Coverage of the Sound of the Bell Ringing from Santa Maria d'Àneu by the Sound Levels in dB

Table 5. The Area Covered by the Sound of Bells (km²) Shown per Sound Levels (dB)

#	General description of weather conditions	Coverage area (km²) by the sound levels					
		05-15 dB	15-30 dB	30-45 dB	45-60 dB	60-90 dB	Total
A.1.	As measured onsite (no wind)	7.12	7.9	1.17	0.28	0.0285	16.49
A.2.	As measured onsite, but with the most favorable wind conditions	3.56	1.49	0.21	0.04	0.0157	5.32
B.1.	Extremely cold and calm winter day	6.57	6.08	0.89	0.24	0.0271	13.8
B.2.	Extremely cold and windy winter day	2.48	0.95	0.18	0.02	0.0054	3.64
C.1.	Extremely hot and calm summer day	4.97	4.53	0.8	0.22	0.0263	10.55
C.2.	Extremely hot and windy summer day	1.88	0.97	0.17	0.02	0.005	3.04

spectively) at a level between 15 and 30 dB under no-wind conditions. In contrast, the church Sant Andreu de València d'Àneu (number 10 on the map) is on the border area in scenarios A.1. and B.1.

The scenarios that include wind are presented in the right column (fig. 6, A.2., B.2., and C.2.). When the wind is introduced, the sound propagation area is shrunk by 3 to 4 times (tab. 5). Only in scenario A.2., which includes the 'favorable wind' blowing from the church Santa Maria d'Àneu towards the village Esterri d'Àneu, does the bell sound reach the churches Sant Vicenç d'Esterri d'Àneu and Sant Martí d'Escalarre (numbers 12 and 14 on the map, respectively) at a level between 5 and 15 dB. In B.2.,

