FROM SPATIALIZATION TO SCIENTIFIC PROBES OF ACOUSTIC SPACES

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1. ABSTRACT

As the number of loudspeakers increased from four to many at Stanford U., novel uses were seen beyond presenting concert music. With measurement and analysis, they have been used to model spaces whose acoustics are significant to both humanistic and scientific research — with Chavín de Huántar establishing the methodology, to the Hagia Sophia to one of the oldest and most intriguing of all, the Chauvet Cave.

2. INTRODUCTION

After being introduced to the idea of computer music by Max Mathews' seminal article [17] in January, 1964, and after taking a course in programming a digital computer as a graduate student in music composition at Stanford University, I realized that with Mathews MUSIC IV program and newly acquired programming skills, there were possibilities open to me in composing music for loudspeakers that did not require access to electroacoustic music studios that were rare and for the well-connected.

Some of the possibilities were seen immediately — based upon music that I heard in Paris during my three years of studies of traditional composition, for example surround sound. But, other possibilities, I could not have seen at the outset of my work because they were dependent upon my acquiring critical knowledge and intense momentary engagement as was the case in my discovery of FM Synthesis.

But the interest here is the evolution of loudspeakers, both in quality and their manner of use. After beginning my work in digital domain surround sound in 1964, I could imagine that there would one day be many more than four loudspeakers. I even considered configuring my four loudspeakers as a tetrahedron to gain a 3rd dimension.[1]

The spatialization of sound was of little interest to others in the field of computer music, but I was inspired, especially by Stockhausen's electronic works.

With evolving loudspeaker technology, affordable multichannel recorders, and the introduction of sub-woofers that allowed the separation of large membrane non-directional long wavelength speakers, spatialization became common practice in centers of research and music production. The Computer Music Journal dedicated its 2016 winter edition to High-Density Loudspeaker Arrays (HDLA).[8]

But there was another development in the use of loudspeakers in recent years that was not foreseen early on. Their use is being extended from the creation and presentation of electro-

[1] The idea was not realizable as the thought of a large loudspeaker somehow suspended over a listener's head was fearful.

acoustic music to use as experimental tools of discovery—probes— in disciplines where the sonic attributes of spaces may inform, even transform, aspects of their research. HDLA can be used to replicate the acoustics of architectural spaces or natural acoustic spaces. The existing monumental architecture from antiquity and the middles-ages can be measured with impulses and sine-sweeps to yield sufficient information that their acoustic signatures can be reproduced with convincing fidelity within a high-density dome of loudspeakers.

This application of high-level signal processing research in spatial audio has come to have importance to acoustics, psychoacoustics, archaeology, anthropology, art history, music composition, and even musicology.

Coupled with laser scanning devices this new research area might be used to reveal aspects of human expression from prehistoric times. For example, the placement of wall paintings in caves such as the Chauvet cave in southern France,[2] may have been determined by the acoustic response at a certain in the cave. To measure, model, and reproduce the acoustic profile of the cave as it sounded when the paintings were created would be an outcome having deep meaning to every human being on this earth.

Figure 1.

[2] Chauvet-Pont-d'Arc Cave in the Ardèche department of France

3. SPATIALIZATION

3.1.Moving Sound Sources

In his 4-ch piece, *Kontakte* (1958*),* Stockhausen created a sound that moves continuously around the audience seated within a square at the corners of which were four loudspeakers. The means of implementing this illusion was to record on a 4-ch tape recorder the output of four microphones arranged in a square on a table at the center of which was a rotating loudspeaker producing the sound to be spatialized, as shown in Figure 1.[20] I realized that with Mathews MUSIC IV program and newly acquired programming skills, I would be able to realize in the digital domain the spatialization effects that K. Stockhausen had produced in his 4-ch piece, *Kontakte,* in the analog domain.

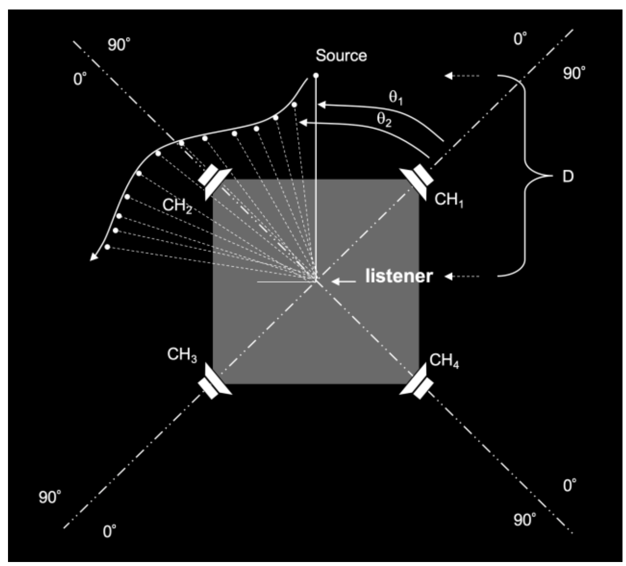

Figure 2. By plotting points at a constant rate, the radial (Doppler shift) and angular velocities were captured in the changing angle θ and length of successive radii, D.

