Archaeoacoustic Research on Caves dedicated to Pan and the Nymphs in Attica, Greece

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Abstract

Recent archaeoacoustic techniques, applied in ancient sacred grottos and other constructions, have paved the way for new research insights in ancient cult and ritual practice, offering the potential to enrich interpretations of how ancient buildings or natural spaces were perceived as loci of divine presence and worship. Here, the acoustic research was focused on selected examples of caves with known historic significance in ancient Greek societies. The caves were selected from a specific geographical region, Attica in Greece, where the combined worship of the hoofed-god Pan with his female companions, the Nymphs, was first organized and performed inside caves during the 5^{th} c. BC. The purpose of this inter-disciplinary research is to enhance our existing knowledge regarding the utilization of sound and acoustics during ritual ceremonies in caves, in an attempt to understand whether sound was a key factor in the selection of caves as appropriate sacred sites. Although access to such caves introduces significant difficulties, acoustic measurements were obtained in two caves (Parnitha and Vari) at different source receiver positions at locations where historic evidence indicates that such rituals were taken place. The single channel measurements were used for extraction of the acoustic parameters of the caves. For the same positions, binaural responses were recorded using a dummy head. These will be later utilized via virtual listening scenarios for presentations and controlled evaluation of the cave acoustics by listeners in the laboratory using appropriate pre-recorded audio samples [1] which according to the archaeological and historical data were reproduced during ancient rituals, made people believe that they were the abodes of these sacred spirits. The tests and analysis provide novel findings with regards to the suitability of cave acoustics for such ritual ceremonies.

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1. Introduction

Visual senses overwhelm aural senses in Western culture and have dominated modern scientific thought [2]. However, in the past few decades there has been an increasing interest towards the acoustical and sensual properties of the material past. Especially within sensual archaeology, current research considers the aural perspectives of ancient sacred grottos and other rural sacred places, offering the potential to enrich interpretations of how ancient buildings or natural spaces were used, and proclaiming the importance of sound as one of the determinants in their identification as places of divine presence and worship [3, 4, 5, 6].

Caves are understood as complicated enclosed spaces composed of numerous surfaces, objects, and geometries, creating an acoustic space which behaves differently from open-air spaces [7]. Likewise, the underground sanctuaries dedicated to the Nymphs and Pan in ancient Greece should not only be perceived as *landscapes* with certain visual characteristics, but also as *soundscapes* with important auditory features [8]. As a result, an acoustic survey of these caves and an appropriate analysis of their aural characteristics, combined with archaeological and musical methods is necessary, in order to understand whether sound was a determining factor in the selection of caves as appropriate sacred sites to host the combined cult of Pan and the Nymphs in antiquity.

2. Historical background

The principal area of Pan's worship was Arcadia and from there his name and cult spread over other parts of Greece [9] [1]. The Athenians were the first who established Pan's cult inside a cave after Pan's worship appeared in Attica in the first quarter of the 5^{th} c. BC (Herodotus, *Histories* , VI, 105106). The presence of water sources, evidence of previous use, closed entrances, high altitude and liminality, made caves particularly attractive as homes and sanctuaries of the Nymphs and Pan [10]. A cave had also similarities to Pan's mountainous homeland and suited his bucolic characteristics [11].
Note that Pan is a deity connected with natural sounds, echoes and loud noise; sound is an important component of his cult. For the sake of Pan's love of noise the ritual protocol involved the production of various sounds (Lucian, Bis *Accusatus*, 9-10) and the resulting resonating and echoing effects of caves would have been regarded as signs of his divine presence. During a Pan ritual, the participants, through their noise-making, dancing, music, and feasting, were creating a system of ritual action, in which they themselves became agents of the god's epiphany.
Within the geographical region of Attica, fourteen underground cult sites have been identified so far dedicated to Pan and the Nymphs (Acropolis, Marathon, Dafni, Mt Hymettus, Mt Penteli etc). However, here only two caves were selected for archaeoacoustic research, because in order to investigate their sonic qualities they must be archaeologically well documented and not severely damaged. These are the "Cave of the Nympholept" at Vari and Cave "Lychnospilia" on Mt. Parnitha.

