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On the Acoustics of the Underground Galleries of Ancient Chavín de Huántar, Peru

J. S. Abel[a], J. W. Rick[b], P. P. Huang[a], M. A. Kolar[a], J. O. Smith[a] and J. M. Chowning[a]

[a]Stanford Univ., Center for Computer Research in Music and Acoustics (CCRMA), Dept. of Music, Stanford, CA 94305-8180, USA
[b]Stanford University, Archaeology Center, P.O. Box 20446, Stanford, CA 94309, USA
kolar@ccrma.stanford.edu

Chavín de Huántar is a monumental World Heritage archaeological site in the Peruvian highlands, predating Inca society by over 2000 years. The importance of site acoustics is suggested by distinctive architectural features, notably an extensive network of underground galleries used in part for ritual purposes. The labyrinthine galleries are stone-walled and arranged in a series of small rectangular alcoves off narrow corridors. In this work, we initiate research that seeks to understand how the acoustics at Chavín may have influenced auditory experience.

Acoustic measurements and models of a site can be used to archive site acoustics, estimate the acoustics of inaccessible or alternative site architectures, and reconstruct the acoustics of modified or damaged sectors; they may also corroborate aspects of rituals suggested by other archaeological data. Preliminary measurements at Chavín show a short reverberation time, dense and energetic early reflections, and low inter-aural cross correlation. The short reverberation time would enable rhythmically articulated playing of Strombus shell trumpets found on site. The early reflection patterns would provide strong acoustic reinforcement and resonances in gallery alcoves. The wide soundfields would provide a sense of spaciousness and envelopment, contributing to ritual experience.

1 Introduction

Chavín de Huántar, a World Heritage archaeological site in the north-central sierra of Peru (Figure 1), reached the end of its monumental construction stage around 600 B.C. [1,2]. An extensive underground network of labyrinthine galleries, corridors, shafts, and drains built of cut stone remains intact and primarily without post-period modification.

Fig.1 Chavín de Huántar, aerial photograph.

The importance of acoustics at Chavín has been suggested by archaeological work positing the site as a ritual center important in developing authority, and is supported by the 2001 discovery of twenty identically prepared Strombus shell trumpets in the Caracolas Gallery.

In this study, we make preliminary acoustic measurements and analyses of three galleries: Doble Ménsula, Laberintos, and Ofrendas. Figure 2, adapted from Kembel [2], highlights these galleries within their context in the complex. The rectilinear shapes, narrow width, short height, and zig-zag layout of the galleries imply dense and energetic early reflections with little inter-aural cross correlation. The geometries and material composition correspond to acoustic features that add an auditory dimension to the sensory disorientation induced by this underground, maze-like environment.

We discuss our measurement methods in Section 2, present an analysis in Section 3, and summarize our findings in Section 4.

2 Measurement Methods

Preliminary measurements were made using a system designed for portability, shown in Figure 3. A swept exponential sinusoidal test signal of length 2^{17} at a 48 kHz sampling rate was used.