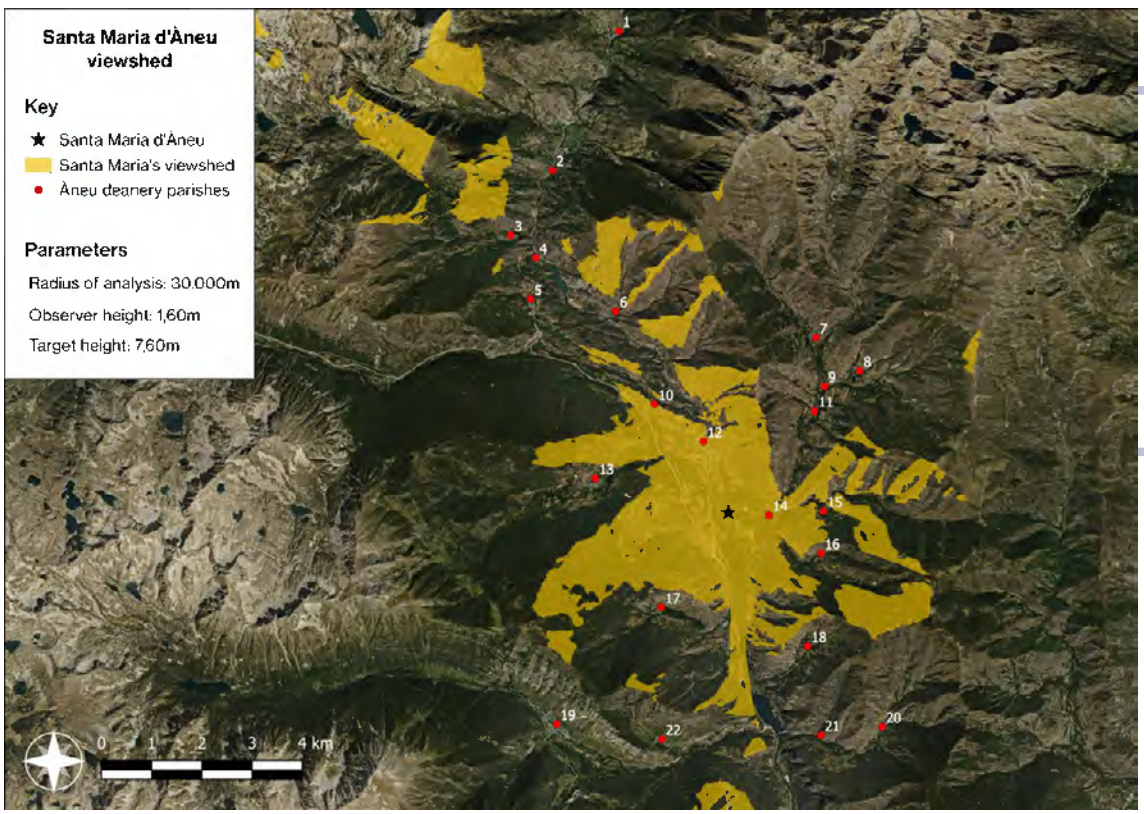

Figure 7: Individual Viewshed from Santa Maria d'Àneu

the church Sant Martí d'Escalarre (number 14) is on the border of the bell sound propagation area.

Results of the Visibility Analysis

Our visibility study comprised three distinct procedures: defining the individual viewshed of Santa Maria d'Àneu to determine the visible areas from that location; generating the cumulative viewshed of all the parish churches in the Àneu deanery to assess whether Santa Maria d'Àneu was in a notably visible position; and mapping the intervisibility network among these religious centers to examine their visual relationships.

Starting with the individual viewshed analysis (fig. 7), we observe that the visible area from Santa Maria d'Àneu does not encompass the entire Àneu valley. Still, it does cover its central and most fertile parts. Although the church is situated at the bottom of the valley, just a few meters from the Noguera Pallaresa River, its central location in the broad plain between La Guingueta and Esterri d'Àneu offers a commanding view of the surrounding area. From here, it has direct visual connections with three significant parish churches: Sant Andreu de València d'Àneu, Sant Vicenç d'Esterri d'Àneu, and Sant Martí d'Escalarre. Additionally, its field of vision extends toward the vicinity of Sant Joan de Burgo, which would be visible if the church had a bell tower at least 17.42 meters high. Notably, the viewshed of Santa Maria d'Àneu also includes the castle of València d'Àneu, one of the main fortresses of the Counts of Pallars Sobirà, whose historical ties to Santa Maria d'Àneu have been well-established.

In the cumulative viewshed analysis of the Àneu deanery (fig. 8), we used a color gradient to

