ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Architectural Acoustics
Session 3pAAa: Virtual Concert Hall Acoustics II

3pAAa2. Three-dimensional sound spatialization at Auditorio400 in Madrid designed by Jean Nouvel

Emiliano Del Cerro* and Silvia Mª Ortiz

*Corresponding author's address: Universidad Alfonso X el Sabio, Madrid, 28691, Madrid, Spain, ceceresc@uax.es

The auditorium 400 was designed by the team of Jean Nouvel, the French architect, Pritzker Prize winner in 2008. It belongs to the organization of the National Museum and Reina Sofia Art Centre in Madrid, and is incorporated in a special room within the cultural life of Madrid (Spain). The center collaborates with the Spanish Ministry of Culture, and organizes a series of concerts of contemporary music and electronic and computer music. To achieve the sound projection equipment, the direction of the audience chose the system Acousmonium, designed by the GRM inside the ORTF in Paris. This paper will explain the involvement of the group LIEM (laboratory for Computer and electronic Music), from Reina Sofia Museum with space in music: The musical relationships and implications of this choice, as well as the technical, architectural and signal processing techniques used for the design of algorithms for spacialization of sound. After giving a very general overview of specific algorithms for spacialization, we explain some musicals examples designed specifically for this space, and the impact of its implementation and diffusion in the auditorium400 that have very special technical and artistic features.

Published by the Acoustical Society of America through the American Institute of Physics
1. INTRODUCTION

The Auditorio 400 was designed by the team of Jean Nouvel, the French architect, Pritzker Prize winner in 2008. This space belongs to the organization of the National Museum and Reina Sofia Art Centre in Madrid, and is incorporated in a special room within the cultural life of Madrid (Spain). The center collaborates with the Spanish Ministry of Culture, and organizes a series of concerts of contemporary music and electronic and computer music. This paper explains the involvement of the group LIEM (laboratory for Computer and electronic Music), from Reina Sofia Museum with space in music: The musical relationships and implications of this choice, as well as the technical, architectural and signal processing techniques used for the design of algorithms for spacialization of sound. To achieve the sound projection equipment, the direction of the CDMC (Center for the diffusion of Contemporary Music) chose the system Acousmonium, designed by the GRM inside the ORTF in Paris.

2. MUSICAL SPACE

The parameter “space” was not considered part of music concept until recently. Nevertheless, we need to make mention of several authors that make interesting use of this parameter. The term space makes reference to three basic concepts: space and localization of sound sources, the moving of trajectory of sound, and the sense of a virtual space where the audience is just inside the sound.

First, Gabrielli made concerts for several choirs at the Venice cathedral. Lately, in the Twentieth century the North American Charles Ives and Henry Brant used several orchestras distributed in different spaces[3]. In the second half of the past century, Stockhausen, Carter, Cage, Xenakis, and others used several groups and orchestras to have the sensation of music into the space. [4] However, the big revolution took place when electronic and computers introduced technology into the music. Xenakis designed the POLYTOPE space in Paris, where he used sound and light to produce a new concept of spatiality. Stockhausen developed at Osaka World Exhibition a semi-spherical hall with 50 speakers. A new spatial designed hall for Space “Salle de Projection” was constructed at IRCAM (Institute of Recherche pour la Composition et Acoustique Musicale) in Paris. [5]
3. SPACE AND LOCALIZATION

Computers use the advantage of specially design algorithms to simulate a virtual space. Auditory localization is the human perception of the placement of a sound source. In listening to music in a concert hall, a listener receives cues for sound location from the placement of the actual sound sources in the hall. With an understanding of the perception of sound source location, the placement of the apparent source of sound can also be used as a compositional element. A 3-D sound system uses processes that either complement or replace spatial attributes that existed originally in association with a given sound source. The space can be simulated with an appropriate array of speakers.

The sense of space in an auditorium comes from the acceptance of three characteristics that can define the feeling of 3D sound: Direction, Distance, and Motion.

The direction is commonly expressed in terms of two angles: the azimuthal angle which is measured in the horizontal plane passing through the center of the listener's head; and the elevation angle, which is measured in a vertical plane bisecting the listener.

The distance is defined by concepts derived from SPL, Reverberation (D/R, Early Reflection, late Reverberation) and for the way the hall adapts the sound due to air absorption and walls material.