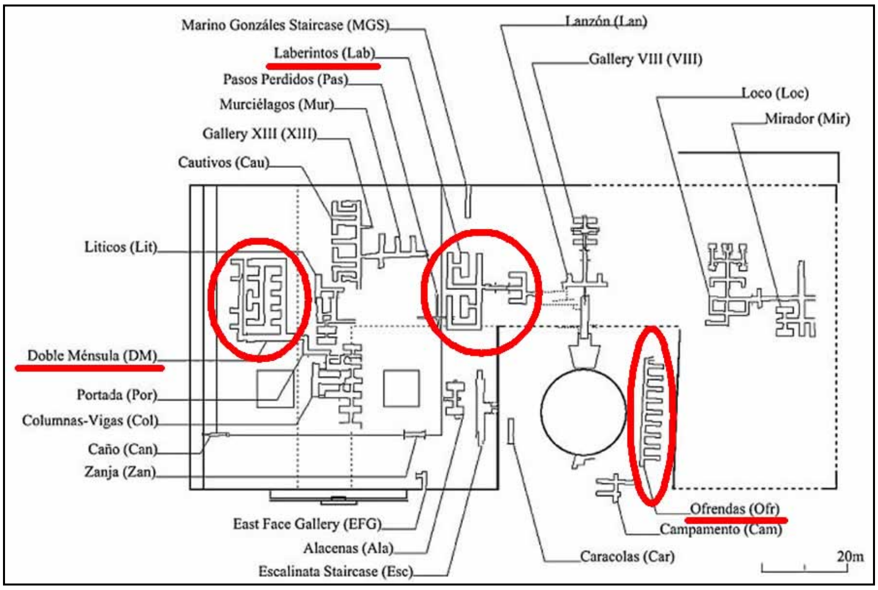

Fig.2 Gallery layout at Chavín de Huántar, adapted from Kembel [2]. From left: Doble Ménsula, Laberintos, and Ofrendas.

The test signal was sourced from an iPod through a K&H O110 monitor positioned at Chavín-period human head height (to approximate Strombus trumpet and human voice sources). Two sets of receivers were used: AuSIM in-ear omnidirectional microphones (Sennheiser capsules) through a Grace Lunatec V3 preamplifier and analog-to-digital converter (ADC), and the onboard cardioid microphones and ADC of a Sony PCM-D50 recorder.

Fig.3 Data collection in Doble Ménsula.

Gallery impulse responses were collected between 10 source and 27 receiver positions. Source-receiver positions were selected from a representative range of gallery geometries, after reviewing initial balloon pop tests.

Using a circular version of the method described by Farina et al. [3,4], impulse responses were generated by inverse transforming the ratio of one period of the transfer function of the system response to that of the repeated sine sweep. This method gives a signal-to-noise ratio (SNR) gain roughly inversely proportional to frequency (see, for instance, [5]). In our measurements, the signal-to-noise ratios were typically greater than 60 dB, but varied depending on the equipment used and the distance between source and receiver.

An example response taken via the in-ear microphones at a co-located source and receiver position in Doble Ménsula, shown in Figure 4, has a signal-to-noise ratio near 70 dB.

3 Measurement Analysis

3.1 Short Reverberation Time

Reverberation 60 dB decay times (T60) were computed in octave bands from the slopes of lines fit via least squares to the time evolution of measured impulse response band energies.

Measured T60s for the three galleries are short, generally less than 0.5 seconds, ranging from 150 milliseconds to around 1 second, as shown in Figure 5. As is typical of reverberation time, the T60s are longer in the lower frequencies. While Doble Ménsula and Laberintos have similar reverberation times, the T60s in Ofrendas are significantly shorter. Among other effects, short T60s would allow for and perhaps encourage rhythmically articulated Strombus playing in the Chavín-period ritual context.

Within a gallery, relative T60s are similar across frequency, with the overall T60 weakly dependent on source and receiver positions. In particular, reverberation times are correlated to the number of turns in the path between source and receiver. Source/receiver positional combinations along a straight axis result in the shortest T60s within a gallery, while source/receiver combinations separated by more turns yield longer T60s (see Figure 5).

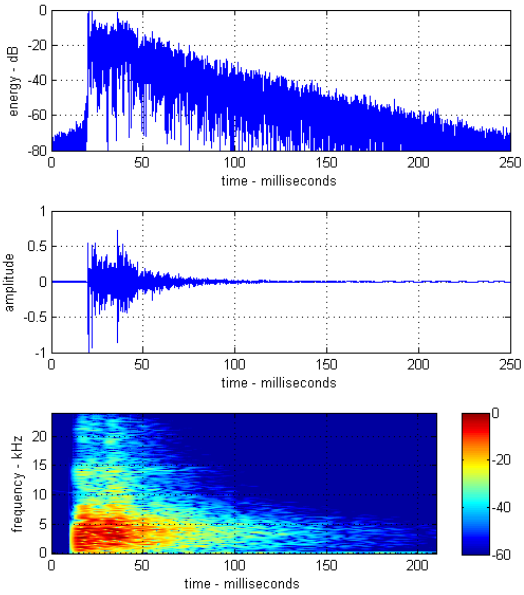

Fig.4 Example impulse response measured from a co-located source and receiver pair in Doble Ménsula (position “D” in Figure 8). From top: response energy, amplitude, and spectrogram.

