A Computational Acoustic Model of the Coupled Interior Architecture of Ancient Chavín (#8696)

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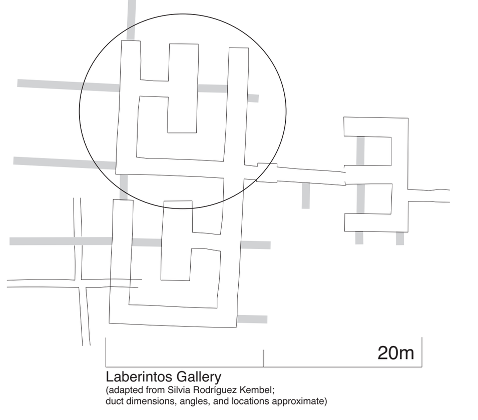
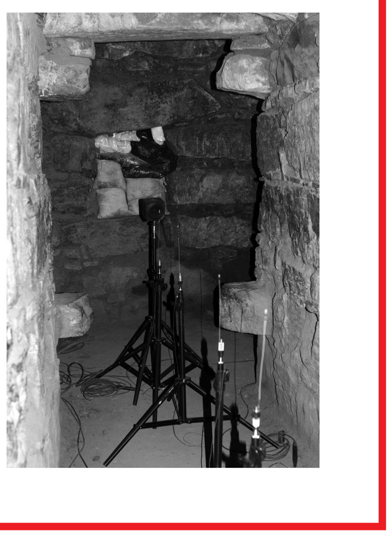
Objectives

In this paper, we seek

- to broaden and advance the methodologies of archaeoacoustics,
- to represent the acoustics of the well-preserved interior architecture at the 3,000-year-old Andean ceremonial center at Chavín de Huántar, Perú, and
- to further evaluate the suitability of digital waveguide networks in large reverberant volumes like rooms.

Below (left) is the floorplan of the "Laberintos Gallery," a small portion of the labyrinthine network of corridors at Chavín. Encircled is the site of our experimentation. To the right is a photograph of the horizontal corridor connecting the two most northwest vertical corridors.





Assumptions

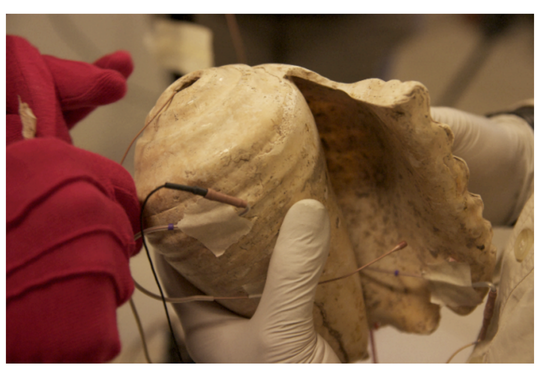
In order to reduce our model computationally, we assume that

- the architectural structure of the underground galleries at Chavín is a *digital waveguide network* in which long, rectangular corridors are modeled by waveguides and the openings that connect them can be encapsulated by instantaneous, planar *scattering junctions*, and
- the physical measurements (height, width, length) of each corridor are rectangular.

Because sound waves in a waveguide propagate in a planar fashion, our model becomes a one-dimensional approximation. Energy is dissipated within the waveguides, and the scattering junctions are lossless. Therefore, any energy arriving at the scattering junctions flows into the two adjacent waveguides.

Background

Previous research ([1]-[5]) has indicated that the acoustic environment of the galleries may have had significance in onsite rituals. Our previous model prototype [6] translated the acoustically coupled topology of Chavín gallery forms to a model based on digital waveguides (narrow passageways and ducts) connected through reverberant scattering junctions (larger corridors). Here, we represent all of these volumes as waveguides.