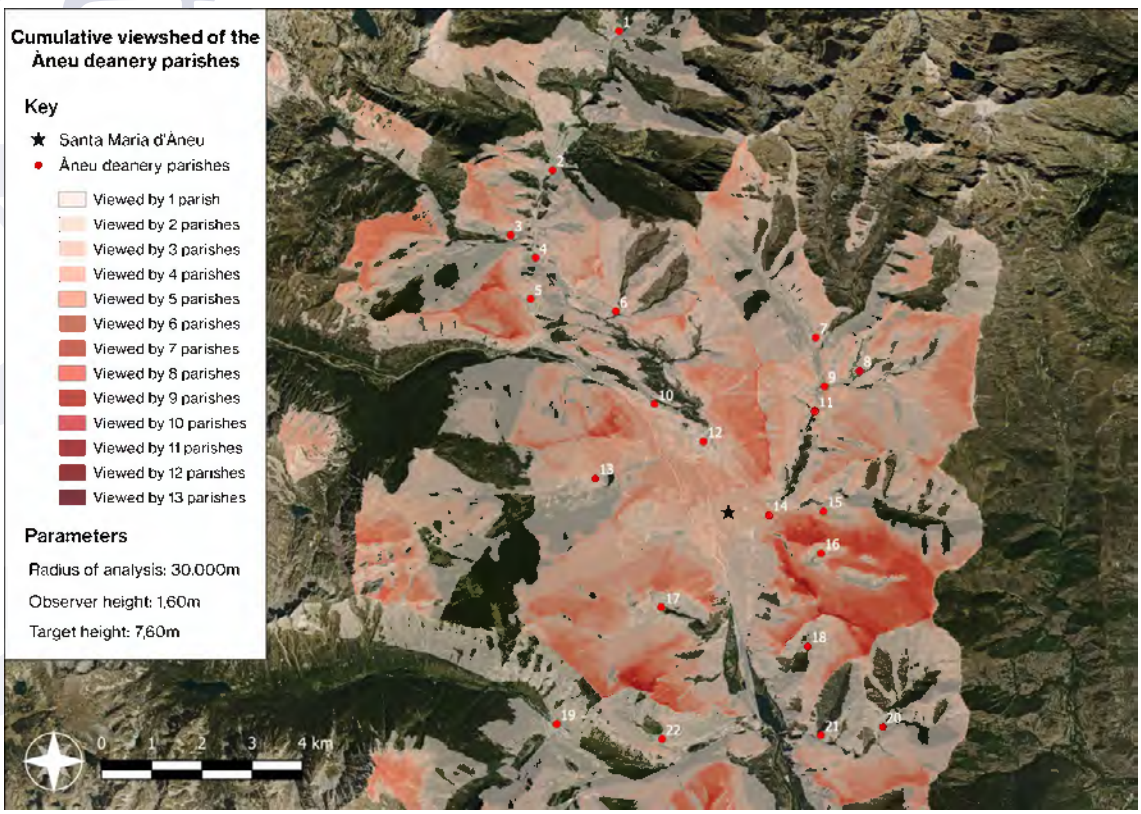

Figure 8: Cumulative Viewshed of the Àneu Deanery

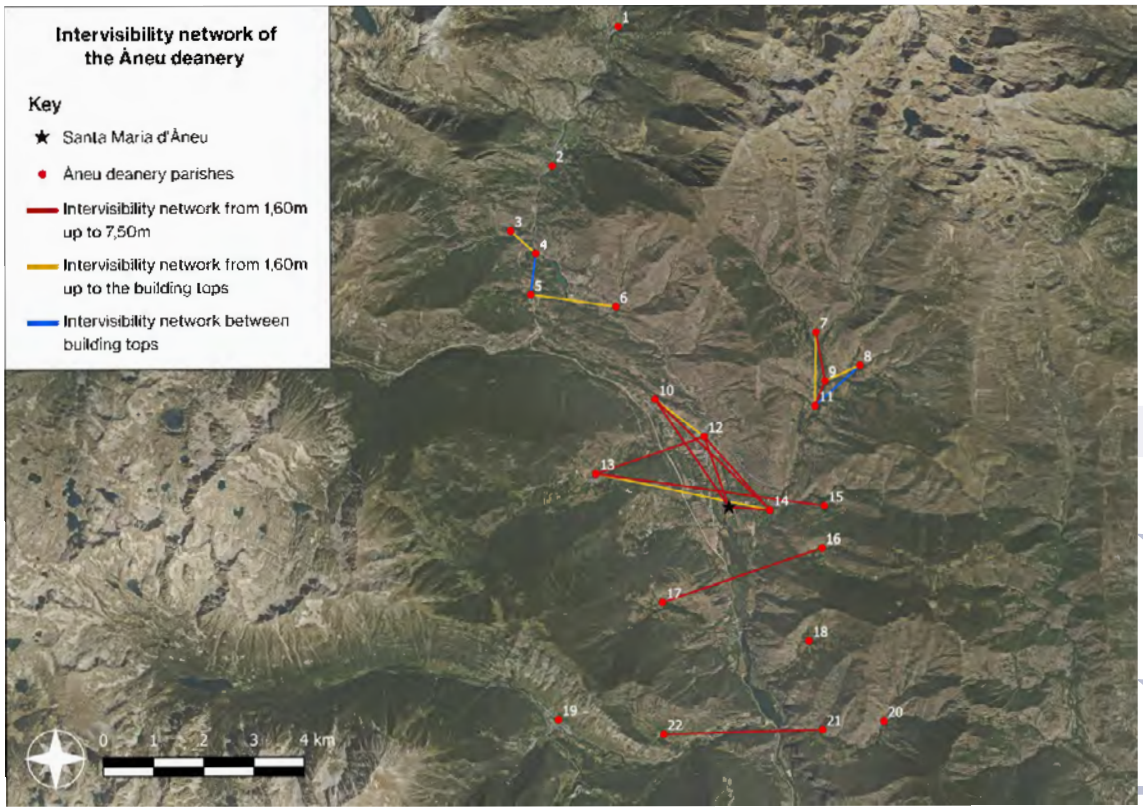

Figure 9: Intervisibility Network between the Àneu Deanery Parish Churches

indicate the number of parishes that can see each raster pixel. This analysis reveals that Santa Maria d'Àneu, visible from three different observation points, is situated in an area relatively well monitored by the surrounding parish churches. Apart from the slopes and peaks of the highest mountains, which are visible from most of the valley, only a narrow strip of land between Santa Maria and Esterri—visible from one additional observation point—has a higher visibility index.

Finally, the various intervisibility network simulations demonstrate no continuous visual communication between all the parishes of the Àneu deanery. The region's abrupt geography creates isolated points and at least three visually independent subsystems (fig. 9). Of these, the one in the central valley plain—including Santa Maria d'Àneu—is the most intricate, with up to six fully interconnected churches. Notably, Santa Maria d'Àneu, with its three connections, was one of the most visually controlled churches in the deanery, at least before many surrounding parishes were outfitted with tall bell towers in the modern era. These new towers created additional connections, especially when analyzing the visibility from their top. This suggests that while the network was not fully interconnected during the Middle Ages, efforts to maximize intervisibility across the network may have been sought as much as possible.

Discussion

In this section, we will discuss three main topics that arose from our research: 1) The limitations of the SpreAD-GIS script when exploring the propagation of bell sounds in the landscape, 2) The audibility of bell sounds concerning background noise, and 3) The aural network with Santa Maria d'Àneu as the central church of the Àneu valley.

Table 6. Distances of the Closest Parish Churches to the Coverage Area of Àneu's Bells

Parish church number the maps and name	Minimum distance from Àneu's bell coverage (meters)
