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# ACOUSTIC CHARACTERIZATION OF THE "CUEVA DEL PÁJARO AZUL": ARCHITECTURAL REFERENCE OF THE SOUND HERITAGE OF GADIR

**Payo, Damián**[1,2*] **Rodríguez-Montaño, Víctor M**[3]
**Fernández-Zacarías, Francisco**[3] **Hernández-Molina, Ricardo**[3]
[1] Facultad de Arquitectura y Urbanismo, Universidad Católica de Salta, Salta, Argentina
[2] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina
[3] Laboratorio de Ingeniería Acústica, Instituto Universitario de Investigación en Lingüística Aplicada, Universidad de Cádiz, Cádiz, Spain

## ABSTRACT

This study analyzes the acoustic characteristics of the "Cueva del Pájaro Azul", a historical site located under the present city of Cádiz, at a depth of 4.5m, which was part of the ancient Phoenician port of Gadir and preserves vestiges of its past, such as a cistern. Converted into a flamenco club during the 1960s, this environment combines a rich archaeological heritage with an outstanding cultural legacy. The cave is characterized by its remarkable acoustic heterogeneity, with significant variations in reverberation times of up to 2 seconds due to the acoustic behavior of some sectors that act as coupled resonators.

In situ recordings were made using a binaural head, omnidirectional microphones and a dodecahedral omnidirectional source, defining the distribution of specific source-microphone pairs considering the historical archive and the current use of the space.

The results obtained are presented and a tool that allows future auralizations contemplating traditional musical practices in Cádiz is presented.

**Keywords:** *Architectural Acoustics, Flamenco, Acoustic Heritage, Coupled Resonators.*

*__Corresponding author__: sdpayo@ucasal.edu.ar


## 1. INTRODUCTION

Cádiz, the oldest city in the West, is an enclave where past and present intertwine in a mosaic of history, culture and tradition. Since its foundation by the Phoenicians in the 9th century BC under the name of Gadir, the city became a strategic enclave for navigation and trade in the Mediterranean [1-3]. Its port, protected by the natural relief of the bay and the islands of Cadiz, allowed the development of the prosperous commercial activity that connected it with civilizations such as Tartessos, Carthage and, later, Rome [4].

One of the vestiges of this maritime past is the rock-hewn port cliff dating from the third century BC, discovered in the so-called "Cueva del Pájaro Azul". According to archaeological studies, this structure would have served as a drydock for the construction and repair of Phoenician-Punic ships, playing a crucial role during the Second Punic War [5]. With the arrival of the Romans, the port was reused and, over time, the sediments of the Guadalete River transformed the landscape, integrating the ancient infrastructures into the urban expansion of Gades [6,7].

This cliff was located on the shore of the channel that separated the main island of Cádiz from other islets of the bay, and its design reveals its port functionality: it has a staircase carved into the rock to descend into the water and a ramp at one end that would have served to beach boats. Around this space several structures have been identified that, according to research, could have been warehouses of the port itself or naval shipyards [8]. Next to this enclave there is also a large cistern, an essential infrastructure for water supply.

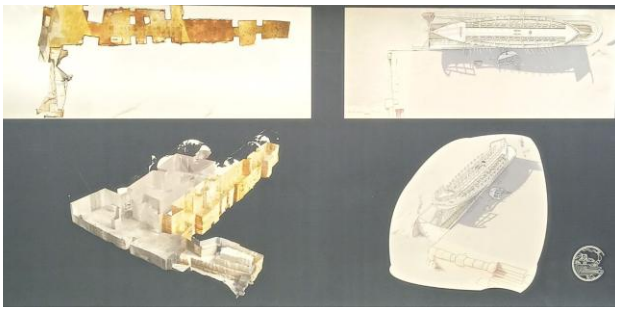

**Figure 1**. Plan of the deposit. Source [5].

Over time, this space has undergone several transformations. At the beginning of the 19th century, during the Liberal Triennium, the smuggler Francisco Fernández, known as “El Pájaro Azul”, reportedly used these subway passages to traffic illegal goods [5,9]. Decades later, in the 20th century, this space took on a new identity when, in 1958, the businessman Manuel Fedriani decided to convert it into a flamenco club [9].