3. Location and properties of the caves

3.1. The "Lychnospilia" cave

Cave "Lychnospilia" is located at the southwest foothills of Mt. Parnitha, at a height of $35m$. from the left bank of the Goura stream at an altitude of $773m$ above sea level. The cave is accessed through a path that has been opened since the antiquity leading from the medieval settlement "Roumani" to the north side of the cave's terrace. The cave was partly excavated by Andreas Skias in 1900-1901 revealing extensive evidence of the worship of Pan and the Nymphs especially in the 5^{th} - 4^{th} centuries BC [12].
The triangular mouth of the cave located at the southern part of the plateau is $1.05m$ wide. The opening

Figure 1. Votive relief depicting the dance of Pan and the Nymphs from Mt. Parnitha, Attica, no. 1448, National Archaeological Museum (©Greek Ministry of Culture and Sports/ National Archaeological Museum).

is surrounded by rough carvings and niches for the placement of votive offerings, as well as Late Roman inscriptions. The grotto is $62m$ long and extends from east to west, while its width ranges between 3.00-14.40m. Immediately next to the entrance lies a large plateau (9.00x8.00m), while deeper in the interior the ground elevates near the southern wall. In Fig.1 it is shown a votive relief found in the cave Lychnospilia.

3.2. The "Nympholept" cave

The cave of the "Nympholept" at Vari is located at the southern foot of Mt. Hymettus at an altitude of $290m$ above sea level. It is preserved in a very good condition and access to it must have been relatively difficult in antiquity. First traces of habitation date back to the 6^{th} century BC, while in the third quarter of the 5^{th} century BC Archedimos the Nympholept, seized by divine inspiration established there the cult of Pan and the Nymphs.
The cave's oval mouth is vertical (4.00x2.00m), while a roughly carved staircase leads to the interior (21.00x23.75m, height 2.50m, depth 15.00m). A massive calcite formation separates the cave into two chambers: the southern is large and fairly bright (17.5x11.5m). The northern chamber is narrower, much darker, without any special configurations and decorated with rich stalactite formations (18.5x8.00m). The shape of the interior facilitates the anticlockwise movement of the visitor, first through the steep, narrow and dark space to a much larger and brighter chamber. The latter is identified with the main sanctuary as most configurations are located there, such as the statue of a seated figure, altars, desks and niches for the placement of votive reliefs or other offerings, as well as scattered inscriptions from both ancient and modern visitors. During the excava-

[1] Pan is the god of the wild, shepherds and flocks, nature of mountain wilds and rustic music, and also companion of the Nymphs. The god was depicted as a goat-legged man with horns and goat-tail, and with thick beard, snub nose and pointed ears.

tions at the southern section of the second chamber a retaining wall was unearthed which supported earth and rocky material that created a flat plateau suitable for rituals [13].

4. Acoustical measurements

The measurements took place on 23 and 24 November 2017. The caves, are both located far from any access road, being isolated and difficult to reach. Lychnospilia cave is reached after half an hour walk, then having to descend a $10m$ slope (Fig. 2a). The Nympholept cave (Fig.2b) can be only reached by off-road vehicles and after special permission to use roads closed for the public by barriers. At such inaccessible locations, the heavy load of the equipment for the measurements was carried by the team of University of Patras and workers of the Ephorate of Antiquities.