I wrote a program to plot a sound trajectory as shown in Figure 2. The data was then used to calculate control functions for distribution of energy between speaker pairs. Providing control over the perceived distance of a sound was an important attribute of this implementation of spatialization: the perceived distance is a function of the ratio of direct to reverberant signal energy $\frac{I_{direct}}{I_{reverb}}$. I introduced the distance cue by varying the intensity of the direct sound source according to $\frac{1}{D^2}$, while maintaining the reverberation at constant intensity. [4]

Reverberation is to perceived distance in audition as perspective is to perceived distance in vision: each provides the perceptual system information about loudness and size respectively — loudness constancy [23] and size constancy, see Figure 3. A demonstration of this effect can be heard in *Turenas*, a piece I composed in 1972. [5] It is a culmination of my work beginning in 1964, including the discovery of FM synthesis in 1967.

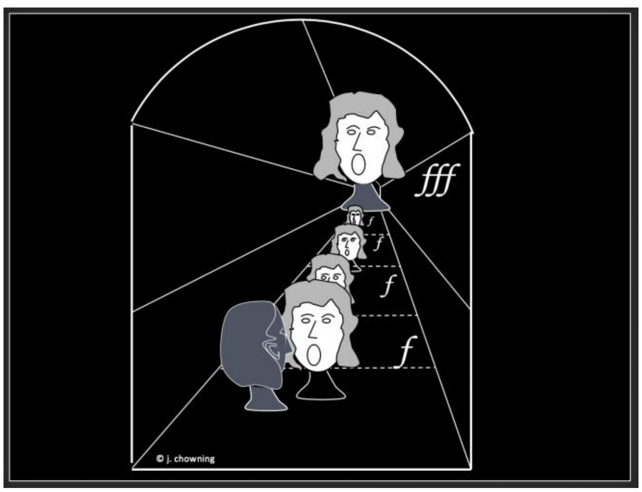

Figure 3. With perspective providing context, we see the singer to be the same size at increasing distances. Likewise, with reverberation providing context, we hear constant loudness at increasing distance. The intensity of the reverberant signal is constant while the intensity of the singer's signal decreases according to $\frac{1}{D^2}$.

4. MEASURING AND MODELING SPACES

While composing a work based upon the Oracle of Delphi, I became curious about the acoustic properties of ancient and prehistoric spaces that might have similar relationships to ancient ritual as has the Temple of Apollo in Delphi and the Corycian Cave on Mount Parnassus high above, to the Pythia, the most prominent oracle of the ancient world.

In 2007, a search for such ancient spaces revealed an archaeological site, Chavín de Huántar in the highlands of Peru.

4.1.Chavín de Huántar

Chavín is known in the world of art because Pablo Picasso famously said: " Of all the ancient cultures I admire, it is Chavín that amazes me the most. In fact, many of my works are inspired by it."[3]

Located in the high sierras of Peru about 200 km north of Lima, Chavín is one of the earliest complex cultures in the Americas, almost 2000 years before the Inca. The excavations are under the directorship of John Rick, a professor of archaeology and anthropology at Stanford University. The site is especially interesting because Rick hypothesized that the underground complex of rectilinear corridors and galleries was used for sensory manipulation in the context of ritual associated with the Lanzon, a 4m carved monolith in one the galleries. [13]

While excavating one of the galleries in 2001, Rick's hypothesis was advanced when he uncovered, 20 nearly 3000-year-old carved strombus trumpets, conch shell horns or "pututus," all showing extensive use-wear. [6]

[3] "De todas las culturas antiguas que admiro es la de Chavín la que más me asombra. De hecho, en ella están inspiradas muchas de mis obras."