The motion of the sound uses the consequences of the Doppler Effect. In addition, it is necessary to mention the effect that the pinna (outside ear), produces in the sense of the sound. [6]

4. SOFTWARE ALGORITHMS

The processing the audio signal for real or virtual space can take advantage of some packets for DSP that are available for the composer sound engineer, or any other person that can be interested in this subject. In the early 80’s appeared the C program and with this development, the old music software as MUSIC V, developed for Max Mathews, took new look and C-music (San Diego University), C-sound (MIT) and C-mix (Princeton University) gave the technicians a big power to manipulate the audio signal. In the 90’s, real time technology, and C++, changed again the universe of sound processing, and programs like MAX/MSP and Pure Data, offered a new look to process the sound.

Inside this program, the theory derived from space distribution of acoustic signal, allowed the design of patches and algorithms for the auralization of a sound source.

Several techniques have been used to simulate the sense of space of a audio signal: HRTF (Head Related Transfer Function), Ambisonics, Holophony, Binaural Sound, Q-sound, and the last one and maybe the best one WFS (Wave Field Synthesis).

Among them, there are some specific for headphones, as binaural and HRTF, an others, designed for speaker situation. HRTF, can work well in a hall settings, if the transfer function is well selected, but it is difficult to introduce it in a hall with dimensions like a concert hall with dimensions as the Auditorio 400. It is very interesting because with convolution and digital filters, HRTF is able to simulate the harmonic change produced by the pinna section of the ear.

The best situation for the simulation of space in concert hall setting is accepted the Ambisonics technology. The first use of this technology was a recording with four microphones that gave information of the sound localization inside a hall. [7]

At the present moment, the computer can generate information that is introduced in the information of the sound, and gives good sense of localization.

In 1997, Pulikki [8] introduced the concept of VBAP (Vector Based Amplitude Panning), and it was the first approach to the concept of sound spatialization in programs as Pure Data and MAX/MSP.

These properties imply that VBAP produces virtual sound sources that are as sharp as it is possible with any loudspeaker configuration and amplitude panning.
The gain factors corresponding to each loudspeaker are summed up to form one gain factor for each loudspeaker. The resulting gains are normalized. The listener perceives still a single virtual source.

\[ P = g_m l_m + g_k l_k + g_n l_n \]

The VBAP implementation consists of three objects: “define_loudspeakers~”, “vbap~”, and “matrix~”. An schematic representation of the implementation is shown in Figure 2.

A VBAP object is attached to each generated sound signal. The user may design controls for direction and spreading for it. The loudspeaker setup is defined using “define_loudspeakers~”. The “matrix~” object performs distribution of sound signals to loudspeakers. When the patch is applied for different loudspeaker setups, only the settings of “define_loudspeakers~” and “matrix~” object has to be updated.

The first parameter is the dimensionality of the loudspeaker setup, which can be 2 or 3. If the dimensionality is 2, the following entries are the azimuth angles of the loudspeakers. If the dimensionality is 3, following numbers are azimuth and elevation coordinates of the loudspeakers. The directions are represented in order of the loudspeaker channel numbers.

The VBAP object calculates gain factors depending on special panning direction and on received loudspeaker setup information. It takes as input the loudspeaker setup data from object “define_loudspeakers~”, panning angle as azimuth and elevation parameters, and a parameter that controls spread of the virtual source. When the “VBAP~” object receives a bang, it performs calculations of VBAP and MDAP and outputs the gain factors for all loudspeaker channels.

The matrix~ object performs the panning process of audio signals. It receives audio signals from MSP objects and gain factors from VBAP object(s). It outputs each audio signal to each loudspeaker channel gained with corresponding gain factor. There is an “object l_delays” is used to delay the loudspeaker signals to compensate different loudspeaker distances.

### 4.1 Spatialisateur

The IRCAM developed a packet to work as part of the MAX/MSP called SPATIALISATEUR. The Spatialisateur project started in 1991 as a collaboration between Espaces Nouveaux and Ircam. Its goal is to propose a virtual acoustics processor which allows composers, performers or sound engineers to control the diffusion of sounds in a real or virtual space.

Spat~ is an effort to organize and optimize the experimental patches developed in the Spatialisateur project, in order to make them accessible to musicians and researchers who work with Max/MSP. The current release allows reproduction on multi-channel loudspeaker systems in studios or concert halls. It also integrates 3D stereo reproduction modes for headphones (binaural) or 2/4 loudspeakers (transaural), as well as Vector Based Amplitude Panning (VBAP,) and Ambisonics.
The library of Max objects which compose Spat~ is divided in three main categories of objects: DSP objects, low-level control objects, high-level control objects. The purpose of this organization is to allow easy configuration and construction of custom remote control panels or mechanisms for Spat~.

