Portfolio of Original Compositions

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Julián Ávila Sausor

School of Arts, Languages and Cultures

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Word count: 13,379

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Portfolio of musical works

Title	Year[1]	SD[2] level	Media	Duration
Crescencia	(2014)	1	symphonic orchestra	12:13
Travesía	(2015)	2	collaborative installation	Indefinite (8min. aprox.)
Kantaber	(2015)	1,2	Amplified tuba	12:53
Pronomos Space [e]	(2015)	1,2,3	Ponomo flute & electonics	07:56
Time Folds II	(2016)	1,2	Ensemble & Helmholtz resonators	07:09
Unfold	(2016)	1,2,3	Alto flute & electronics	14:12
Garabatos	(2016)	1,2,3	Cl., VC., Perc & electronics	08:52
Worstward	(2017)	1,2	Bass clarinet & electronics	10:47
Low	(2017)	1,2	Guided improvisation for BCl., SBFl., Tba. & electronics	15:00
Casicristal III	(2017)	1	Fl., A.Sax., Pno., V., Vla., VC.	7:57

Total time 97:59

[1] Chronology of works do not correspond to a sequential development of SD levels.
[2] Spectral Diffusion (SD).

List of performances

Crescencia	26 and 27-12-2015, Orquesta y Coro de Radio Televisión Española, Madrid.
Travesía	From 27th of February to 3rd of March 2015, ARCO[3] Casa del Lector - Matadero Madrid.
Pronomos Space [e]	22-06-2015, Julián Elvira, The Segal Theater, The City University of New York.
	17-09-2015, Julián Elvira, MANTIS festival, Manchester.
	12-12-2015, Julián Elvira, BBVA Foundation, Madrid.
	04-03-2016, Julián Elvira, Conservatori Superior de Música de València.
	23-04-2016, Julián Elvira, Sa Nostra fundation, Palma de Mallorca.
	01-09-2016, Julián Elvira, Cras Músicas, Barge House, London
	08-11-2016, Julián Elvira, Cruce art gallery, Madrid.
	10-11-2016, Julián Elvira, Medialab Prado, Madrid.
	09-12-2016, Julián Elvira, La Casa Vieja, Albacete.
Time Folds II	28-11-2016, Vertixe Sonora, 400 Auditorium, Madrid.
Unfold	29-02-2015, Gabin Osborn, MANTIS Festival, Manchester.
	23-02-2017, Julián Elvira, Colegio de España en París
Garabatos	09-11-2017, CSMCLM ensemble, New Music Festival, Rauch Planetarium, Kentucky.
Worstward	23-02-2017, Marij van Gorkom, Colegio de España en París.
	04-03-2017, Marij van Gorkom, MANTIS Festival, Manchester.
	08-03-2017, Marij van Gorkom, The Monfort University, Leicester.
Kantaber	23-02-2017, Sérgio Carolino, Colegio de España en París.
Low	23-02-2017, Julián Elvira, Marij van Gorkom and Sérgio Carolino, Colegio de España en París.
Cuasicristal III	11-06-2017, United Instruments of Lucilin, ENSEMS festival, València.

[3] Madrid International Contemporary Art Fair.

List of awards and commissions

-ORTVE commission of *Crescencia*, 2015.

-Prix de composition musicale 2015 Colegio de España/INAEM Instituto Nacional para las Artes Escénicas y la Música.

-Colesp/INAEM comission of *Low*, 2016.

-Francisco Guerrero Marín award in XXVII 2016 Premio Jóvenes Compositores Fundación Sgae-CNDM.

-CSMCLM – ERASMUS+ commission of *Garabatos*.

List of publications

Ávila, J., 2016. Koch's Space. In G. Bresson, Jean; Agon, Carlos; Assayag, ed. *THE OM COMPOSER' S BOOK III*. Paris: Delatour.

Ávila, J., 2017. *Cuasicristal III*, Madrid. Available at: https://www.amazon.es/Cuasicristal-III-saxophone-violin-Cusasicristales/dp/197317684X [Accessed March 3, 2018].

Ávila, J., 2016. *Time Folds II*. In *XXVII Premio Jóvenes Compositores Fundación Sgae-CNDM*. Madrid: Fundación SGAE.

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  - Crescencia Score
  - Crescencia ST Premiere Recording - RTVE Orchestra.wav
  - README_Crescencia
- 6.2_Travesía
  - Patch and Audios Travesía
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  - Travesía Video.mov
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Abstract

This portfolio of original compositions presents ten pieces which investigate the potential of applying Spectral Diffusion techniques to music composition. The main objective is to explore new possibilities for creative expression through the identification of the full potential of these techniques and their application to a range of different musical genres.

The systematisation of Spectral Diffusion methodologies is organised into three different levels of complexity, which represent the depth of these techniques and the new compositional vocabulary emerging from them.

As a result, this portfolio provides examples of the usability of Spectral Diffusion integrated in the field of mixed media composition and instrumental music in computer aided composition, including ensembles of acoustic instruments, solo pieces, live improvisations and interactive installations.

Declaration

I hereby declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or any other institute of learning.

Copyright Statement

Acknowledgements

I am very grateful to the University of Manchester for giving me the opportunity to study in this great research centre. Moreover, over the three years that I have spent in my research I have also learned how one of the best universities of UK is organised. I also thank the School of Arts and Languages for funding my PhD studies with a McMyn fellowship.

I have really enjoyed being part of the NOVARS research community and having at my disposal all the facilities and resources to work on my PhD.

I would like to thank Prof. Ricardo Climent, for encouraging and guiding me throughout the PhD journey. Also thanks to the studio director, Prof. David Berezan, for sharing his deep knowledge of the acousmatic field and spatial research.

This work could not be completed without the huge contribution from performers such as, Julián Elvira, Sérgio Carolino, Marij van Gorkom, Gavin Osborn, United Instruments of Lucilin and RTVE Orchestra.

Finally, I would like to dedicate this thesis to two very important women in my life. Firstly, to my wife Amparo who is my reference as a model human being. And secondly, to my daughter Martina, who despite being nine months old at the final stage of submission, kindly allowed me the time to finish this PhD.

1. The concept of Spectral Diffusion (overview)

Spectral Diffusion (hereinafter SD) is a sound processing technique in which two sub-processes are involved. Firstly, the frequency domain is decomposed into frequency bands. Secondly, these frequency bands are spatialised or located in the performance space. The term *Diffusion* refers to the spatial aspect of this technique. *Spectral* references the fact that the spatialisation is related and linked to the frequency content of a sound.