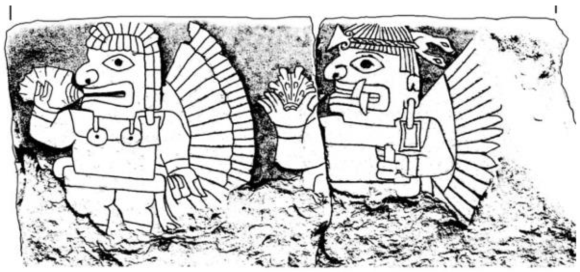

Figure 4. Carved Stone Cornice Fragment showing Strombus trumpet

Researchers at CCRMA contacted Rick and pointed out that within the body of knowledge of current digital sound technology and research, it might be possible to create reasonably accurate acoustic models of the Chavín galleries that would provide him a powerful platform for hypothesis testing. Thus, began the first of CCRMA's projects in measuring and modeling spaces.[13]

In 2007 a team of researchers from CCRMA joined Rick for a week exploring the site to determine the feasibility of using audio

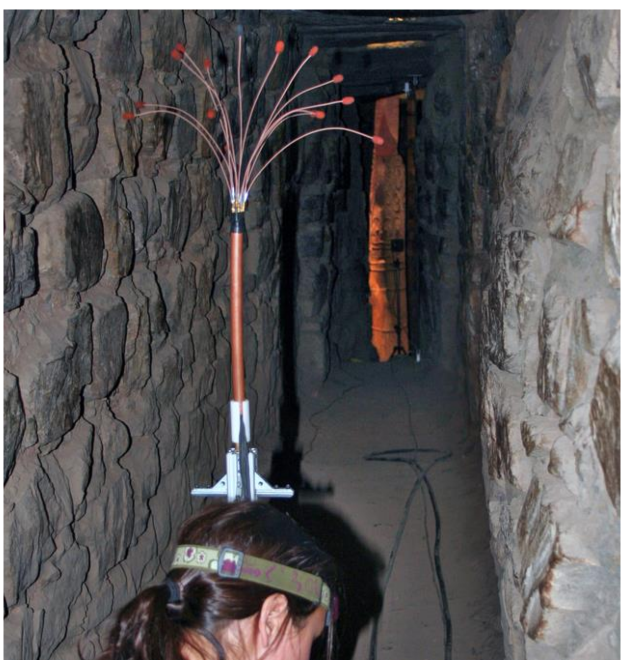

Figure 5. Miriam Kolar using the bouquet array and in-ear microphones to make acoustic measurements in the Lanzon Gallery.

measuring gear and computers in a remote environment having no electrical power source. Miriam Kolar took on the project on as her PhD dissertation topic working with Rick and Jonathan Abel who developed novel microphone arrays for capturing spatial information in the enclosed spaces. [1]

Researchers performed an acoustic analysis of the conch shell horns. "Knowledge of the specific acoustic capabilities of these pututus allows us to understand and test their potential as sound sources in the ancient Chavín context, whose architectural acoustics are studied simultaneously by our research group." [6]

The success of this project, reflected in the many publications, [13] had a profound impact on CCRMA's future research, establishing its position in the field of archaeoacoustics — research in measuring and modeling spaces.

It led directly to a major interdisciplinary study of the Hagia Sophia, [18] involving art history, spatial acoustics analysis and modeling, liturgical performance practice, high-density, domed, loudspeaker arrays implemented by Fernando Lopez-Lezcano[15] [16] and public performance where the Hagia Sophia's acoustic signature is imprinted on live performance of Byzantine chant 7000 miles away from the original performance space where music can no longer be performed.

In 2017, CCRMA initiated a similar project at Longyou Grottoes,[2] a mysterious collection of 40+ underground excavations in Zhejiang Province, 360km southwest of Shanghai, for which there is no historical record, nor evidence of purpose, that would have required managing an army of workers.

Convinced in an initial visit to the grottoes that their acoustics were unique. They all have a similar profile, with a high vertical face — the highest more than 20m — with a small opening at the top, and a ceiling that descends at a 45° angle, however, their area and vertical dimensions are different. All of the surfaces except the rock floor have an identical chiseled band of courses 0.6m in height.

CCRMA and the Norwegian University of Science and Technology (NTNU) , assisted by the Shanghai Conservatory of Music (SHCM), and supported by the Longyou Tourism Agency, organized and successfully executed a five-day measurement project in 2017 to measure two of the five caves that are open to the public.[2] Based upon those measurement data and resulting acoustic models, CCRMA and NTNU proposed with SHCM a 5-day music festival where composers from international centers in China, Europe, and the United States of America, would be invited to compose and perform based upon the acoustic models. The festival will be held from October 23 – 27, 2019.