**Figure 2**. Performance by Santiago Donday and Eloy Blanco at the “Cueva del Pájaro Azul”. Source: [9].

Since then, the “Cueva del Pájaro Azul” became one of the epicenters of flamenco in Cádiz, hosting legendary figures such as Camarón de la Isla, Lola Flores and Paco de Lucía [5,9]. For more than two decades, this space was a temple of flamenco singing until its closure in the 1980s. Its reopening as a *flamenco tablao* keeps alive the essence of a place where history and art converge in the same space.
When music is performed in a venue, there is a close relationship between its architecture, its acoustics and the style of music being performed, so that listening to the work depends on both musical factors and the particular acoustics of the hall [10]. This relationship has been studied extensively in relation to academic music and theatre [11,12], but there is only a small body of work that examines specific popular music practices and their relationship to unconventional architectural spaces [13,14].
The acoustic characteristics, derived from the particular architecture of the “Cueva del Pájaro Azul” and its relationship with flamenco singing, allow us to evaluate the space, based on the relationship between the intangible heritage of flamenco and this space as an associated tangible heritage [15].
In the absence of guidelines for the acoustic assessment of this type of space, and given that hearing is highly variable between individuals and cultures [16-18], this paper presents a methodological design of acoustic characterization where, on the one hand, the different arrangements of the singers and the audience both in the 1960s and today are considered, and on the other hand, decisions made by the researchers in order to reflect the heterogeneity of the space.
The study is completed with an evaluation of monaural temporal cues, such as Reverberation Time ($T_{30}$) and Clarity ($C_{80}$), and binaural indexes such as Interaural Cross Correlation (IACC). Finally, a design is presented to perform binaural auralizations by means of audio convolution, from an own recording of voice and guitar made in a semi-anechoic chamber.

## 2. METHODOLOGY

### 2.1 Description of the space

This space (approximate volume of 393 m$^3$), located at a depth of 4.5 m, consists of three main areas (see figure 3), all of them covered by barrel vaults that reach a maximum height of 3.7 m. The current access is through a staircase that, in its original state, was not part of the complex, being separated from the rest of the architectural complex by a glass wall.
The first area, which we call *warehouses*, due to its original use, measures approximately 4x12 m (158 m$^3$). Originally, this area did not have internal divisions, but at present there is a partial partition, leaving the upper part open, forming the current store of the premises.
On the upper right is the *drydock*, a narrow space of approximately 2x16 m (115 m$^3$). To its left, the old *cistern*, measuring 4.5x9 m (120m$^3$), is finished in cement mortar and silicate paint, differing from the exposed brick and oyster stone of the rest of the complex, although all of them retain the original limestone pavement.


**Figure 3**. Current plan of the "Cueva del Pájaro Azul".

Figure 3 shows the positions of the sound source and the microphone, used in the study. Source positions 1 and 2 were located where live performances currently take place, while source 4 corresponds to the original position used for these events. However, due to the presence of the current store, the latter location does not exactly match the original one. The position of source 3 was added by the authors for the purpose of analyzing the acoustics of the *cistern*. As for the position of the microphones, they were strategically distributed to record both direct and reflected sound in the different spaces of the cave.

### 2.2 Materials and measuring methods

The GRAS 45BC KEMAR Head and Torso simulator (GRAS Sound & Vibration, Holte, Denmark) was used to evaluate the acoustic response of the human ear to different sound stimuli. The ear height of this equipment was placed at 1.30m, corresponding to the approximate ear height of a seated person, a common circumstance when a show is performed in this space.
A sound level meter HBK 2270 (Hottinger Brüel & Kjaer, Virum, Denmark) was also used to measure sound pressure levels in the study space. The omnidirectional source HBK 4296 (Hottinger Brüel & Kjaer, Virum, Denmark) was positioned at a height of 1.5m, representing the usual height of a singer's mouth during a performance. This ensures a controlled sound field consistent with the actual venue conditions during a performance.
MOTU 8PRE and MOTU 828 ES audio interfaces (MOTU, Cambridge, Massachusetts, USA) were used for audio signal processing and interconnection between the different acoustic equipment. Also, the HBK 2716 amplifier (Hottinger Brüel & Kjaer, Virum, Denmark) was used to guarantee an adequate amplification of the acoustic signals, ensuring quality and fidelity in the measurements performed.
The method used to obtain the Impulse Responses (IR) was the traditional Exponential Sine Sweep (ESS), proposed by Angelo Farina [19]. A 20-second sweep of a 20 to 22 kHz sine wave was used. To ensure correct alignment of the IRs, a loopback was recorded.
Considering the source and microphone positions in Figure 3, 13 IRs were recorded following the source-microphone (S-M) pairs shown in Table 1.
A self-developed software in Python called *IRMa* [20] was used to generate and record the stimuli in situ.