Spatialisation of sound has been well studied[4]. A considerable number of tools are available to spatialise sound in many different ways using different systems. Similarly, filtering by frequency analysis is a common technique in electroacoustic composition. Although there exists compositional research focusing on the two key individual elements (spatialisation or spectral content), there is less research and compositional outcome focused on how to successfully embrace both.

<u>Examples of SD in other fields</u>

Although SD might be seen as very specific to sound process, it is present in a number of other fields.

In radio frequency band organisation, country legislation often dictates which bands of radio frequency (in the telecommunications spectra) should be used in media broadcast. Similarly, digital TV channels have a fixed band width and have frequency constraints. Comparably, emergency service telecommunications, Wi-Fi or free spectral bands for wireless audio communications are defined and organised across the radio-frequency spectra.

In nature, as described by Bernie Krause in the book *The Great Animal Orchestra* (Krause 2013), Krause depicts audio using spectrograms of how natural ecosystems have a particular spectral footprint in which each animal species or living organisms occupy different spectral bands. In this case, a concrete spectral division, as well as a spatial distribution of them, depends on the observed ecosystem. Krause uses this phenomenon to demonstrate how different environments have been damaged over decades, losing their spectral richness.

[4] See **Three-level system** (3rd level of SD) in chapter 4.

In the field of biophysics, *Spectral Diffusion* is the term that describes a process for analysing liquids (Stein & Fayer 1992) or proteins (Fritsch et al. 1996) using Fast Fourier Transform[5] (hereinafter FFT) techniques similar to those used in sound analysis.

Figure 1 shows band divisions and subdivisions in the electromagnetic field (as used in biophysics and radio frequency communication) and sound spectra division created by different instruments.

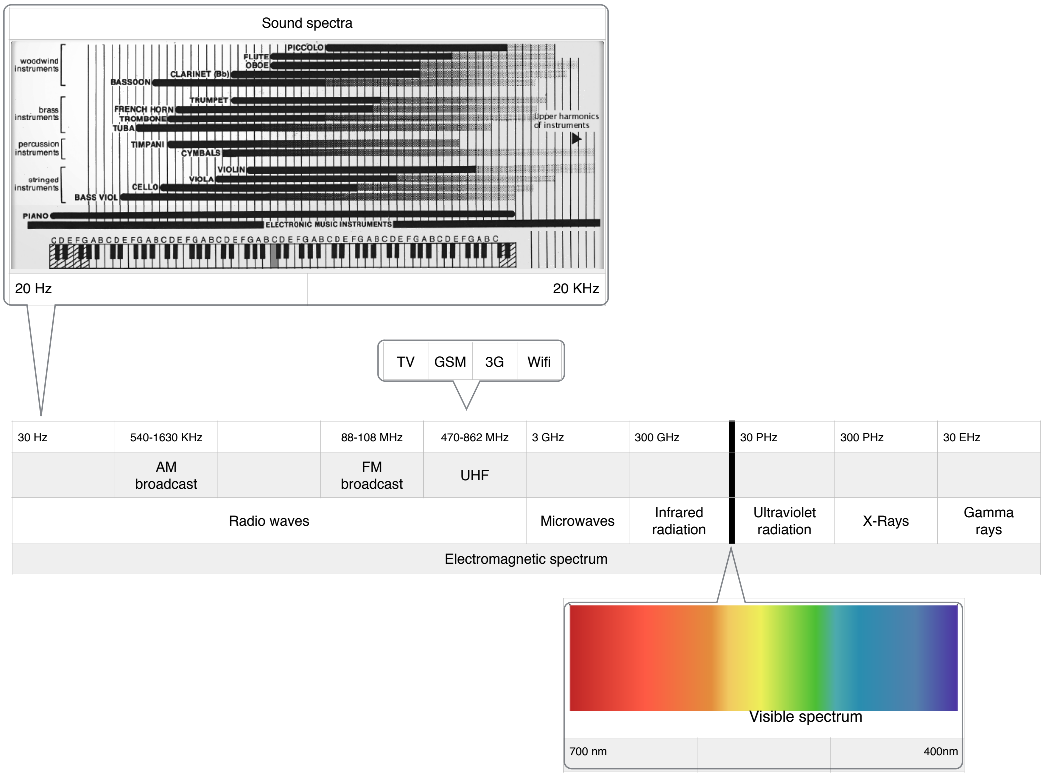

Figure 1. *Band frequency table in electromagnetic spectrum and sound spectra.*

This portfolio does not directly transfer these examples into the compositional field, however, it is informed by them. In the same manner, related techniques mould the emerging vocabulary from SD, a vocabulary which has been employed in this composition portfolio.

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[5] A Fast Fourier Transform (FFT) is an algorithm that relates time and frequency. In music is widely used to analyse spectral content and time transformations.

Implementations of SD in composition

Digital Signal Processing and FFT analysis as a creative process are found in many electroacoustic music compositions which make use of signal analysis and processing for the transformation of sonic materials. These include convolution, cross-synthesis, vocoders and spectral gates, to mention but a few. They use FFT analysis and resynthesis as a way to transform sound in the frequency domain.

Another example of FFT application in composition is spectralism[6]: frequency analysis and resynthesis via instrumental forces. This school of thought uses FFT sound analysis as a way to identify sonic features to be used as ground material for instrumental resynthesis. These include partial tracking, virtual fundamental, interpolations, modulations, frequency shift, etc.[8]

Although this research is not based on spectralist compositional techniques it does share some of the concepts and methods of spectral analysis and band division. However, it takes it further by linking them to sonic diffusion and spatialisation techniques. It does so by providing each individual band with its own spectral energy, different from the original sound source. As a result, the spectral energy will always be a consequence of band division and will be dependent upon the spectral content of the former sound.

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[6] *Spectralism is a tendency in contemporary art music that takes the material attributes of sound as the point of departure for composition. Originating in France and Romania in the 1970s, partly in reaction to the perceived hegemony of serialism and other high modernist styles, since the 1980s the influence of spectral ideas and techniques has spread across Europe, Asia, and North and South America. Its most prominent representatives are Gérard Grisey (1946–98), Tristan Murail (1947--), and Horatiu Radulescu (1942-2008).* (Drott 2016)

[8] To mention a few spectral techniques (Fineberg 2000).

Pre-Thesis investigation

This author's[9] interest in this technique starts before the beginning of this PhD thesis. In works such as *Blau*[10] (for ensemble and electronics) and *Koch's Space*[11] (for saxophone and electronics) the germ of this compositional technique is intrinsic in the language and grammar of these two pieces. In *Blau*, the score is restricted to a range of one octave only and divided in bands or small clusters, mimicking the effect found in colour spectra division. One of the roles of the electronic part is to spatialise these clusters in the surrounding array of loudspeakers. In *Koch's Space,* a Koch fractal is used to shape and enhance the instrumental part and to create a band-pass topographic filter[12] that is projected via loudspeakers from behind the audience, creating a type of sonic shadow of the saxophone sound. These pieces could be seen as a proto-SD since both use concepts related to SD in the instrumental and electronic formalisation.