The ephemeral nature of sound presents real difficulties in establishing relationships between material archaeology and sound. In an article in *Acoustics Today* Kolar writes "Archaeoacoustics probes the dynamical potential of archaeological materials, producing nuanced understandings of sonic communication, and *re-sounding silenced places and objects* (my emphasis).[14]

4.2.Chauvet

Perhaps the longest silenced — 32,000+years — and most interesting places is the The Chauvet-Pont-d'Arc Cave in the Ardèche department of southern France. Discovered in 1994, the Chauvet cave is the world's greatest and best-preserved repository of Upper Paleolithic art. The story of its discovery and the gradual understanding of its importance to humankind's common history is recounted by Joshua Hammer in the Smithsonian Magazine in 2015.[11] The cave was closed to the public in 1994 to avoid the consequence of allowing wide public access that would lead to the growth of mold on the walls, damaging the art as happened to the Lascaux Cave in the Dordogne region of southwestern France.

Prehistorians are reluctant to ascribe meaning to the paintings, engravings, and marks because the traditions of the culture responsible for the motifs[4] are unknown. Jean Clottes, the French prehistorian who headed up the first research team at the Chauvet Caves wrote, *'In instances where these traditions survive, we have no way of knowing, when native informants elucidate an image for us, whether the art really means what they say it means. Their understanding can be influenced by various factors - by their gender or status, for example; and they may modify their explanation of the art when speaking to outsiders deemed unqualified to share meanings so sacred or secret. And when dealing with art for which no ethnological data are known, our predicament is worse still. What appears obvious may not be obvious at all. Does a painting of a bird depict an eagle, a supernatural spirit, or a shaman whose soul has taken flight? Is a bear really a bear, or a human transformed*?'[7]

Of interest in this paper are questions that have been raised regarding the possible relationship between the acoustics of the spaces and the motifs. The hypothesis that the acoustic properties of certain chambers may have determined the content or subject of the motif and its position on the cave wall was first proposed by Dauvois and Reznikoff in 1988 [19]. Their work was not good science by the standards of today — for example, they did not use impulses or reproducible intensities of their excitation sources and used a watch or subjective counting to measure reverberation time (RT) — but their idea was provocative. For example, they proposed that the motif of the horses, **Figure 6.** (in motion!) may be related to the interactions of sound with the physical features of that particular location in the cave. As example, do two rocks clapped together produce an acoustic response that suggests galloping hoofs?

[4] Current researchers use "motif" rather than painting or art to avoid ascribing cultural meaning to images, engravings, or objects.

Figure 6. Image from Chauvet Cave estimated to be 32,000 years BP.

A recent study in 2017, "Cave acoustics in prehistory: Exploring the association of Palaeolithic visual motifs and acoustic response," by B. Fazenda [9], an acoustician, is rigorous, extensive, and well-documented. His conclusions are "*an association of the location of Palaeolithic motifs with acoustic features is a statistically weak but tenable hypothesis, and that an appreciation of sound could have influenced behavior among Palaeolithic societies of this region."*
However, his research does not include Chauvet, which has been closed since 1994 to all but a few scientists and prehistorians.

4.2.1. Replica of Chauvet

In April 2017, a $62.5 million 7-year replica, the Caverne du Pont d'Arc, was completed and open to the public, recognizing that the widely distributed wall paintings had engendered an international audience that wanted to visit the Chauvet Cave. Hammer writes [11] "*Five hundred people—including artists and engineers, architects and special-effects designers—collaborated on the project, using 3-D computer mapping, high-resolution scans and photographs to recreate the textures and colors of the cave. "This is the biggest project of its kind in the world," declares Pascal Terrasse, the president of the Caverne du Pont d'Arc project and a deputy to the National Assembly from Ardèche. "We made this ambitious choice... so that everybody can admire these exceptional, but forever inaccessible treasures."* The replication is extraordinary in its authenticity. Hammer continues, "*At the entrance to the recreated cave, a dark passage, the air was moist and cool—the temperature maintained at 53.5 degrees, just as in Chauvet. The rough, sloping rock faces, streaked with orange mineral deposits, and multi-spired stalactites hanging from the ceiling, felt startlingly authentic, as did the reproduced bear skulls, femurs and teeth littering the earthen floors. The paintings were copied using the austere palette of Paoleolithic artists, traced on surfaces that reproduced, bump for bump, groove for groove, the limestone canvas used by ancient painters.*" Why this emphasis on the replica's authenticity in a paper about acoustic probes of spaces?

*4.2.2. What did **they** hear?*

Reznikoff and Dauvois's (and Fazenda's in different caves) hypothesis that motifs' positions may have been determined by the acoustic response at a certain point in the cave is based upon what they heard in 1994, 32,000 years after the motifs were created.[5] What has changed? Geologists have determined that there has not been earth movement that would have altered the shape of the cave. But what is known about the stalactites and stalagmites in the Chauvet cave and does their existence matter acoustically?