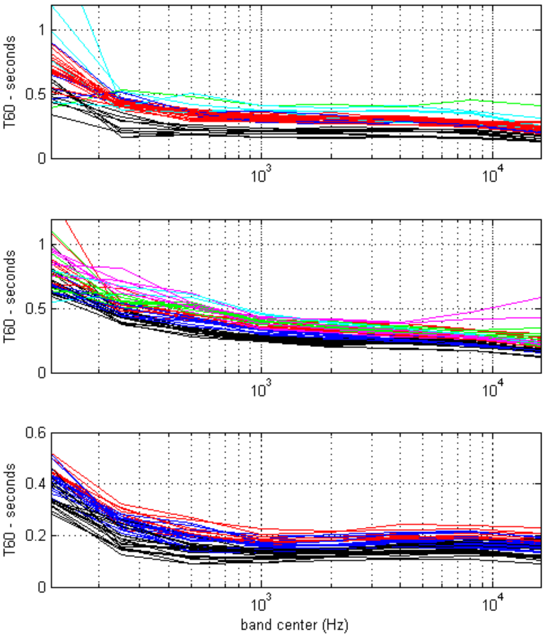

Fig.5 Reverberation time in octave bands per gallery. From top: Doble Ménsula, Laberintos, Ofrendas. Line color represents the number of structural turns between the source and receiver positions: 0 to 5 turns are labeled in black, blue, red, green, cyan, magenta, respectively.

3.2 Dense, Energetic Early Reflections

The normalized echo density profile (NEDP) [6,7] measures echo density along a reverberation impulse response on a normalized scale. Normalized echo density (NED) takes on values ranging from near zero, indicating the presence of relatively few reflections, to around one, implying an echo density similar to that of Gaussian noise. In our analysis, the NEDP was computed using a 10 ms Hanning window.

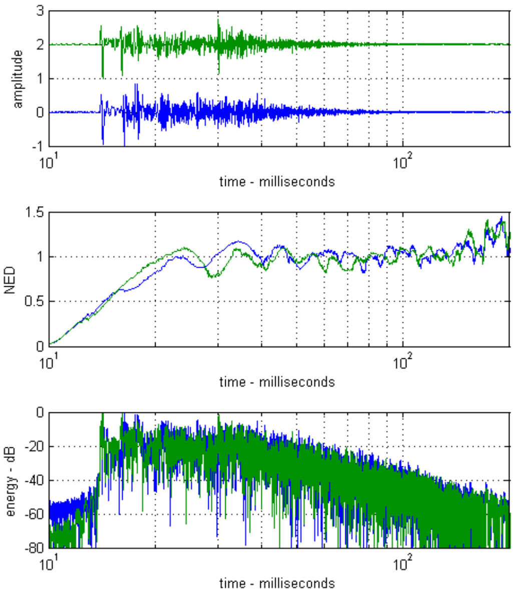

Fig.6 Binaural impulse response measured in Doble Ménsula, where the receiver is co-located with the source in an alcove (Fig. 8, position “D”). From top: response amplitude, normalized echo density profile, and energy.