At the core of this PhD research is the idea of dividing sound spectra to create a spatial formalisation which aims to connect timbral with spatial sound properties in the concert space.

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[9] Brief information on this author's musical background: nowadays he works as a Lecturer in Electroacoustic Composition at CSMCLM (Castilla la Mancha Conservatory). He is invited lecturer for the Master of Ephemeral Arts programme at Madrid Polytechnic University.
He focuses on the area of electroacoustic composition based on space and multidisciplinary projects, specialising at NOVARS in Manchester, IRCAM in Paris, University of Alcala de Henares in Madrid, and CDMC (Centre for the Diffusion of Contemporary Music in Madrid).
Music Degree in composition and saxophone at RCSMM (Madrid Royal School of Music). A Master's Degree in Performing Arts at URJC (King Juan Carlos University). Advanced contemporary composition course at CSMA. Sound technician course at the Centre of Technology for the Performing Arts of INAEM (Ministry of Culture, Spain).

[10] This work is attached to this portfolio as an annex A.

[11] This work is attached to this portfolio as an annex A.

[12] A topographic filter is a filter where one or more parameters of the filter are linked to spatial sound position, e.g. cut frequency, quality factor, etc. (Ávila 2016).

2. Research enquiry: Spectral Diffusion and sound energy as a compositional focus.

SD has been considered until today as a spectra-spatial sound process (similar to other signal processes such as flanger or filtering), at the composer's disposal. At the core of the enquiry is whether the formalisation possibilities of SD and its application in instrumental music can provide deeper levels of musical expression and open new avenues of sonic expression.

Another important aspect of the investigation is to understand (if not demonstrate) whether SD can become a compositional tool (beyond being a straight-forward sound processing technique) capable of creating new methods for the formalisation of musical ideas and novel musical thinking hitherto constrained by the connections and interferences between timbre and space.

This research will address the core of the enquiry by providing an original corpus of musical compositions. The research has been structured and driven by the new vocabulary emerging from SD and is also informed by pre-existing spatial and spectral musical literature.

The principal hypotheses, and their related research questions, are:

1. SD can be a compositional technique by itself.
    - Does this technique facilitate the creation of new avenues of musical expression?
    - Can SD cohabit with other macro formal organisation techniques in music composition? E.g. fractals, mathematical models, etc. and if so, what forms of relationships will emerge? E.g. in terms of musical structure, form, sound organisation, to mention but a few.

2. Musical structure can be formalised by SD techniques.
    - How many typologies of SD can be used in musical formalisation?
    - Which aspects of SD techniques are more successful (depending on their application to different acoustic and electronic forces and musical genres)? E.g. instrumental music with live SD versus fixed SD, interactive multimodal installations, improvisations, etc.

3. Spectral Diffusion up-to-date.

SD techniques are often found as signal audio processes in which FFT analysis and resynthesis are used as the main tool for connecting sound spatialisation and frequency. Since the 1990s, when FFT sound processes became a standard for spectral analysis (and resynthesis), SD has received different names (as listed below), although they describe similar processes. Although thre is plenty of musical research and composition based on the use of FFT, as part of the compositional methodology, there is much less investigation which focuses on the connections between sound spectra and spatial diffusion, which go beyond creating an '*interesting musical effect*' (Kim-Boyle 2004).

In this chapter, different points of view related to signal audio processing are outlined, where frequency is linked to spatialisation over the last 20 years.

In 1994 the idea of creating spatialisation linked to frequency arose: *'Frequency Dependent Spatialisation'* (Settel & Lippe 1994). This sound process highlights the possibilities of IRCAM's *Signal Processing Workstation* and the Max programming language. This is in addition to other FFT techniques such as convolution, cross-synthesis or spectral gates. The main idea behind this paper on '*Frequency Dependent Spatialisation*' is that it is possible to change the energy of each bin[13] or FFT band to create a panning image of the sound and to allocate each bin into different positions between two loudspeakers.

A follow up paper explained how to implement this technique in stereo or quadraphonic systems. In this article the idea of spatialising sound linked to frequency is named *'Spectral Spatialisation Technique'* (Torchia & Lippe 2004). This explored the possibility of making divisions of 64, 128 or more bands (powers of 2 that matches half of the FFT window size), and their spatialisation in stereo or quadraphonic systems. In addition, a process module is implemented in order to achieve circular distribution of binaries in a quadraphonic system.

In 2004, Keyes explains how to root a stereo signal in a system of 8 loudspeakers using a SD technique called *'Spectral Spatialiser'* and defined as *'frequency-domain filtering to spatialize (one could also use the term 'animate') stereo sources over an even number of*

[13] A bin is each FFT band defined by $Number\ of\ bands = \frac{\textbf{FFT window size}}{\textbf{2}}$; Eg. if 512 samples are defined as a FFT window size, there will be 256 FFT bands or bins.

playback channels' (Keyes 2004). This sound processing proposal could be seen as an extension of the previous proposal but using stereo sound as input source.

The papers reviewed so far handle spatiality between pairs of loudspeakers from the point of view of ILD[14] (Interaural Level Difference). It seems logical that ITD[15] (Interaural Time Difference) could also be used as a system for virtualising sound sources. Nevertheless, the problem with this idea is that the minimum delay of a FFT process is determined by window size. Using the minimum window size obtains a minimum delay of 11 milliseconds approximately, while ITD delays around 0 to 0.6 milliseconds. Kim-Boyle designed a method to work around the problem. His*'Spectral Delay'* is able to create, in the author's own words, *'interesting musical effects'* (Kim-Boyle 2004).

Kim-Boyle proposes another implementation for spectral spatialisation based on the spatial principles of Torchia & Lippe (2004). In this case a *boids*[16] algorithm controls the location of the different bands of frequencies. The big difference with this implementation, as well as the previous ones, is that band division is dissociated from spatialisation; on the one hand, the FFT processes band division, and on the other hand, the *boids* algorithm processes the spatialisation. Spatialisation, however, is still implemented as a quadraphonic system (Kim-Boyle 2006). In addition, Kim-Boyle wrote a paper, *'Spectral Spatialization – An Overview'* in which all the techniques explained are reviewed, adding the possibility of controlling spectral spatialisation by stochastic means (Kim-Boyle 2008).