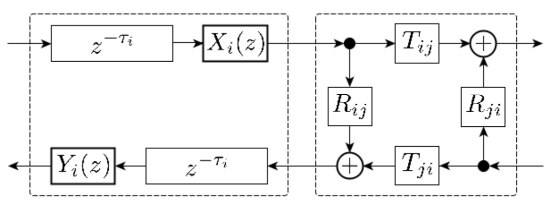


Model Architecture

Each architectural volume (i.e., room, corridor, duct) represents a reverberant, bi-directional digital waveguide in our model. We captured the 2 IRs of each waveguide with a speaker and four Countryman B6 omnidirectional microphones located at opposite boundaries. The waveguide G_i includes a forward-going filter $X_i(z)$ and a backward-going filter $Y_i(z)$, multiplied by the delay $z^{-\tau_i}$. We write it in the column vector

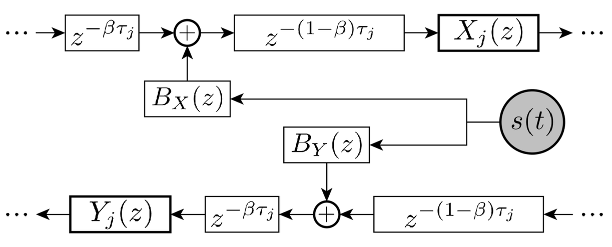
$$G_i(z) = \begin{bmatrix} X_i(z) \\ Y_i(z) \end{bmatrix} z^{-\tau_i}. \tag{1}$$

The signal flow between waveguides G and scattering junctions $\boldsymbol{K}$ is detailed in the figure below.

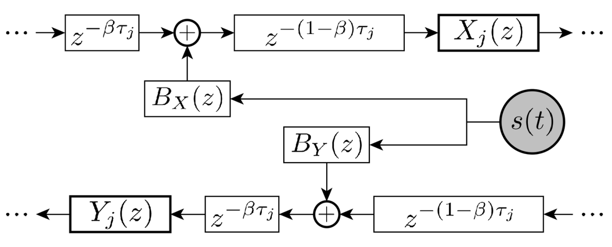


Waveguide G_i Scattering junction $\boldsymbol{K}_{ij}$

Sources affect the transfer function of a given waveguide by introducing a delay β associated with its position along the waveguide and a radiation pattern $B(z)$ in both the x and y directions.



The signal heard by a listener is likewise associated with a delay α according to its relative position in the waveguide, and its antenna pattern $A(z)$ in both directions.



Model Element Design

SCATTERING JUNCTION FILTER DESIGN. We design our formulae for the reflection and transmission coefficients to be the ratio between this surface area implied by the reverberation time T_{60}, call it A_α, and the measured surface area entryways (modeled as connected waveguides in a room), A_{ij},

$$A_\alpha = 0.161\frac{V}{T_{60}}, \tag{2}$$

where V represents the room volume. The reflection coefficients are then given by $R_{ij} = \sqrt{\frac{A_{ij}}{A_\alpha}}$, where A_α refers to the total absorbing area of waveguide G_i. By the conservation of energy, the transmitted energy accounts for all of the energy that is not reflected, implying that $R_{ij}^2 + T_{ij}^2 = 1$.

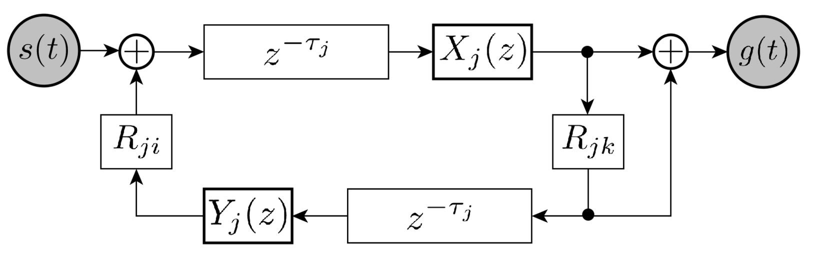
WAVEGUIDE FILTER DESIGN. The transfer function of the jth waveguide in the x-direction is given by $G_X(z) = S(z) + H_{X_j}(z)R_{ji}H_{Y_j}(z)R_{jk}G(z)$ where $H_{X_j}(z) = z^{-\tau_j}X_j(z), H_{Y_j}(z) = z^{-\tau_j}Y_j(z)$. Solving for G, we have