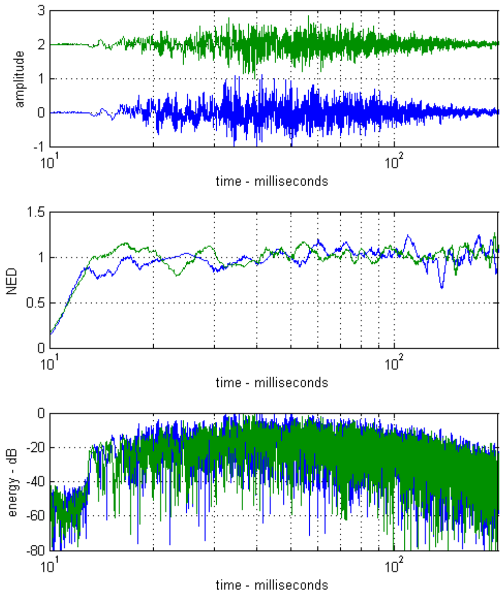

Fig.7 Binaural impulse response measured in Doble Ménsula, with receiver and source in different alcoves (Fig. 8, positions “D” and “K”). From top: response amplitude, normalized echo density profile, and energy.

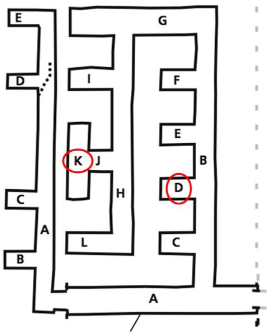

Fig.8 Map of Doble Ménsula, adapted from Kembel [2]. “D” marks the source position for impulse responses in Figures 4, 6, and 7. “K” marks the receiver position for impulse responses in Figure 7.

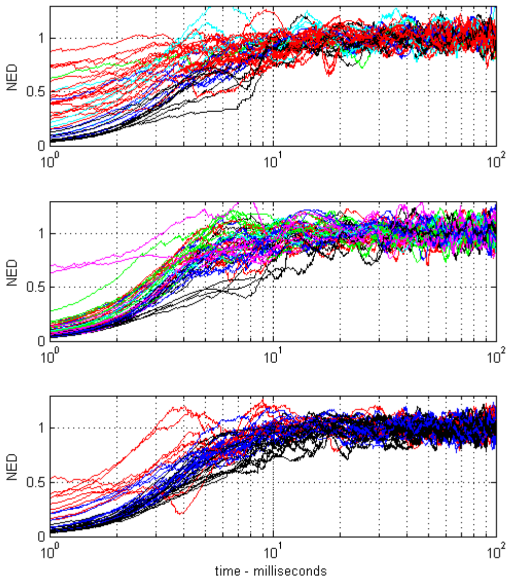

Fig.9 Normalized echo density profiles per gallery. From top: Doble Ménsula, Laberintos, Ofrendas. Line color represents the number of structural turns between the source and receiver positions: 0 to 5 turns are labeled in black, blue, red, green, cyan, magenta, respectively.

Figure 6 shows impulse responses and normalized echo density profiles for the co-located source-receiver pair in Doble Ménsula also presented in Figure 4. Note the logarithmic time axis. The direct path and several early reflections are evident in the impulse response. The NEDP shows an increasing echo density, with the late field starting after about 10 milliseconds.

Figure 7 shows the NEDPs for a measurement where the source and receiver were located far apart in separate alcoves, with four turns between them (“D” source and “K” receiver positions as labeled in the Figure 8 map). Here the early reflections are already quite diffuse upon arrival due to initial wavefronts having reflected off many surfaces before reaching the receiver. The response is fully diffuse within a few milliseconds.

All three galleries have a quick onset; that is, they reach fully Gaussian statistics well under 20 milliseconds. In addition, a significant amount of the impulse response energy occurs after the direct path. The more turns between source and receiver, the higher the initial NED and the faster the late field onset. The top plot of Figure 9 shows that for all source-receiver pairs in Doble Ménsula, the echoes quickly build into a diffuse late field over the short period of about 10 milliseconds. The other two galleries exhibit similar behavior: this rapid transition to the late field is consistent with the small distances between structural surfaces within the galleries. The quick transition to the late field along with the large fraction of energy arriving after the direct path would tend to obscure the perceived arrival direction and perhaps distance cues.