13: Sant Just i Sant Pastor de Son	300–350
15: Sant Joan de Burgo	200–250
16: Sant Miquel de Llavorre	250–300
17: Sant Pere de Jou	350–400
18: Sant Bartomeu de Dorve	350–400

The Limitations of the SPreAD-GIS Script

The simulation of sound propagation in the landscape, especially for sounds of large percussion instruments such as bells, is an underdeveloped area of research. The SpreAD-GIS script used in this archaeoacoustic study is not designed explicitly for bell sound propagation. Although our simulation was validated by on-site acoustic measurements and followed by weather scenario simulations, several script limitations should be highlighted.

The SpreAD-GIS is a static model that represents the spatial pattern of bell sound propagation around the church for a snapshot in time. This model does not account for the cumulative effect of repetitive bell ringing. The script omits reflections and foliage effects, as accurately representing these factors would require higher-resolution data sets that are not widely available. Consequently, the simulation is somewhat simplified and does not provide precise predictions, particularly at the map's borders.

The sound map provides a frozen image of sound propagation in one moment. It fails to transmit the dynamics of soundscapes. As Mlekuž (2004) pointed out, the soundscape is relative to the listener, in a permanent process of construction and stratification by the listener as (s)he's moving across the landscape.

The Audibility of the Bell Ringing

While the SpreAD-GIS script allows for introducing ambient sound conditions to predict where the bell sound would exceed background noise, we did not utilize this feature. Our hesitation stemmed from the absence of studies on the audibility of bells in landscapes with varying background noise levels. However, the SPreAD-GIS script developers indicate that some sounds can be heard below background noise levels (Keyel et al. 2017). In addition, previous studies have shown that repetitive sounds can be heard even more than 10 dB below background noise levels (Almagro-Pastor et al. 2021), though none have included church bells.