The solution that is closest to SD is described by Normadeau as *'Timbre Spatialisation':*

> *'What is unique in electroacoustic music is the possibility to fragment sound spectra amongst a network of speakers. […] This is what I call timbre spatialisation: the entire spectrum of a sound is recombined only virtually in the space of the concert hall' (Normandeau 2009).*

This concept is implemented in works by Normandeau (for example in *Clair de terre* 1999-09*, StrinGDberg* 2001-03*, Éden* 2003 *and Palindrome* 2005-07) using 4 band-pass filters for splitting a source sound and routing each filter output to one loudspeaker. When one or

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[14] ILD, interaural level differences that our ears receive when listening a sound and our brain uses for locating a source in space. ILD is recreated in panning systems for sound virtualisation, for example mixers, plugins, etc.
[15] ITD, interaural time difference that our ears receive when listening to a sound and our brain uses for locating a source in space. ITD could be implemented for virtualising sounds in space by delaying one channel between 0 and 0.6 milliseconds.
[16] *Boids* algorithm implements the movements of flocks of birds in Max.

more parameters of the band-pass filters change in time domain, the concept of a *'Dynamic Filter'* emerges.

Two more concepts that resemble SD are *'Spatial Decorrelation'* and *'Spectral Splitting'*. The first one is related to the paper *'The Decorrelation of Audio Signals and Its Impact on Spatial Imagery'* (Kendall 1995) and implies different audio processing techniques for decorrelating[17] a sound source and routing each output to one loudspeaker . The second term is very close to SD nevertheless its focus is on the sound quality difference of loudspeaker systems:

> *This notion perhaps has it origins in non-homogenous loudspeaker systems intended for diffusion, in which, due to the varying frequency responses of different loudspeakers, their relative proximity and orientation, the onset times of different sounds or components, and a number of psychoacoustic considerations, sounds seem to separate out spatially to different parts of the array.(Wilson & Harrison 2010)*

There is a follow-up paper entitled *'Considerations on the Handling of Space in Multichannel Electroacoustic Works'* (Barreiro 2010), in which the term *Spectral Diffusion* is included and attributed to Keyes (Keyes 2004), notwithstanding, this term does not appear in Keyes's text. For this reason, the term *Spectral Diffusion* can be attributed to Barreiro. In Barreiro's 2010 article, there is an implementation of an SD system for Max in which FFT bins are grouped to create bands. That means that the bandwidth is not determined by FFT window size but by the length of each band, and each frequency band is integrated by one or more FFT bins.

Lynch and Sazdov in 2017 introduce another term and technique, *'Dynamic Spectral Subband Decorrelation'* (Lynch & Sazdov 2017). This research emerges from a previous paper in which this technique is included as a *'future work'* (Lynch & Sazdov 2011) and later in Lynch's thesis (Lynch 2014). *'Dynamic Spectral Subband Decorrelation'* consists of applying the same technique as in Normandeau's *'Timbre Spatialisation'* and decorrelating the output of each band-pass filter by adding different delay times to each loudspeaker. This technique could be seen as a sort of spectral diffusion delay.

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[17] Sound decorrelation *'refers to a process whereby an audio source signal is transformed into multiple output signals with waveforms that appear different from each other, but which sound the same as the source*" (Kendall 1995). These multiple outputs can be obtained via reverb, chorus, delay and filters, to mention a few.

The above studies have focused on SD techniques in a direct or indirect way. In this PhD, the SD form has been used to reference any sound process or compositional process in which frequency is linked to spatialisation. Similarly, most of the articles that have been referenced in this chapter have two things in common: 1) band division is obtained through FFT and 2) spatialisation is driven by changes of intensity in the FFT bins. As a result, a simple panning is used to spatialise sound.

Nonetheless there are other filtering techniques that could be applied to SD to obtain band division; for example, traditional filters, bandpass filters with more or less overlapping, etc. There are also a number of spatialising procedures (Vbap, Spat, Ambisonics, etc.) which are not discussed in these papers.

In the chapter *'New methods of spatialisation based on sound analysis'* (Roads 2015) and referring to Torchia & Lippe (2004), Curtis Roads says:

> *"These are all experimental methods. Analysis-based spatialisation methods face both technical and aesthetic challenges in terms of choosing appropriate sounds for applying them, as well as issues of interactive control. Effective use of these techniques will likely require a great deal of testing and tuning." (Roads 2015, p.251)*

4. Levels of Spectral Diffusion

The systematisation of the compositional process

For the purposes of this investigation and in order to systematise and catalogue the use of SD and to analyse all the combinatorial possibilities of the technique, three levels of SD have been established. This classification is based on compositional parameters that are controlled by SD. As a result, there are pieces in which only one level of SD has been used and there are other works in which any combination of levels of SD simultaneously are possible. This means that the simultaneous use of different levels of SD is not incompatible as each level controls different musical parameters.

One-level system (1st level of SD)

At this level, concepts and techniques of spectral diffusion are applied to instrumental composition. Consequently, harmonic material is divided into bands, and those bands have characteristic processes of band frequency transformation (for example, elastic deformations, divisions into glassy systems[18] or disordered systems, etc.). This is the same idea that Grisey applies in *Partiels* (Grisey 1978), but with a new technique. In *Partiels,* the concept of additive synthesis is applied to harmony and orchestration, transforming an electroacoustic technique (additive synthesis) into a technique for orchestration. In this case, the parallelism is the same since the techniques of SD in the electroacoustic field are applied to instrumental works.

Of the three levels this level represents the most open framework, due to the fact that the application of band division could be handled in many different ways and applied either to vertical or temporal organisation. Similarly, this level is largely metaphorical in terms of the spatial element as instrumental forces have spatial limitations compared to electroacoustic media.[19]

The main aspects dealt with at this level include examples of successful applications as well as a glossary of terms that have developed into a specialist vocabulary. (Listed in the next chapter).

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[18] Glassy systems and other novel SD terminology are explained in chapter 5.
[19] The spatial element in the 1st level of SD resonates with Smalley's *Spectral Space* that is also a metaphor of spectral content. Similarly, the spatial element in the 1st level can be seen as a metaphor of harmonic formalisation (as happens for example in *Cuasicristal III*).

Two-level System (2nd level of SD)

At this level, SD techniques are applied to electroacoustic forces. There are two principal variables; the first one is the loudspeaker band division, and the second one is the features of the sound that are introduced in the system. These two variables can be dynamic or static. A static surrounding matrix is a glassy system in which all the band ranges are fixed and, therefore, no changes can be applied. In contrast, a dynamic system is a surrounding matrix with elastic deformations in the time-domain. In these systems, the features of the sound introduced in the surrounding matrix represent another variable that interacts with the final diffusion of the sound through the system. If the sound is static (with no changes over time), it will spread into space according to band division and distribution, although it will not change in time, therefore it will be a topographic filter.[20] If the sound has variations, the content of each band will change and the diffusion of sound will vary.