**Table 1.** Source-Microphone pairs analyzed.

| | **M1** | **M2** | **M3** | **M4** | **M5** |
|---|---|---|---|---|---|
| **S1** | x | x | x | | x |
| **S2** | | x | x | | x |
| **S3** | | x | | x | x |
| **S4** | x | | x | | x |

### 2.3 Analysis Methodology

The monaural parameters $T_{30}$ and $C_{80}$, and the binaural parameter IACC were evaluated, following the method proposed by the European standard ISO 3382 [21]. The monaural parameters were computed using *IRMa* [20] and the IACC calculations were analyzed in MatLab R2024a. The resulting graphs were generated with R.

## 3. RESULTS

### 3.1 Reverberation Time ($T_{30}$)

When considering emitters and microphones inside the *drydock* and at the entrance to the enclosure (S1-M1, S1-M2 and S2-M2), the lowest values are found throughout the enclosure ($T_{mid}$ = 0.92s). However, a considerable increase in these values is observed when the emitter is placed in the *cistern* or at the end of the *warehouses* (S3 and S4). In these cases, the $T_{30}$ presents values that exceed 2s ($T_{mid}$ = 2.41s).

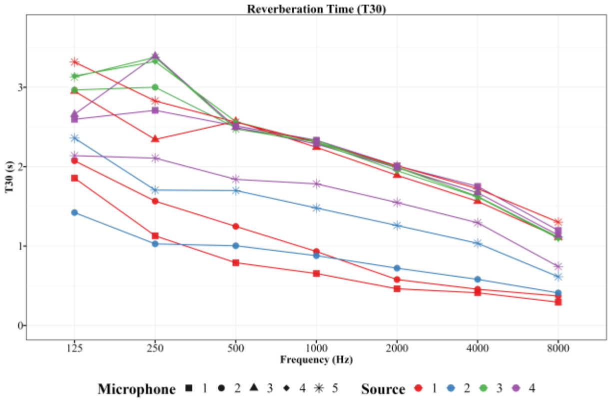


**Figure 4**. Reverberation times ($T_{30}$) obtained in 13 Source- Microphone pairs, inside the enclosure: S1 (red), S2 (blue), S3 (green) and S4 (violet). The different microphone positions are presented in the shape of the dot.

The only receptor evaluated in the *warehouses* (in close proximity to the connecting arch between this space and the *cistern*) is M5, which exhibits analogous values for the sources within the same space ($T_{mid}$ = 1.7). However, when positioning the emission point is situated within the *cistern* or at the base of the *drydock* (S2 and S4), there is a substantial increase in the $T_{30}$ ($T_{mid}$ = 2.41s). This increase may be due to the influence of the *cistern* as a coupled resonator and the noticeable loss of the direct on the reverberation tail at the receiving point. This phenomenon is replicated in the S3-M1 pair, yielding analogous outcomes ($T_{mid}$ = 2.42s).
The space behaves homogeneously and presents high reverberation times when combining, in any way, sources or microphone with the *cistern* (S1-M3, S1-M5, S3-M2, S3-M3, S3-M5, S4-M1 and S4-M3, $T_{mid}$ = 2.42s).
Additionally, an augmentation in the 250 Hz octave band for the aforementioned S-M pairs is discernible, which may be attributable to modal loading within the space

### 3.2 Clarity ($C_{80}$)

In general terms, the emitter inside the *cistern* (S3) has the lowest clarity indexes ($C_{80}$ = -3.82dB). The source S4, although it presents low clarity values (for M1 and M3 $C_{80}$= -5.03dB), for the microphone M5, a notorious increase of the index is perceived ($C_{80}$ = 4.24dB).

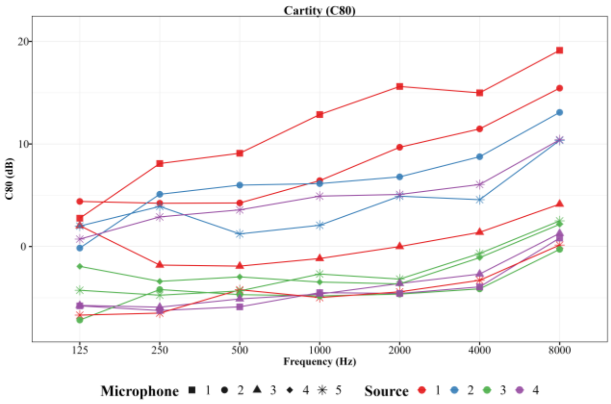


**Figure 5**. Clarity ($C_{80}$) obtained in 13 Source-Microphone pairs, inside the enclosure: S1 (red), S2 (blue), S3 (green) and S4 (violet). The different microphone positions are presented in the shape of the dot.