$$G_X(z) = \frac{H_{X_j}}{1 - R_{jk}R_{ji}H_{X_j}(z)H_{Y_j}(z)}. \tag{3}$$

Similarly, the transfer function in the y-direction is

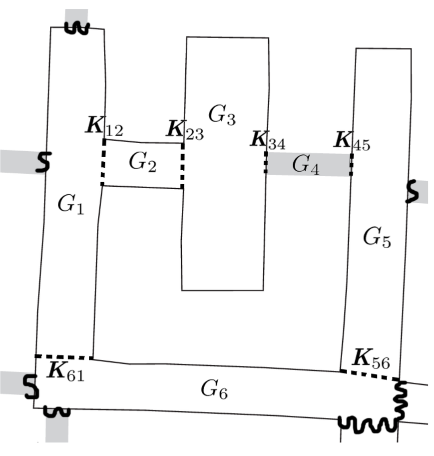
$$G_Y(z) = \frac{H_{Y_j}}{1 - R_{ji}R_{jk}H_{Y_j}(z)H_{X_j}(z)} \tag{4}$$

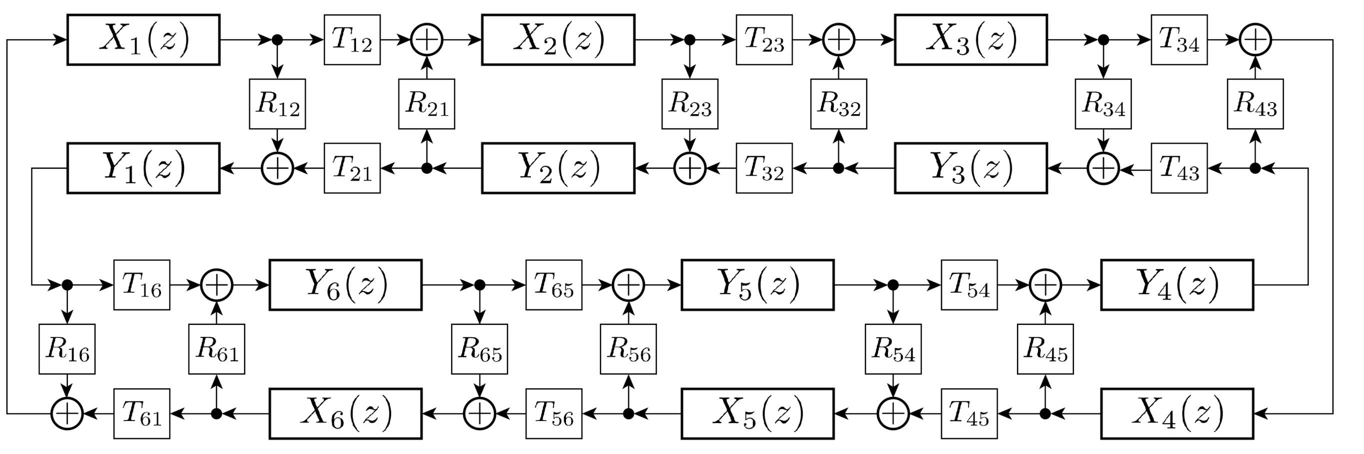
when the source is positioned such that sound enters from the "end" of the waveguide and the microphone is switched to the "beginning" termination. Below is the signal flow from one scattering junction $\boldsymbol{K}_{ji}$, through waveguide G_j, to a second scattering junction $\mathbb{K}_{jk}$.



Modeling the Laberintos Gallery

We named our waveguides and scattering junctions as depicted in the below (left) figure. On the right, we have the resulting signal flow diagram of the Laberintos Gallery at Chavín de Huántar.