The measurement stimulus signal was a logarithmic sine sweep [14] of $T = 10sec$ duration at $f_s = 44100Hz$ and an $SPL = 88.5dB/1m$ with a bandwidth covering $40Hz$ to $20kHz$. Both single channel and binaural responses were measured. The ears of the dummy head were at a height of $1.2m$, which represents the mean height of Greeks of the period and the omni mic was positioned $15cm$ above the dummy head at 45° angle vertically.
The source and receiver measurement positions for both caves are shown in Figures 3a and 3b. The source positions were chosen according to archeologist's assumptions for the potential positions that an ancient musician would be located to perform and the receivers were at the possible positions where participants of the rite were supposed to stand or dance. Especially in the cave of Nympholept, there is an obvious path that the worshippers followed entering the cave to get the catharsis and finally reach the main hall. There were 9 measurement positions inside the cave of Lychnospilia and 12 measurement positions in the cave of Nympholept. Double measurements were made in positions where the source and the receiver were considered to be seated instead of standing, by placing either the source or the receivers closer to the ground. In the cave of Nympholept an additional set of 14 binaural measurements were taken following the path to catharsis (Fig. 3b black dashed line followed counterclockwise).
Given that there was no access to electric mains power in the caves, a portable gas power generator was used positioned about 50m away from the entrance of the caves. The background noise level measured is shown in Table I and is very low to allow measurements with good SNR. The temperature and humidity levels were very stable: in Lychnospilia it was $8°C$ with 55% relative humidity and in the cave of Nympholept it was $17°C$ with 80% relative humidity.

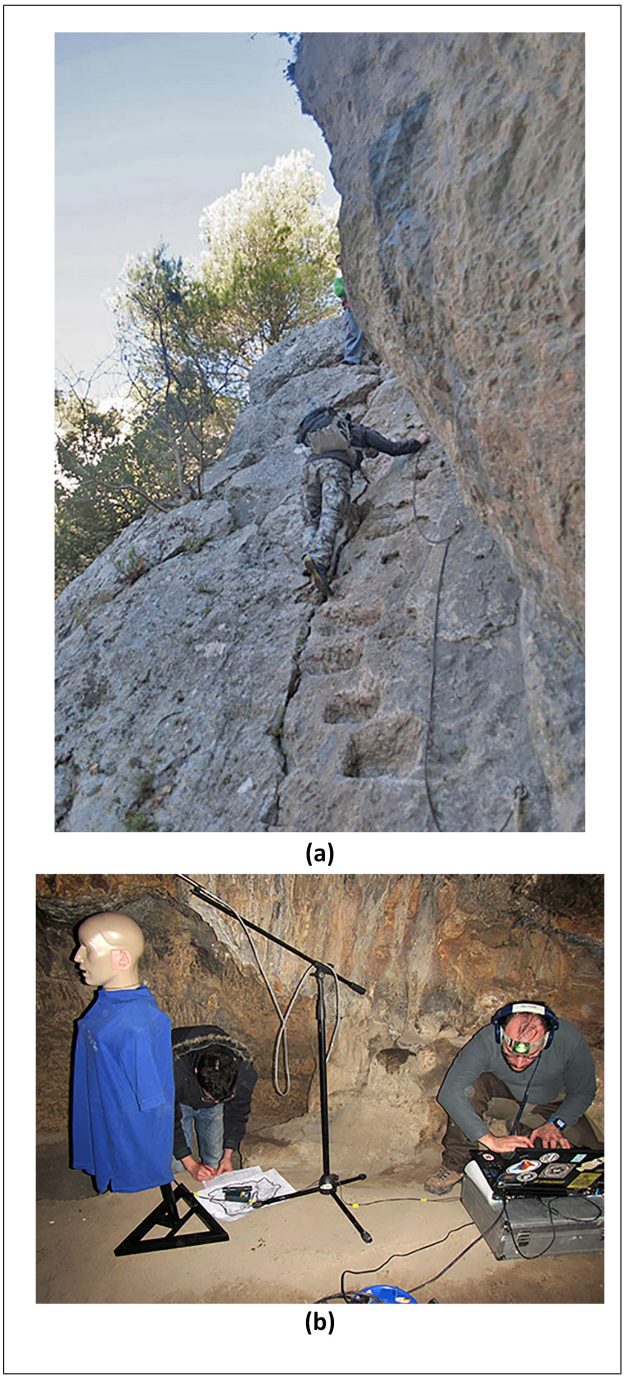

Figure 2. The "last step" to reach the cave Lychnospilia at Mt. Parnitha(a), the Audiogroup during the measurements in cave of Nympholept at Vari (b).