![Diagram showing the signal processing in Spat~](image)

**FIGURE 3** Schema of Spatialiteur [10]

The signal processing in Spat~ is divided in four successive stages, separating directional effects from temporal effects:

- Pre-processing of input signals (Source~)
- Room effects module (reverberator) (Room~)
- Directional distribution module (Pan~)
- Output equalization module (Decoder~)

### 4.2 Other Options

Many other composers and sound engineers have developed extensive diffusion systems involving multiple loudspeakers. Jonty Harrison, famous for his work with BEAST (Birmingham Electro-Acoustic Sound Theatre), proclaimed that eight speakers (the “main eight”) were “the absolute minimum for the playback of stereo tapes.” In 1974, François Bayle created a “loudspeaker orchestra” called the **Acousmonium**. This construction “consisted of eighty loudspeakers of various sizes placed across a stage at different heights and distances from the prosenium.”

In the late 1980s, Peter Otto and Nicola Bernardini (and others) developed a system called TRAILS (Tempo Reale Audio Interactive Location System), a “multi-loudspeaker network [consisting of] a twenty-four-by-eight spatialization matrix.” This configuration involves 192 speakers.

There is a special program designed by Ton Erbe, SOUNDHACK, where the sound can be manipulated to give any of the formats for sound spatialization: Binaural, Ambisonics, HRTF, etc.

Other program inside the MAX/MSP packet, is VIMIC (virtual microphone) where it is possible to simulate the position of several different microphones, with different information of distance, reverberation,…

### 5. AUDITORIO 400

The Auditorio 400, part of the ampliation of the Museum Reina Sofia in Madrid, adapted the system Acousmonium as sound design for the concerts that every season the Spanish Ministry of Culture offers in this hall.

The system has 32 speakers from different models and names: Meyer, Bose, Genelec, Yamaha, etc. On the stage there are 16 speakers: 4 Bose, 8 Meyer, (including 2 subwoofers), 2 Genelec, 2 Yamaha. On the audience area there are 12 Meyer around the public, as the crown in Acousmonium setting, and finally four Yamaha in the middle of the audience.
This can suggested an Area of Best Listening, just in the center of the Auditorium. The authors of this paper realized some testing and simulations to see how the speakers work in the hall. The SPL in the hall, with the entire system working, has a reasonable acceptable level.

In order to study how the Acousmonium works for the space, we simulated and study of the behavior of several speakers. Some examples of this simulation is presented in the figure 5.

In this figure, it can be seen that the SPL close to every speaker is bigger than in the rest of the area, if only this speaker is radiating energy. The area close to each speaker is not adequate for 3D-sound.
The reverberation of the hall, as it has been stated earlier, is one of the big references in localization of source. From the reverberation, the early, cluster, and late, it can be obtained special cues in the direction of the source. From these values, the hall present problems with speech clarity C50, especially when the source sound presents fragments with spoken voice, what is normal in contemporary music. From the same reason, the musical clarity C80, present problems with harmonics and definition of the qualities of a specific instrument. This is also accentuated, because the absorption in the area reduces harmonic content, depending on the situation of the listener.

6. ACOUSMONIUM

The Acousmonium, as new instrument for music diffusion was thought for “tape music” and was conceived after the ideas of Pierre Shaffer in the book “Traité de objets musicaux” where he explains the techniques for “musique concret” used from 1948. It was presented in Paris by François Bayle in 1974 inside “L’Espace Cardin” as a new Acoustic Experience.

The Acousmonium system allows two different ways to present a piece:

- Offers the piece as it is, as the final product without sound manipulation. According with the original recording, the composer or sound engineer, only need to choose which track goes to which speaker.
- Offers a real time version inside a specific space, changing some parameters of the piece, as localization of sound sources, equalization, and the introduction of some effects.

This last possibility gives the option to have a real player or group as sound source. The Acousmonium is like introducing a degree of freedom inside a fixed media like is the recording of a musical piece. The acousmatique concert offers the composer a final stage in composition process with the possibility of multiplication and diversification of listening points.