Sound sensitivity and perception depend on various factors, including frequency, sound type, auditory expectation, and age (Plack 2018). Our subsequent research will question whether the bell sounds lower than the background noise can be heard and, if so, by how much. This psychoacoustic question warrants investigation with a statistically significant number of respondents.

The Aural Network and Santa Maria d'Àneu as a Central Church of the Àneu Valley

According to the simulations and sound maps (fig. 6), Santa Maria d'Àneu appears centrally positioned, especially for churches 10-18. In scenarios without wind, the bell sound propagation encompasses two or three parish churches (10, 12, and 14). As presented in tab. 6, several churches are positioned close to the bell sound propagation area of Santa Maria d'Àneu (13, 15-18) at a distance of 200 to 400 meters. Even if the Santa Maria d'Àneu bell ringing doesn't reach these parish churches directly, it could be heard in the nearby area. This would be sufficient to alert or notify the neighboring parish, which would then ring their bells and thus broadcast the signal further into the deanery.

This soundscape analysis was based on the acoustic measurements of a modern bell in Santa Maria d'Àneu. We do not know about the bell used in the medieval period. However, we expect that the medieval bell's acoustic characteristics differed somewhat from those of the modern bell.

As shown in the testing of weather scenarios, wind strongly affects sound propagation in the landscape, drastically shrinking the area covered by bell-ringing sounds. However, strong winds are rare in this area, and we should keep in mind that the weather scenarios tested in this research (A.2., B, C) are extremes that occur once every several years or even decades.

The results of the visibility analysis are perfectly in line with those of the virtual sound propagation simulation. Once again, Santa Maria d'Àneu seems to be in a central position, with a good field of vision and a high visibility index. Likewise, the three churches that can virtually hear its bells (10, 12, and 14) can also see it. The developed models allow us to go a step further and suggest that all these churches were part of a much wider network of intervisibility, something that we can only guess at for the aural dimension.

To fully understand the aural network of the Àneu deanery during the Late Middle Ages, it would be crucial to simulate the sound propagation of bells from all 22 parish churches and verify these simulations with onsite testing. Additionally, this research should be expanded to include the numerous suffragan churches that existed alongside the parish churches in each district, as they undoubtedly influenced the density and stability of the Àneu deanery's aural network. Expanding the study this way could reveal auditory or visual connections between some of the isolated points on our maps and integrate the three subsystems we identified as independent within the intervisibility network.

Conclusion

This archaeoacoustic study determined that the bell sounds of Santa Maria d'Àneu are audible in at least two of the parish churches and several more parish districts that comprised the medieval Àneu deanery. Due to its central location in the valley, Santa Maria possessed the auditory capacity to initiate an aural network among all the surrounding parishes, allowing auditory messages to be promptly broadcasted throughout the Àneu deanery. This supports the hypothesis that Santa Maria d'Àneu was an ecclesiastical center of the valley during medieval times, although it is insufficient to prove it definitively.

The results of this study encourage further investigation into the medieval aural network of the Àneu deanery. A deeper understanding of what happens at the borders of the sound propagation maps is fundamental. High-resolution DEM and NLCD data are necessary to achieve more precise sound propagation models. Additionally, measuring the acoustic properties of medieval bells still in use in the Catalan region and exploring the audibility of bell sounds concerning background noise would significantly advance our understanding of the medieval auditory network of the Àneu deanery.

Data Availability

The data supporting this study's findings are available at CORA—Repositori de Dades de Recerca: https://doi.org/10.34810/data1756.

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Author contributions

Zorana Đorđević: Conceptualization, Investigation, Methodology, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. Xavier Costa-Badia: Conceptualization, Investigation, Visibility analysis, Writing – original draft. Natalia González Vázquez: GIS and Sound Mapping Tool simulation, Visualization. Lidia Alvarez Morales: Methodology, Formal analysis, Validation, Data curation, Writing – review & editing.