Table I. Background noise levels in both caves.

Cave	Background Noise dB(A)
Lychnospilia	26.6
Nympholept	22.8

5. Results and discussion

From the omnidirectional microphone impulse response measurements at the above positions, the

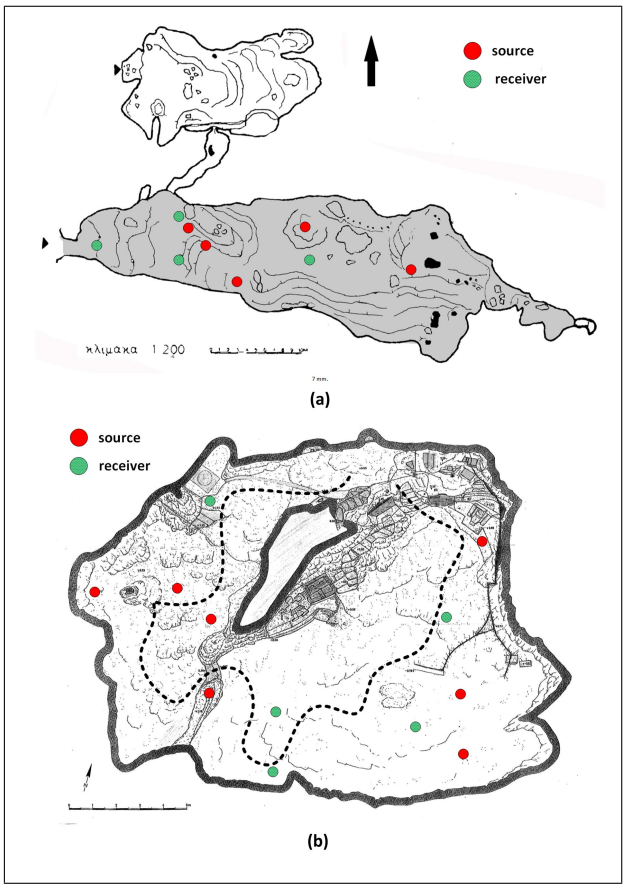

Figure 3. Top view and source and receiver positions for the cave of: (a) Lychnospilia at Mt. Parnitha and (b) Nympholept at Vari.

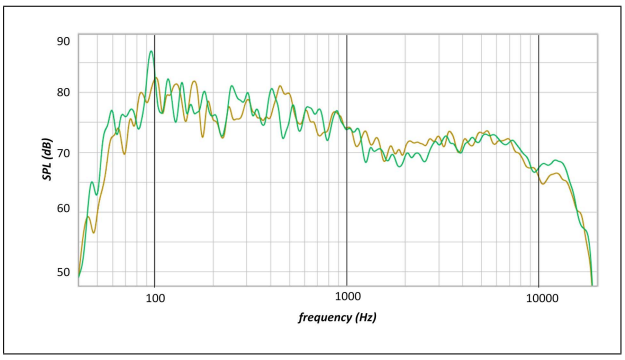

Figure 4. Frequency responses of the "Lychnospilia" cave (Brown line) and "Nympholept" (Green line).

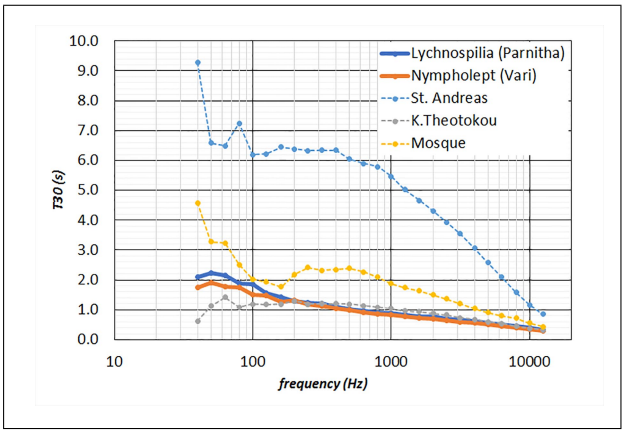

Figure 5. Reverberation time of the two caves compared to other spaces of worship.