The echo density in Doble Ménsula may be influenced by its protruding ceiling supports – the "double courses of corbels" [2, p.95] that enabled its wider construction (see Figure 10). Such architecture is more angular in cross-section than that found in Laberintos and Ofrendas, whose corridors and alcoves are narrower and whose walls form right angles with their ceilings, as shown in Figure 11.

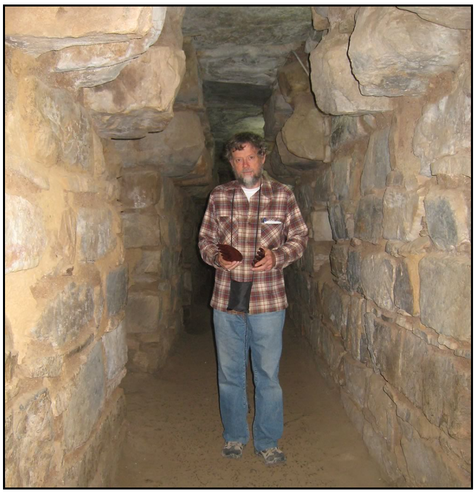

Fig.10 Doble Ménsula Gallery, named for double corbels.

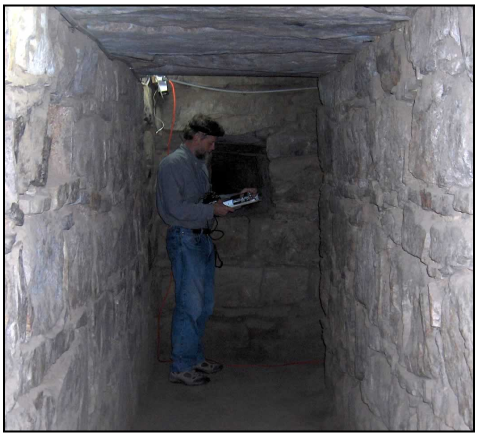

Fig.11 Laberintos Gallery is rectangular in cross-section.

3.3 Consistent Resonances

The Ofrendas Gallery consists of nine similar alcoves, each less than 1 meter wide by approximately 3.5 meters long, all in parallel off a common corridor (see Figure 2, lower right corner). These alcoves are exemplary of small rectilinear structures found throughout the complex. Figure 12 displays the first 15 milliseconds of impulse responses measured at two receiver positions within an alcove relative to the source at its termination. The early reflections that result from these dimensions and simple geometries are apparent in the impulse responses.

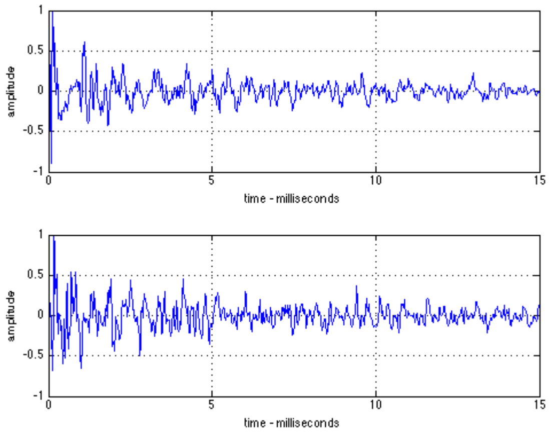

Fig.12 Early portion of impulse responses measured in an Ofrendas alcove. The source is located at the alcove termination. Top: mid-alcove receiver position. Bottom: receiver position at junction of alcove and main corridor.

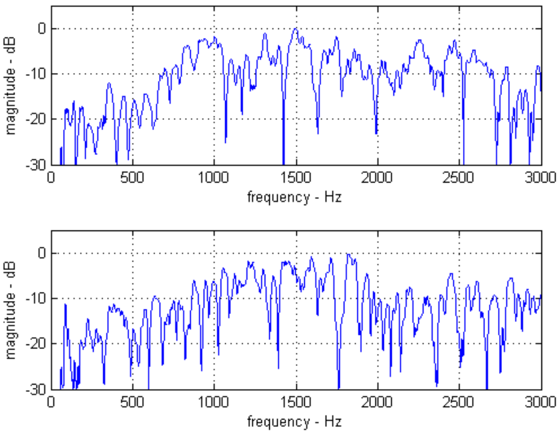

Fig.13 Frequency response up to 3 kHz of impulse responses measured in an Ofrendas alcove.