In this level, as well as in the third, there are several techniques that could be used to divide spectral content into bands. For instance, traditional filters, biquads, FFT process, etc. The use of one or other of these techniques does not change the essential two variables in the level (band division and loudspeaker routing). As a consequence, these are technical elements that do not affect the level definition.

Most of the readymade tools available to perform SD are suitable to implement this level of SD (Eg. BeastTools[21] or plugins such as MSpectralPan[22]). Nevertheless, there is room for new implementations and specific developments applied to particular compositions inside the second level of SD.

Three-level system (3rd level of SD)

A three-level system consists of adding the last possible variable to the previous level. This new variable is applied to the position of the bands in the concert space. At this level, the different audio signals of each band are not routed to a single loudspeaker. Rather, each audio signal is one audio source that is moved inside the performance space using any of the spatialisation tools available, for example Vbap (Pulkki 1997), Spat (Carpentier et al.

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[20] A topographic filter is a sequence of band-pass filters each one allocated in a different position inside the concert space.
[21] Beast Tools are multichannel sound tools programmed for developing sound material. https://www.birmingham.ac.uk/facilities/ea-studios/research/beasttools.aspx
[22] MSpectralPan is a plugin that allows panoramas at each individual frequency. https://www.meldaproduction.com/product/keyword?keyword=free

2015), Ambisonics (Malham & Myatt 1995), etc.[23]

In this level, the variable of sound spatialisation is added to the variables of the previous level. Whilst in the second level, the spectral bands are directly routed to a loudspeaker, in the third level each spectral band is treated as a sound object that will be spatialised with 2D or 3D virtual sound systems.

Figure 2 depicts the three levels of SD as well as the combinatorial possibilities:

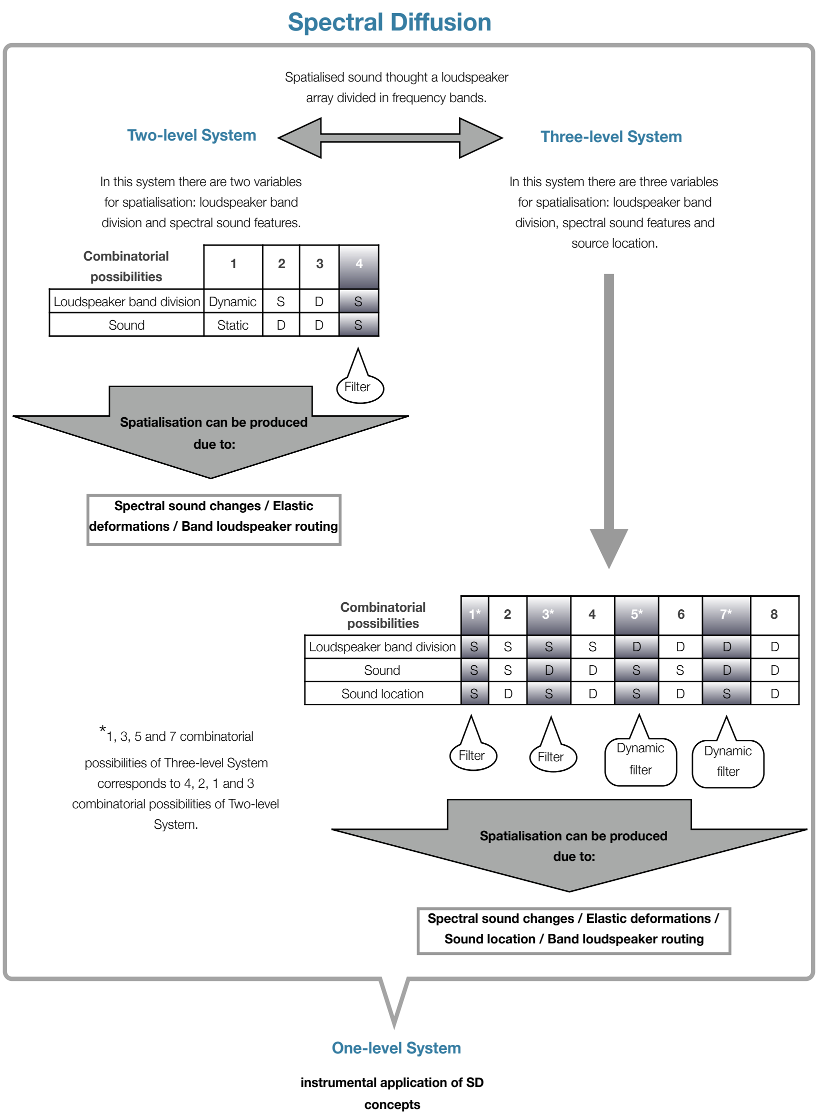

Figure 2. *Conceptual synthesis of SD levels.*

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[23] (Begault 1995; Baalman 2010; Bates et al. 2007; Bates 2009) have guidance on the use of the different spatialisation techniques available in terms of source location accuracy in each piece included in this research.

Figure 3 shows a block diagram of the step processes of the 2nd and the 3rd level of SD enhancing the similarities and differences between both levels.