mean frequency response and the acoustical parameters of T30, C50, C80, STI and IACC were calculated. Except of the frequency response (Fig.4 which is 1/12 octave smoothed), the parameters are calculated in 1/3 octave bands, according to ISO382 [15] using the Audacity 2.0.5 [16] with Aurora plug in software [17]. The IACC parameter was calculated from the corresponding binaural impulse response measurements. The STI was calculated using WinMLS2004 [18] software for reference of a standard 80dB Speech over an NR25 background noise curve [19].
The results are here compared to other spaces of worship: a very large orthodox church (St. Andreas, in Patras), a small orthodox church (Kemiseos Theotokou church in Komotini) and a mosque (Yeni Tzami of Komotini) measured previously [20]. The church and the mosque are chosen because of their similar volume to the caves, as is shown in Table II, along with the period of construction, the reference RT_{ref} (derived from simple acoustic theory), and the measured RT_{meas}.

The frequency response of both the caves (Fig.4) are very similar and have some minor resonances at the low frequencies, a "flat" response up to $1kHz$, a slight attenuation around $2kHz$ and a smooth roll-off at higher frequencies. Overall, the responses are balanced and dominated by the diffuse nature of the acoustic field at mid-high frequencies.

The reverberation time of the caves is almost identical and ideal for speech (Fig.5). The slight rise at the low frequencies gives warmth to the sound and the value of 0.9s to 1.3s at the mid frequencies gives clarity to speech. In comparision, the more recent spaces of the orthodox church and the mosque have reverberation more prominent at mid frequencies.

The clarity index for speech C50 (Fig.6) and music C80 (Fig.7) for the caves has acceptable values (above 0 dB) from almost 200Hz, in contrast to the churches and the mosque which reach acceptable values at the mid frequencies (above 400Hz) and clearly, the St Andreas large church having the least appropriate values. The STI (Fig.8) values of the caves indicate good to excellent speech intelligibility. On the other hand, the two churches and the mosque have an acceptable STI and the St. Andreas church having STI below the acceptable limit of 0.5.

With respect to the spatial qualities of the measured spaces, the IACC (interaural cross-correlation coefficient, Fig.9) was derived from the corresponding binaural impulse response (BRIR) measurements. The results for the two caves, along with all the other spaces of worship exhibit the expected nearly

Table II. Details of the measured caves, along with other spaces of worship.

Place	Period	Volume (m^3)	$RT_{ref}(s)$	$RT_{meas}(s)$
Lychnospilia	5^{th} BC	2250	2.0-3.0	1.0
Nympholept	5^{th} BC	2100	2.0-3.0	1.1
St. Andreas	1970	143520	6.0-10.0	5.5
K. Theotokou	1580	1520	1.8-2.6	0.9
Mosque	1580	950	1.7-2.5	1.8

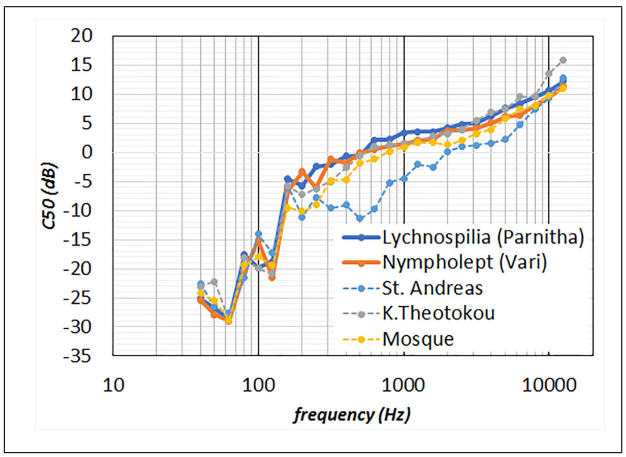

Figure 6. Clarity C50 (for speech) of the two caves compared to other spaces of worship.