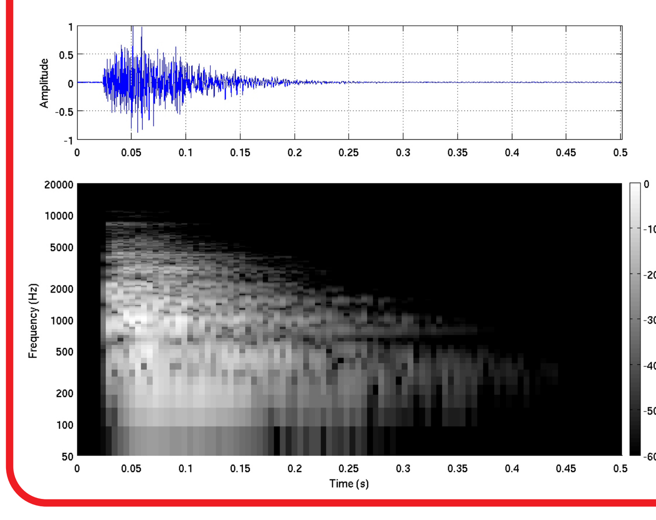


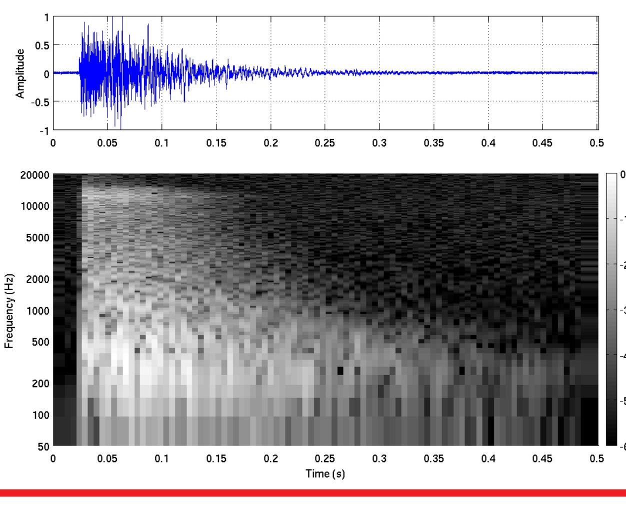
During measurement, entryways to each G_i were blocked with thick, polyester-wool blankets. Small ducts that exit the Laberintos Gallery were blocked with sandbags, in order to use the measured IRs to estimate reflection coefficients for the boundary scattering junctions based on energy within each unit, and not on circulation through the network. IRs were also taken with unit boundaries open to represent the coupled architectural acoustics of the entire network.

Wgd. ID	Dimensions of wgd. in meters	Proportion of dirt to A_α
G_1	1.2w × 7.3l × 1.9h	0.1899
G_2	1.05w × 1.8l × 1.8h	0.1825
G_3	1.8w × 5.6l × 2.2h	0.1990
G_4	0.54w × 1.9l × 0.5-0.6h	0.0000
G_5	1.3w × 7.3l × 1.8h	0.2007
G_6	1.0w × 8.1l × 1.8h	0.1807

Model Evaluation

Additional measurements were taken to analyze the response of microphones located in all volumes of the selected network, without blocking unit terminations, thus capturing the acoustic coupling of the architectural acoustic system. In one such example, the loudspeaker was placed in the southeast corner of waveguide G_6. We changed the orientation of the speaker 17 times, and summed these impulse responses to simulate a hemispherically radiating source. In the figure below (left), we give as an example the impulse response recorded from a microphone located in the center of waveguide G_3. in the open network. The modeled equivalent is shown in the figure below (right).





Via informal listening tests to compare these measured and modeled impulse responses, we conclude that this preliminary modeling method produces a somewhat metallic sound quality. We hypothesize that this is a result of room modes accentuated by repeated convolution.

Future Work

- Evaluate the perceptual validity of the model beyond informal listening tests.
- Test archaeological hypotheses regarding differences in ancient structural conditions should be tested easily; for example, a change of filter parameters would allow the model to simulate the acoustics of ancient Chavín galleries with wall surfaces of clay plaster.
- Optimize for real-time implementation to enable greater interactivity with dynamic source and listener positions, perhaps borrowing techniques from [7].

References

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