Bourdin, C., Genty, D., Douville, E. were among the few scientists allowed to enter the caves to analyze one of the speleothems.[6] In 2009 they published "Climatic and hydrological control on trace element variations

[5] It is surprising that none of the research in the association of Palaeolithic visual motifs and acoustic response mentions that their data has been corrupted by thousands of years of speleothem growth.

[6] A mineral deposit, such as a stalagmite or stalactite, formed in a cave from the dripping of mineral-rich water

in a speleothem from the Chauvet Cave, France," [3] They reveal a detailed understanding of the chemical composition of the stalactites and stalagmites. The rate at which they have grown varied according to the climatic and geologic conditions over the 30,000+ years since the motifs were created, the end of the ice age 12,000 years ago being a major one.

Was the change enough to be significant acoustically? To get some idea of scale the average rate of growth in a limestone cave [21] is

$$0.13mm/year * 30{,}000\ years = 3.9m \quad (1)$$

That is more than 12.5 ft. If the growth rate accelerated as the ice age came to an end the estimation of the age and size of the speleothems would be scaled back accordingly. This is significant because the smaller of the stalactites/stalagmites, as seen in **Figure 7.**, may not have existed at the time the motifs were created, which would have certainly affected the acoustic response as perceived by the motifs' creators.[7] Because of the slow growth of speleothems, even rough estimations would be useful data.

Figure 7.

4.2.3. Creating an acoustic profile from existing data

The choice of an anamorphosis rather than an exact replica of the Chauvet Cave may render any direct acoustic measurement in the replica invalid as an acoustic representation of the original cave. However, the method of creating the replica's shape was based upon a high-resolution 3D laser scanning of the original cave. Jean-Michel Geneste, the Director, National Center for Prehistory, Ministry of Culture and Communication, France, describes the monumental project of creating the replica.

"*Among the array of techniques used for both the research and the replica, 3D modeling based on surveying and mapping with a 3D laser scanner was the clear choice. 3D presented the advantage of being able to process, measure, and visualize the cave's actual areas and volumes in order to rearrange them into various configurations of the replica without any loss of precision or quality."* [10]

From the existing 3D point clouds or surface models consisting of millions of points or triangles, the original interior surface of a given chamber can be accurately described, with all of its surface irregularities and speleothems.

Consulting acousticians for multi-million-dollar concert halls are highly motivated to "get it right."[8] Good studies comparing the acoustics of completed concert halls to the predicted acoustics using CATT-acoustic software, show that the software improves over time. [12] However, even the most advanced acoustic software would be taxed by the complexity within a cave as seen in Figure 7.

[7] One important question is how many of the speleothems have markings if any? Markings would indicate that there was no change at all.

[8] The Frank Gehry designed Walt Disney Concert Hall in Los Angeles cost $164M, completed in 2003. The smaller Bing Concert Hall at Stanford University cost $110M, completed in 2012.

4.2.4. Restore the acoustic profile to the best approximation of 32,000 years ago.

Since the question is: can current acoustic theory and practice be applied to the detailed measurement data acquired to precisely render the replica, be used to approximate what "they" heard?

The task, then, is to *simplify* the acoustic profile of the cave's interior, therefore simplifying the task of the acoustic software's predictive model. Working with the geological data acquired by Bourdin et al., experts in imaging processing can be tasked to eliminate, or reduce in size, the speleothems according to the known or estimated period of growth. For example, if the smaller stalactites shown in Figure 7. were the result of the increase in rate of the glacial melt at the very end of the ice age, then they could be eliminated altogether from the profile. It would seem that there would be a marked change to the acoustic response of the space.

4.2.5. Can it be done and is it worth the effort?

A large effort by an interdisciplinary team composed of geologists, acoustic space scientists and engineers, computer scientists in image processing and rendering, architectural acoustic consultants, and prehistorians, would be a formidable force to bring to the problem. But is it worth the effort?

Yes! Whether or not restoring the acoustics to the original state of 32,000 years ago would change the probability of "*an association of the location of Palaeolithic motifs with acoustic features is a statistically weak but tenable hypothesis,"*[9] the achievement of "hearing what they heard" would certainly be worth the effort, even if only in one of the chambers. The number of visitors to the replica cave the year that it opened in 2015 was 600,000! [11] And the numerous remote media presentations about the Chauvet "cave art", that included HDLAs, would let the audience "hear what ***they*** heard."

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