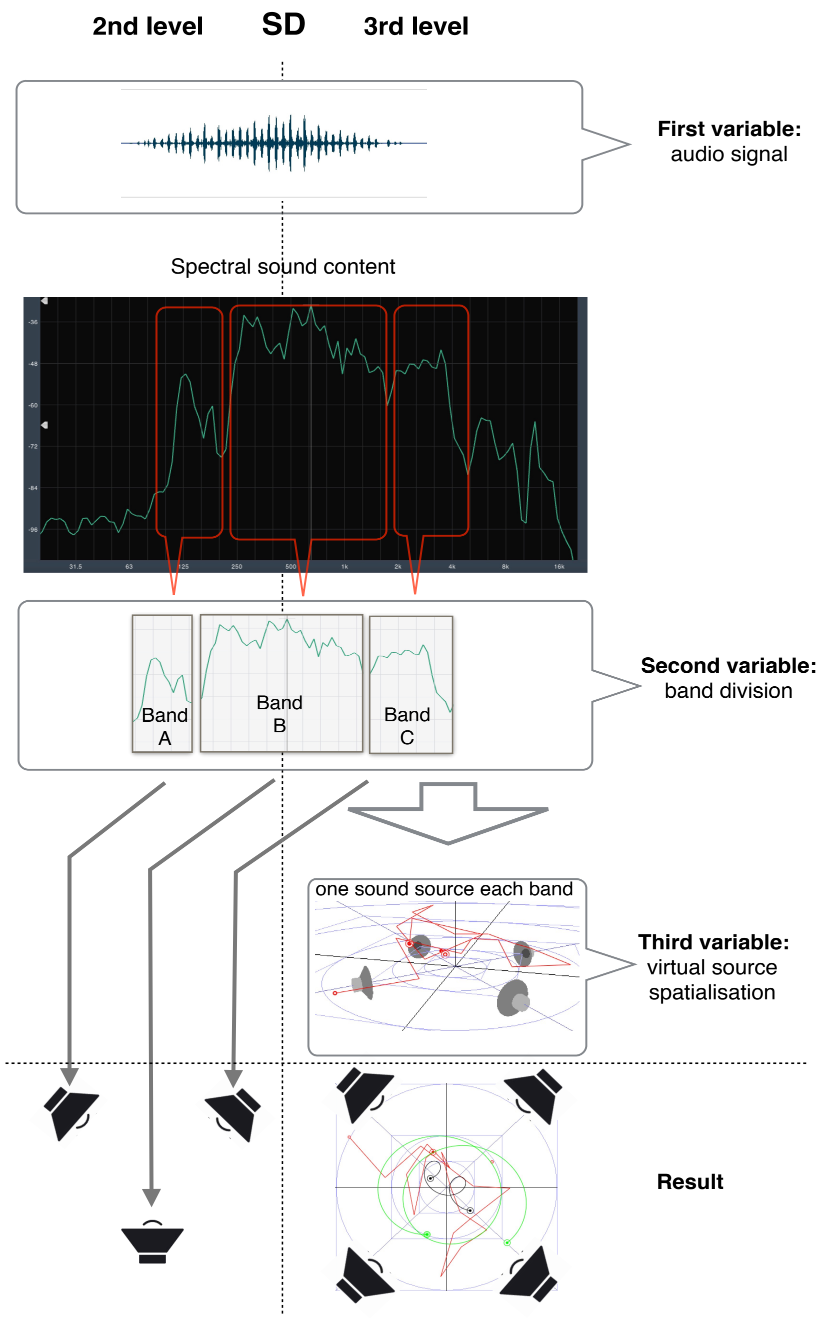

Figure 3. *Differences and similarities between 2nd and 3rd level of SD.*

5. Vocabulary developed in this research

The rationale for developing tailored vocabulary and grammar surrounding the implementation of SD techniques in composition stems from the fact that existing literature often focuses on typologies of sound spectra or spatial spaces and forms. However, in the context of this investigation, which mainly covers the application of electronics to instrumental forces, not enough vocabulary exists to describe the merging of timbre and space.

To develop an adequate vocabulary, this investigation focuses on the relationship between the terminology found in Spectral Diffusion in biophysics[24] (to determine the vocabulary of 'Levels') and Spectral Diffusion in the context of this portfolio. It also includes reference to existing terminology found in Space and Spatial Audio.

However, this does not mean that SD composition in this research has been driven by biophysics processes, even if the terminology used in SD in biophysics has inspired new terminology applied to SD musical composition. For example, papers such as *Spectral diffusion and the energy landscape of a protein* (Fritsch et al. 1996), *Spectral diffusion in liquids* (Stein & Fayer 1992), *Vibrational line shapes and spectral diffusion in fluids* (Skinner 2007), or *Spectral Diffusion and Electron-Phonon Coupling of the B800 BChl a Molecules in LH2 Complexes from Three Different Species of Purple Bacteria* (Baier et al. 2009), have simply informed and influenced terminology decisions, which the author has found more suitable for this investigation, in preference to other sources of spectral and spatial vocabulary.

Figure 4 presents new terminology[25] applied to SD in musical composition, its compositional concept, Smalley's closest Space-form[26] definition and relevance in the different pieces of this portfolio.

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[24] According to Miller-Keane Encyclopedia and Dictionary of Medicine, biophysics is '*the science dealing with the application of physical methods and theories to biological problems*.
[25] Special font format has been used for referring to this new terminology in order to avoid extra foot notes referring to this figure. Eg. *burning frequencies*.
[26] Refers to *Space-form and the acousmatic image* (Smalley 2007).

Term	Compositional concept	Smalley's closest definition	Comments / Alternative definitions	Crescencia	Travesía	Kantaber	Pronomo's Space [e]	Time Folds II	Unfold	Garabatos	Worstward	Low
One-level system (1st level of SD)	SD techniques applied to instrumental music			x		x	x	x	x	x	x	x
Two-level system (2nd level of SD)	System with two variables: band division and spectral sound variations				x	x	x	x	x	x	x	x
Three-level system (3rd level of SD)	System with three variables: band division, spectral sound variations and band location						x		x	x		
Band	Portion of frequency domain			x	x	x	x	x	x	x	x	x
Neighbour band	Contiguous bands			x	x	x	x	x	x	x	x	x
Transition	Overlapping frequencies between bands							x				x
Spectral jumps	Neighbour bands without transitions				x	x	x		x		x	
Surrounding matrix	One particular distribution of bands in the space	***Circumspectral space:*** *The spatial distribution or splitting up of the spectral space of what is perceived as a coherent or unified spectromorphology.*	Only the first part of the definition applies. The aim is not to present a unified spectromorphology sound but to explore timbral-spatial characteristics of a sound.		X	X	X	X	X	X	X	X
Spectral position	Place in the space of a determinate frequency or band of frequencies					x						
Elastic deformations	Band limits changes in time domain	***Diagonal Forces & Planes:*** *The motion of spectral energy towards or away from a spectral region which acts as a plane. Planes can be expressed or implied.*	Also could be seen as a change of spectral energies of bands.	x			x				x	
System impurities	Duplication of frequencies in 2 o more different bands									x		
Holes	Loss of some frequencies or bands									x		
Burning frequencies	Enhancement of frequencies or bands of frequencies				x			x				x
Blinking	Sound that is situated in the boundary of a band and changes between bands due to sound changes or elastic deformations			x		x						
(Ground) states	How a concrete sound is divided into the system or surrounding matrix	***Spectral Space:*** *The impression of space and spaciousness produced by occupancy of, and motion within, the range of audible frequencies.*	Combination of Ground State and Surrounding Matrix	x	x	x	x	x	x	x	x	x
Glassy systems	Band limits that do not change its range	***Scale:*** *Relative Scale across spectromorpholgies.*			x		x	x				
Disordered systems	Random distribution of bands									x		x
Asymmetric system	Non-integer relationship between band distribution									x		x
Jump rate	When all bands are equally distributed, there is a jump each X Hz or Y musical interval	***Tonal Pitch Space:*** *The subdivision of spectral space into incremental steps that are deployed in intervallic combinations - a sub-category of spectral space.*	Not necessary intervallic combinations.				x					
Wander / Sound wandering	Fast change of sound location between bands because of the nature of sound or huge elastic deformations			x		x						
Surrounding matrix	Each speaker that configures the system				x	x	x	x	x	x	x	x

Figure 4. *SD terminology applied to composition related with Space-form and portfolio works.*

6. Corpus of works addressing each level of SD

In this chapter, the works composed during this research are discussed in terms of their contribution to SD development and levels of SD application. This does not mean that pieces are fully analysed; only the aspects related to SD are considered in this chapter.