With these new possibilities, the composer or the sound technician has the possibility to change in real time some parameters of the work and have a “mise in scène” for every space and time. Among the parameters that the Acousmonium allows to control are:

- Dynamic Variation that it can depend on the hall, the public, and some external aspect outside the essence of the music. The faders of the mixer desk allow the possibility to emphasize some moments of the music.
- Color or equalization, the change of the spectrum, both, for adaptation of the hall and for coloration of the music.
- Space: The Acousmonium gives the degree to create a 3D virtual sound space, modify the distance, angles and reverb of the sound source, and change the density of the musical discourse, vertical density (harmonic content) and horizontal density (pulsation o tempo of events)

The localization of the sound comes from speakers characteristics and from the form of the music.

In this sense, it can be controlled:

- Localization of the speakers, stage, side, back, audience level, upside audience, etc.
Density of the music, changing the “orchestration” of a musical source.
- Tutti as layers of orchestral sound, like Ives proposed
- Solo as an unique source, moving and transforming itself inside the hall

Velocity of the motion of elements of the sound. This concept defines the degree of elements that transform its trajectory, as Stockhausen proposes in his early electronic pieces and in the last opera “Light”.

6.1 Lutherie of the instrument

The Acousmonium is based on:
- An Orchestra of Speakers with different color and characteristics, which will be located at stage, and around the audience. This last localization is known as “crown”
- A Mixing Desk, that will be used not for control the total sum of the sound, but the solo and individual speakers of the instrument.
- A Desk of several DSP elements: Equalization, Gates, Compressor, Expander, Reverb, etc...

The speakers must be used after a special study of power, radiation, and answer in frequency. Its implementation requires some special considerations.

The crown can be used as reference, for power amplification, for proximity of sound and for distribution of sound sources. The speakers must be able to create a virtual sound space, for what is require a dissymmetry.

The Mixing Desk, and some DSP associated with the mixer, allow Effects: (sound planes, solo source, sustain); EQ (low, medium and high area of spectrum, Presence high area of frequency) Cross Planes and Velocity (distance, trajectories) and Inclination, (delay, and other considerations).

The Acousmonium, is like a musical instrument, that, besides its origin, can be used for new sound algorithms for spatialization, as VIMIC, Ambisonics, HRTF, Spatialisateur, etc.

7. MUSIC FOR SPACE AT AUDITORIO 400

The LIEM has a special dedication to music though for the space and for the use of the Acousmonium system. There have dedicated several concerts and courses to the music composed taking advantage of 32 speakers. This center organizes a summer festival, in which through the years, the most important musical pieces written for musical space, were presented. It can be mentioned pieces by Xenakis, Stockhausen, Risset, etc.

It must be observed also, that the GRM group offered a concert in the Auditorium 400 at 2007 with several pieces written for the Acousmonium system. Inside the program, it was included the piece “On the stillness on the water” by Emiliano del Cerro in which the work has 10 different sound sources distributed over 10 channels of Audio. This work was a commission on the Spanish Public Radio RTVE and was recorded at SUNYAB studios in New York.

FIGURE 7. Display and setting of “on the stillness of the water” [12]
“On the stillness of the water” is written for soprano, 5 different readers in 5 different languages and a brass quintet. The English text and Aria music is all over the 10 speakers. The different languages (Spanish, German, French, and Japanese are over 2 stereo speakers in different configuration.

The space in this piece is achieved by the method of cutting short fragments of sound files by computer algorithm, using statistic distribution (Gauss, Poisson, …) and distributed them over the speakers, with aleatoric function and the same statistic distribution,

In this way the piece present the use of sound planes, with distance, intensity and angles of situation.

8. CONCLUSIONS

The Auditorio400, designed by Jean Nouvel, has some dimensions that make it appropriate for chamber music and electroacoustic music. The introduction of Acousmonium was a decision of the LIEM (Laboratory for Computer and Electronic Music), and it works reasonably well with electroacoustic music.

The Acousmonium, joint with appropriate software and hardware, can address in an appropriate way the concept of space in a musical discourse. Every single speaker of the crown setting creates a problem of proximity for auralization simulation. The solution has been, in first instance, the introduction of four speakers just inside the hall around the central area of the audience. This solution originates an additional problem, due to the directivity of these four speakers. A new solution can come from the use of speakers with option of change of directivity. This property is being investigated in these moments. Nevertheless, the Auditorio400 has its big problem in the reverberation time in the hall, derived from its geometry and its absorption levels. This is especially serious when the sound source includes spoken voice, because the clarity of the source is reduced.

9. REFERENCES

[9] www.cycling74.com