Summary

In medieval Europe, church bells were more than just time markers; they served as powerful communicative tools in both secular and sacred life. Bells announced significant events, served as alarms in times of danger, and conveyed messages of joy, sorrow, and community identity. The sound of bells permeated the landscape, shaping daily life and reinforcing social bonds. Often called the "voice of God," bells held symbolic and political power, uniting people under a common auditory experience. The sound of a bell can be considered an earcon— a symbolic sonic event that gains meaning through repeated exposure in specific contexts, as defined by Blesser and Salter. As such, bells were crucial in shaping medieval people's emotional responses to their environment, fostering a sense of place and belonging.

The audibility of bells often coincided with parish boundaries, contributing to a shared sense of community among those who could hear them. As unique soundmarks, bells helped define the acoustic communities of medieval parishes. Understanding the range of bell sounds and the inclusivity of these soundscapes is essential for a fuller comprehension of the medieval auditory environment and the communication networks between neighboring parishes. This fits Mills' definition of auditory archaeology, which explores the relationship between people, sound, and their environment. Recent studies have mapped sound in archaeological contexts using Geographic Information Systems (GIS), such as Mlekuž's 2004 simulation of medieval bell sounds in Slovenia. These advancements in sound mapping technologies, particularly SPreAD-GIS, have allowed researchers to understand sound propagation in historical landscapes better.

This paper explores the case of Santa Maria d'Àneu, a church located in the Àneu valley in the Catalan Pyrenees, focusing on its potential auditory relationship with nearby parishes in the medieval Àneu deanery. Although historians have debated Santa Maria d'Àneu's significance within this district, its role as a potential ecclesiastical center remains unclear. Positioned in the middle of a valley without an adjacent settlement, the church's strategic location could have enabled its bells to reach the surrounding parishes. This study seeks to test that hypothesis through an acoustic analysis of bell sound propagation and visibility studies.

The methodology involved a three-part approach: onsite acoustic measurements, virtual sound propagation simulations, and visibility analysis. Sound levels were measured in real-time using sound level meters and audio recorders to capture both the bell sounds and background noise. The virtual simulations were conducted using ESRI ArcGIS Desktop and the SPreAD-GIS script to model the propagation of the bells across the deanery, accounting for variables like distance, topography, and atmospheric absorption. The visibility analysis used QGIS to examine the viewshed of Santa Maria d'Àneu and its visual relationship with other parish churches in the deanery.

Results indicate that Santa Maria d'Àneu's bell sounds were audible in at least two nearby parish churches and several more parish districts within the deanery. Due to its central location in the valley, Santa Maria d'Àneu had the potential to initiate an auditory network that allowed messages to be quickly broadcast throughout the region. These findings support the hypothesis that Santa Maria d'Àneu may have served as an ecclesiastical center during the medieval period, although the evidence is inconclusive.

The study's results highlight the need for further research into the medieval aural network of the Àneu deanery. Higher-resolution DEM and NLCD data are required to improve sound propagation models' accuracy. Additionally, measuring the acoustic properties of medieval bells still in use in the Catalan region and investigating the interaction between bell sounds and background noise would significantly enhance our understanding of medieval auditory networks and their role in shaping community life in the Àneu valley.

Povzetek

V srednjeveški Evropi so bili cerkveni zvonovi več kot le označevalci časa; služili so kot močna komunikacijska orodja v posvetnem in cerkvenem življenju. Zvonovi so naznanjali pomembne dogodke, služili kot alarm v času nevarnosti ter prenašali sporočila o veselju, žalosti in identiteti skupnosti. Njihov zvok je prežemal pokrajino, oblikoval vsakdanje življenje in krepil družbene vezi. Zvonovi, pogosto imenovani »božji glas«, so imeli simbolično in politično moč ter so združevali ljudi pod skupno zvočno izkušnjo. Zvok zvona lahko štejemo za zvočni dogodek – simbolni zvočni dogodek, ki pridobi pomen s ponavljajočo se izpostavljenostjo v določenih kontekstih, kot sta ga opredelila Barry Blesser in Linda-Ruth Salter. Kot taki so bili zvonovi ključni pri oblikovanju čustvenih odzivov srednjeveških ljudi na njihovo okolje, saj so spodbujali občutek kraja in pripadnosti.