6.1 *Crescencia* [1st level of SD]

For symphonic orchestra (12:13 min.). Instrumentation: 2+1, 2+1, 2+1, 2+1/ 4, 4, 2, 1, 1 / Timp., 3Perc. / 12, 12, 8, 8, 6.

Crescencia is a SGAE[27] Foundation and AEOS[28] commission for the Spanish Radio TV Orchestra and Choir. This piece was premiered during the 2015/16 season.

6.1.1 Concept of the piece

Crescencia applies the concept of SD in its harmonisation. As well as in loudspeaker systems, in which each part of the array reproduces one portion of frequencies, each instrument in this piece has its own pitch (with the physical limitations of the orchestra). Harmonic material for this work derives from the computer-assisted analysis of different recorded sounds played at different dynamics, which provide a root chord with more or less extended partials.

This method provides the composer with the possibility to choose and extend the harmonic inner-world of a recorded instrument, contributing to the creation of a rich harmonic field which can be implemented across the orchestral pallet using spectral techniques.[29]

6.1.2 Process

To achieve the main purpose of the piece, a system[30] of three percussion instruments (32” timpani, 28” tam-tam and Chinese glissando gong F#-E) was created with the aim of obtaining very similar sounds. Those sounds were spectrally separated in order to permit the manipulation of their resonances. This creates an instrumental sound that is spectrally

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[27] SGAE: General Spanish Association for Authors and Editors.
[28] AEOS: Spanish Association of Symphonic Orchestras.
[29] Spectral techniques refer to techniques used by spectralists such as G. Grisey, T. Murail, K. Saariaho, J.M. López, etc. See (Fineberg 2000).
[30] It is called *system* of percussion instruments and not *set* because all the instruments are in contact with the timpani head, for that reason, when you strike any of them the entire system resonates at the same time.

divided or stratified in the frequency domain, and it is used as a raw material for harmonic implementation and orchestration during the compositional process.

Figure 5. *System setup based on the three percussion instruments.*

Once the setup of the three instruments was completed, the recording session included different performance techniques to analyse the timbral properties of alternative striking methods. Such techniques have also been used in the final score. The recordings were analysed with Audio Sculpt[31] and the results constituted the main harmonic material of the entire piece.

It is noticeable that for one kind of stroke there are different analytical results depending on the nuance. This is due to the fact that some partials change according to intensity and the number of partials vary in the same way.

After analysing the sounds recorded with AudioSculpt, the analytical results were exported as a Sdif[32] file to OpenMusic[33] in order to calculate spectral processes and generate musical material.

[31] AudioSculpt is IRCAM software for FFT analysis and sound manipulations.
[32] Sdif is a type of text file that allows communication between FFT analysis software.
[33] OpenMusic is an Aided Computer Composition software (ACC) developed at IRCAM, successor of PatchWork.

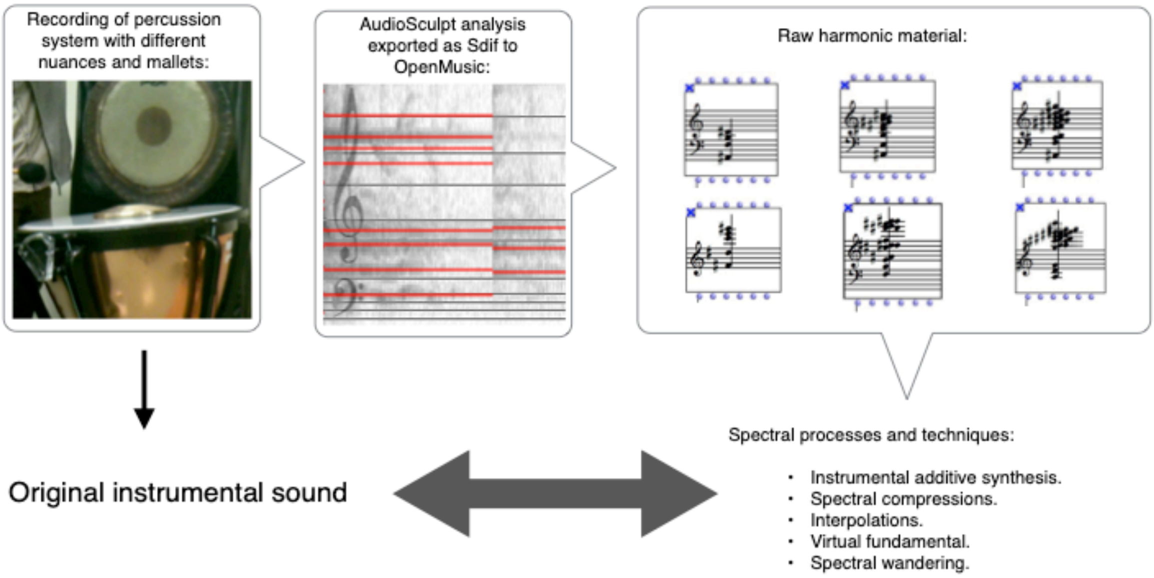

Figure 6. *Block diagram overview of the compositional process.*

6.1.3 Relationship between compositional techniques and 1st level of SD

Different spectral techniques have been explored in order to relate SD to different levels of implementation in the instrumental forces (1st level of SD) as shown in Figure 6. For instance, raw harmonic material extraction is relative to the assigned frequency band division and the frequency range limitation of the instrument. Each single note is allocated to a different band occupation inside a concrete spectrum band or chord. Another example of implementation to reinforce the harmonic identity of each spectrum, is where a virtual fundamental note has been added to each spectrum and later on used in the system of orchestration, depending on whether there is a need to enhance the level of spectral occupation in the low register.