Source S2, presents positive values in the different microphone positions evaluated, showing a better performance in clarity inside the *drydock* (M2, $C_{80}$=5.54dB), than in the same *warehouses* (S5, $C_{80}$=1.65dB).
Source S1, presents dissimilar values in the different microphone positions evaluated. Despite exhibiting the highest levels of clarity of all the samples surveyed (M1, $C_{80}$=10.98dB), a noticeable decrease is observed when the microphone is displaced at a very short distance (M2, $C_{80}$=5.33dB), this may be attributable to the coupling of the *cistern* as a resonator. Finally, the evaluation of a microphone positioned inside the *cistern* again yielded negative values of clarity ($C_{80}$= -1.54dB), it should be noted that, despite being in another room, these values are higher than the samples obtained inside the same room in the case of the *cistern*.

### 3.3 Interaural Cross Correlation (IACC)

The results obtained from the IACC (Table 2) show a higher directionality for the M2 microphone compared to other positions. The *cistern* is presented as an acoustically diffuse space, with extremely low values. It is worth mentioning the pairs S4-M5 and S1-M1 that, despite being at a very close distance, present highly diffuse fields.

**Table 2.** IACC measured in the 13 Source-Microphone pairs.

| S-M Pairs | IACC |
|---|---|
| S1-M1 | 0.10 |
| S1-M2 | 0.40 |
| S1-M3 | 0.18 |
| S1-M5 | 0.14 |
| S2-M2 | 0.28 |
| S2-M3 | 0.11 |
| S2-M5 | 0.14 |
| S3-M2 | 0.15 |
| S3-M4 | 0.07 |
| S3-M5 | 0.26 |
| S4-M1 | 0.19 |
| S4-M3 | 0.06 |
| S4-M5 | 0.10 |

## 4. TOOL FOR AURALIZATIONS

For the realization of virtual auralizations that allow to evaluate the space in a situated way, considering the musical practices dated in the enclosure, a software of own design, accessible to the user, is presented. It is developed in Python, using the customkinter library for its graphical interface.

### 4.1 Obtaining Sound Stimuli

Recordings of flamenco singing and classical guitar were made in the semi-anechoic chamber of the University Institute of Research in Applied Linguistics of the University of Cádiz (Cádiz, Spain). For this purpose, a TLM 103 condenser microphone (Neumann, Berlin, Germany) was used, positioned at approximately 0.50 m from both the singer's mouth and the guitar. The audio signals were processed through MOTU 8PRE and MOTU 828 ES interfaces (MOTU, Cambridge, Massachusetts, USA). Finally, the recording was carried out with REAPER software.
Three songs typical of the Cádiz region were recorded: “Alegrías de Cádiz” (4:23 min), “Malagueña del Mellizo” (9 min) and “Chuflillas” (“Bulerías de Cádiz”) (5:32 min). Two separate recordings (vocals and guitar) were obtained from each song, resulting in a total of six recordings. A mix of voice and guitar from each song was added to this resulting mix, producing three more sound stimuli.

### 4.2 Convolution for acoustic reconstructio

Using each Binaural Impulse Response (BRIR) from the “Cueva del Pájaro Azul”, an audio convolution process is performed with the aforementioned recordings. Waveform convolution is the equivalent of mathematical multiplication of the spectra of each signal [22, 23]. This allows modifying the spectral content of a recording with the spectrum of the room response (BRIR), allowing the acoustic reconstruction of the space considering the Head Relative Transfer Function (HRTF).
Figure 6 shows a summary of the methodological process for each Source-Microphone.
The design consists of 13 BRIR interchangeable by the user, allowing to combine the 9 stimuli obtained in a non-simultaneous way, being able to realize a total of 117 different possibilities. Each listening point displays a photograph with its corresponding plan.

## 5. CONCLUSION

A detailed acoustic study of the “Cueva del Pájaro Azul” was carried out, considering the arrangements of Source-Microphone pairs, according to the use of the space in previous decades and at present. In this study, it was possible to determine that materiality and shape are influential factors for listening, since, in very short relative distances between the source and the microphone, considerable variations are produced.
Of the 4 source positions evaluated, S1 and S2 are currently used. The first, according to informal interviews with staff, is preferably used for solo guitars.
In consideration of the optimal $T_{30}$ as established by Beranek [12], this space is identified as the most conducive environment for musical performances characterized by high chronometric density. Despite the fact that this study was conducted on Baroque and Classical musical movements, the comparison remains valid when taking into account the dynamic envelopes of the instruments that were evaluated.
In contrast, in S2, singers and guitarists are typically positioned, and based on the evaluations conducted (T30, C80 and IACC), this location exhibits the most balanced values for the production of both musical elements when compared to the remaining evaluated positions. It is noteworthy that this particular point exhibits the highest number of constructive modifications, including the addition of a glass door and the removal of the access staircase, resulting in alterations to the original architectural acoustics.