Slišnost zvonov je pogosto sovpadala z mejami župnij, kar je prispevalo k skupnemu občutku skupnosti med tistimi, ki so jih lahko slišali. Kot edinstveni zvočni znaki so zvonovi pomagali opredeliti akustične skupnosti srednjeveških župnij. Razumevanje obsega zvokov zvonov in vključenosti teh zvočnih pokrajin je bistveno za boljše razumevanje srednjeveškega zvočnega okolja ter komunikacijskih omrežij med sosednjimi župnijami. To ustreza Millsovi opredelitvi slušne arheologije, ki raziskuje odnos med ljudmi, zvokom in njihovim okoljem. Nedavne raziskave so kartirale zvok v arheoloških kontekstih z uporabo geografskih informacijskih sistemov (GIS), npr. Mlekuževa simulacija srednjeveških zvonov v Sloveniji iz leta 2004. Ti napredki v tehnologijah kartiranja zvoka, zlasti SPreAD-GIS, so raziskovalcem omogočili boljše razumevanje širjenja zvoka v zgodovinskih pokrajinah.

V tem prispevku obravnavamo primer cerkve Santa Maria d'Àneu v dolini Àneu v katalonskih Pirenejih, pri čemer se osredotočamo na njeno morebitno zvočno povezavo z bližnjimi župnijami v srednjeveškem dekanatu Àneu. Čeprav so zgodovinarji razpravljali o pomenu Santa Marie d'Àneu v tem okrožju, njena vloga kot potencialnega cerkvenega središča ostaja nejasna. Ker je cerkev stala sredi doline brez sosednjega naselja, bi lahko njena strateška lega omogočila, da bi njeni zvonovi dosegli okoliške župnije. Namen pričujoče raziskave je preveriti to hipotezo z akustično analizo širjenja zvoka zvonov in raziskavami vidnosti.

Metodologija je vključevala tridelni pristop: akustične meritve na kraju samem, virtualne simulacije širjenja zvoka in analizo vidljivosti. Raven zvoka je bila izmerjena v realnem času z merilniki ravni zvoka in zvočnimi snemalniki, ki so zajemali zvoke zvona in hrup ozadja. Virtualne simulacije so bile izvedene z uporabo programa ESRI ArcGIS Desktop in s skripto SPreAD-GIS za modeliranje širjenja zvonov po dekaniji, pri čemer so bile upoštevane spremenljivke, kot so razdalja, topografija in absorpcija ozračja. Pri analizi vidljivosti sta bila s programom QGIS preučena pogled na cerkev Santa Maria d'Àneu in njen vizualni odnos z drugimi župnijskimi cerkvami v dekanatu.

Rezultati kažejo, da so bili zvoki zvona v Santa Marii d'Àneu slišni v vsaj dveh bližnjih župnijskih cerkvah in še nekaj župnijskih okrožjih v dekaniji. Zaradi svoje osrednje lege v dolini je imela Santa Maria d'Àneu možnost sprožiti zvočno omrežje, ki je omogočalo hitro razširjanje sporočil po vsej regiji. Te ugotovitve podpirajo hipotezo, da je Santa Maria d'Àneu v srednjem veku morda služila kot cerkveno središče, čeprav dokazi niso prepričljivi.

Rezultati raziskave poudarjajo potrebo po nadaljnjih raziskavah srednjeveškega zvočnega omrežja dekanije Àneu. Za izboljšanje natančnosti modelov širjenja zvoka so potrebni podatki DEM in NLCD višje ločljivosti. Poleg tega bi merjenje akustičnih lastnosti srednjeveških zvonov, ki se še vedno uporabljajo v katalonski regiji, in raziskovanje interakcije med zvoki zvonov ter hrupom iz ozadja bistveno izboljšala naše razumevanje srednjeveških zvočnih omrežij in njihove vloge pri oblikovanju življenja skupnosti v dolini Àneu.

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