Though the early reflections become quickly dense, a number of prominent arrivals are evident. These arrivals are consistent with the alcove dimensions and would provide resonances, as shown in Figure 13, in the ranges of human voice and the Strombus trumpets found on site. Because these alcoves share dimensions and thus resonant frequencies, multiple Strombus players or vocalists in different alcoves would experience acoustic support for certain tunings, allowing and enhancing the coordination of group sound production.

3.4 Wide Soundfields

Inter-aural cross correlation coefficients (IACC) and lateral energy fraction (LF) [8], computed for all impulse response measurements in the three galleries, are plotted in Figures 14 and 15. Small IACC values, calculated from the in-ear microphone responses, imply acoustic diffuseness and envelopment. Lateral energy fraction was approximated by using the sum and difference of cardioid microphones oriented 120 degrees apart; the large LF estimates indicate relatively widely distributed arrival angles. These measures of spaciousness [9] confirm that the gallery architecture produces wide soundfields which obscure localization, contributing to sensory disorientation.

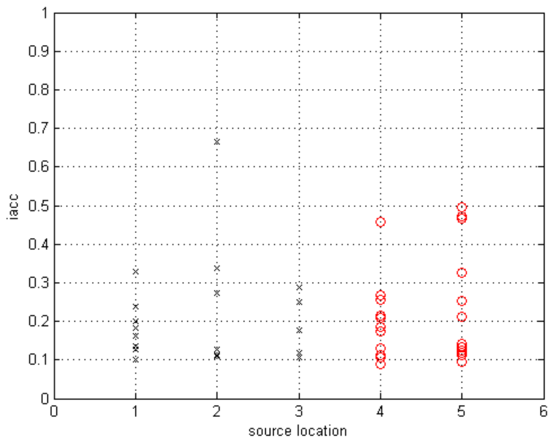

Fig.14 Inter-aural cross correlation coefficient per source location. From left: Doble Ménsula (x) and Laberintos (o).

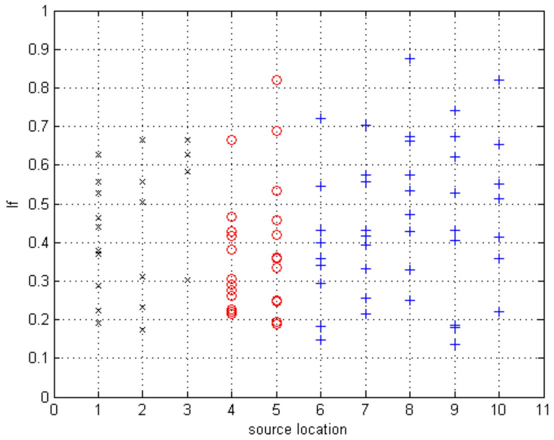

Fig.15 Lateral energy fraction per source location. From left: Doble Ménsula (x), Laberintos (o), and Ofrendas (+).

4 Conclusions and Future Work

Preliminary acoustic measurements of three galleries at Chavín de Huántar indicate short reverberation times. Early reflections are energetic, become quickly dense, and are widely distributed in arrival direction; this predominantly noncoherent energy density results in envelopment and vague localization cues, despite the short reverberation times. Such an auditory space is unusual in the natural world, and may augment the positional disorientation induced by the labyrinthine layout.

Because sensory manipulation played a significant role in Chavín culture [1] and may have determined its architecture, our future work will explore the potential for demonstrating acoustic intention in site design at Chavín. We plan to make extensive acoustic measurements of the extant site and combine this data with Kembel's three-dimensional documentation [2] to develop models that estimate and simulate the acoustics of the complex and its constituent materials, mapping the acoustic effects of construction changes over time.

Acknowledgments

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