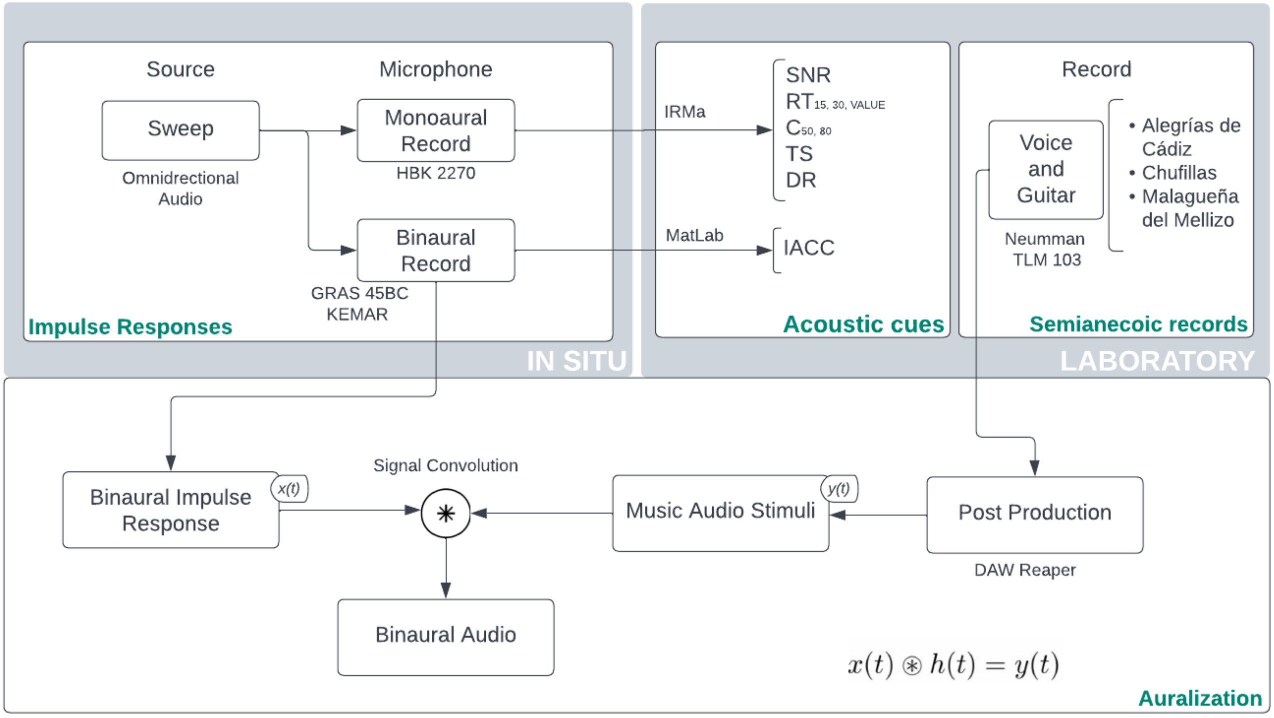


**Figure 6**. Descripción de procesos de trabajo realizados tanto en Laboratorio como in situ, para la realización de cada auralización final.

According to the flamenco club's archives, the position of the S4 source was the most used originally, presenting optimum clarity values inside the *warehouses*, but very high from other microphone positions. It should be noted that, in the archives reviewed, there was no partial wall with an opening at the top between the two spaces, as is the case today, where the current store is located, and this space could function as a coupled resonator.
All the samples recorded in the cistern (S3) present acoustically homogeneous information, although the level of $T_{30}$ and $C_{80}$ does not allow for adequate intelligibility.
The study demonstrates that the room exhibits significant acoustic variability, despite its compact dimensions. Although the study was carried out in an empty room and under the current architectural conditions, which differ from the original ones, mainly in the covering of the walls and vaults, this study gives an approximation of how it was possible to perceive flamenco music in this space in the mid-twentieth century.
The design of specific auralizations, by means of a self-developed software, is presented as a comparative tool in an intuitive way, allowing a historical approach from the acoustic exploration. The proposal can expand its scope by applying numerical simulations considering previous plans and photographic archive. This approach would facilitate a more effective examination of flamenco singing within the context of the intangible heritage of humanity.

## 6. ACKNOWLEDGMENTS

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