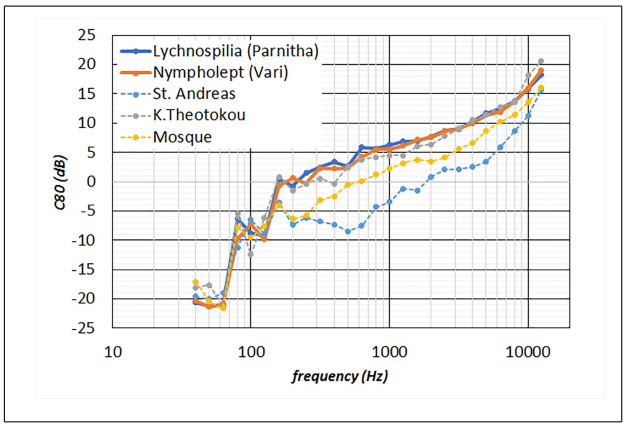

Figure 7. Clarity C80 (for music) of the two caves compared to other spaces of worship.

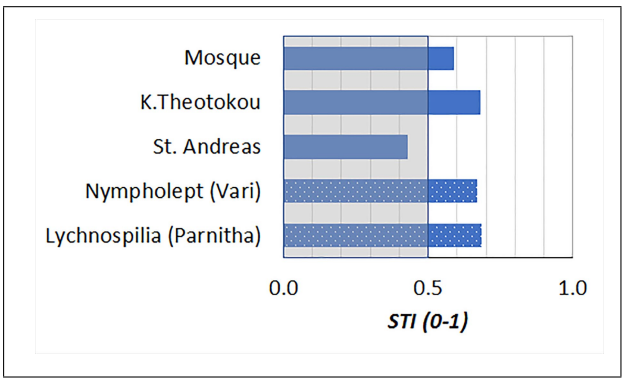

Figure 8. Speech Transmission Index (STI)of the two caves compared to other spaces of worship.

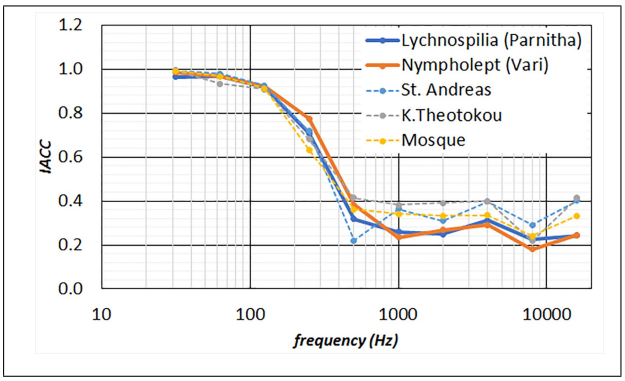

Figure 9. Interaural Cross Correlation (IACC) of the two caves compared to other spaces of worship.

perfect diffuse and spaciousness character for frequencies above approx. 400Hz. Hence, the caves provide an increased sense of spaciousness to the listeners.

6. Conclusions

Overcoming the inaccessibility of the two caves with well established historical links to ancient rituals of Pan and the Nymphs in ancient Greece, a set of acoustical measurements has been recently obtained and analysed.
Apart from the quietness and isolation offered in such spaces, the results indicate that these caves had low reverberation time for their volume, exceptional clarity for speech and music and generate increased feeling of spaciousness to the listeners, achieving also very good speech intelligibility within the range of positions where the ceremonies were performed. In most respects, such acoustic performance is better to more recent spaces of worship of comparable volume.
As future work, the measurements obtained in the current work, will become available in public databases [21] and will be compared to other ancient places of worship [22]. Virtual auralizations of ancient musical instruments and speech [1] along with perceptual tests will compare the listener preference for such ancient and modern spaces of worship.

Acknowledgement

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