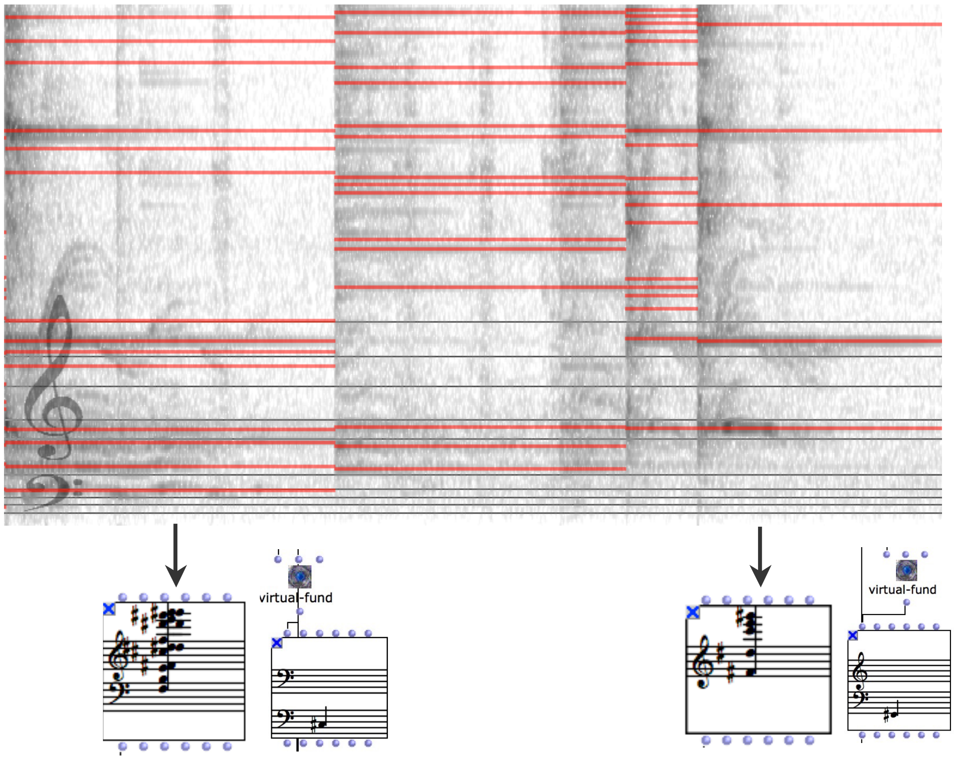

Figure 7. *Chord extraction from same instrument with different stroke intensity and virtual fundamental.*

For example, the two chords in Figure 8 arise from the analysis of two strokes on the gong using a hard-plastic mallet at forte and piano dynamics. Depending on the orchestral forces playing in a certain bar, one or another chord is used. In bars 14 and 15 there is an example of this instrumental synthesis in which there is a juxtaposition between real sound and instrumental synthesis.

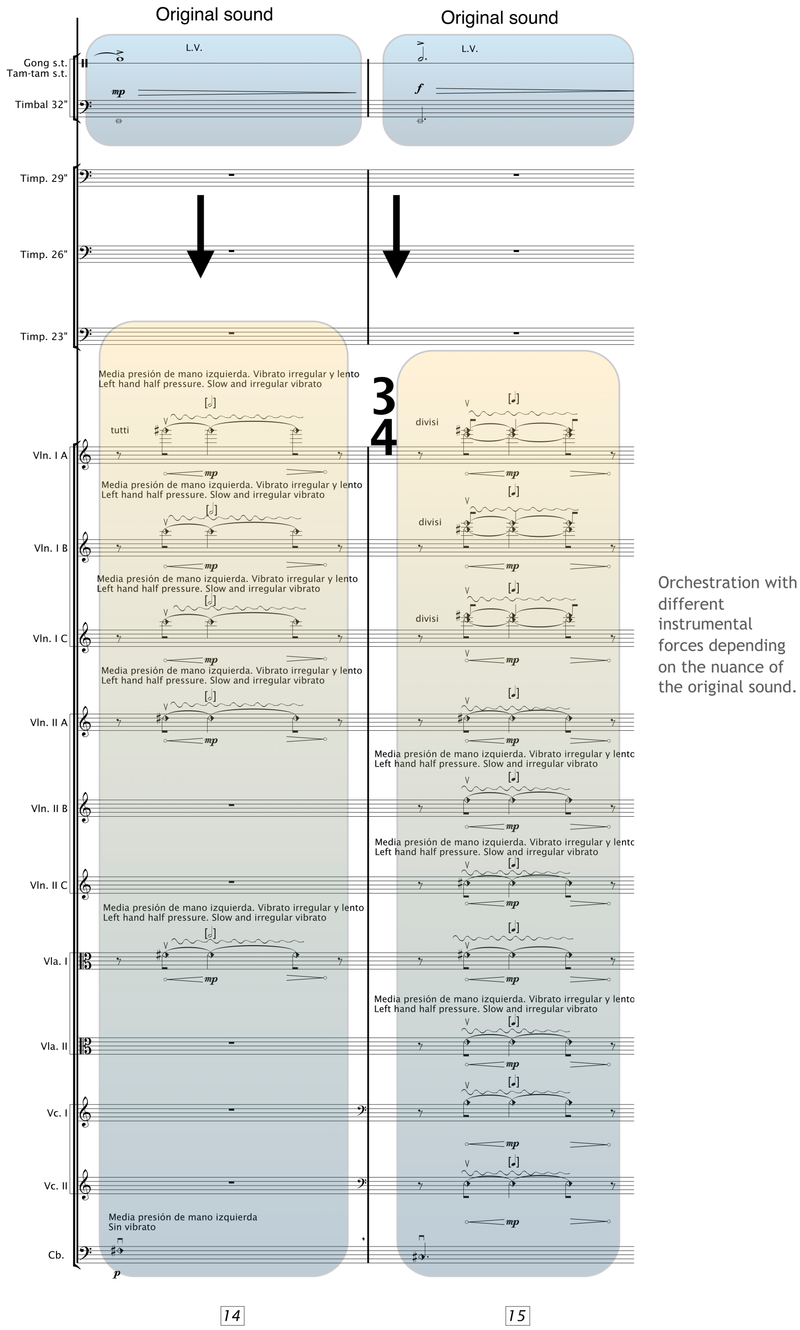

Figure 8. *Bars 14-15 of Crescencia: real sound plus instrumental synthesis.*

Spectral compressions are assimilated into `elastic deformations` in which all the band limits change dynamically. In this case, all the individual notes of one spectrum are multiplied by a ratio that expands or compresses the limit of the spectrum. Examples of this process can be found in bars 76-93, 154-169 and 190-195 in strings section.

Similar to spectral compressions there is another type of process in which a chord morphs into the next chord by interpolating intermediate stages. This is another implementation of `elastic deformations`, nevertheless, in this case these deformations are less dramatic than in places where spectrums are compressed until they become converted into one single pitch. The next example (Figure 9) shows the formalisation in OpenMusic of an `elastic deformation` as a spectral interpolation. A perturbation factor has been added to enrich the individual melodic shapes of each voice. Its musical realisation can be seen in bars 125-127 in Fl.1, Fl2, Cl1 and Fg1.

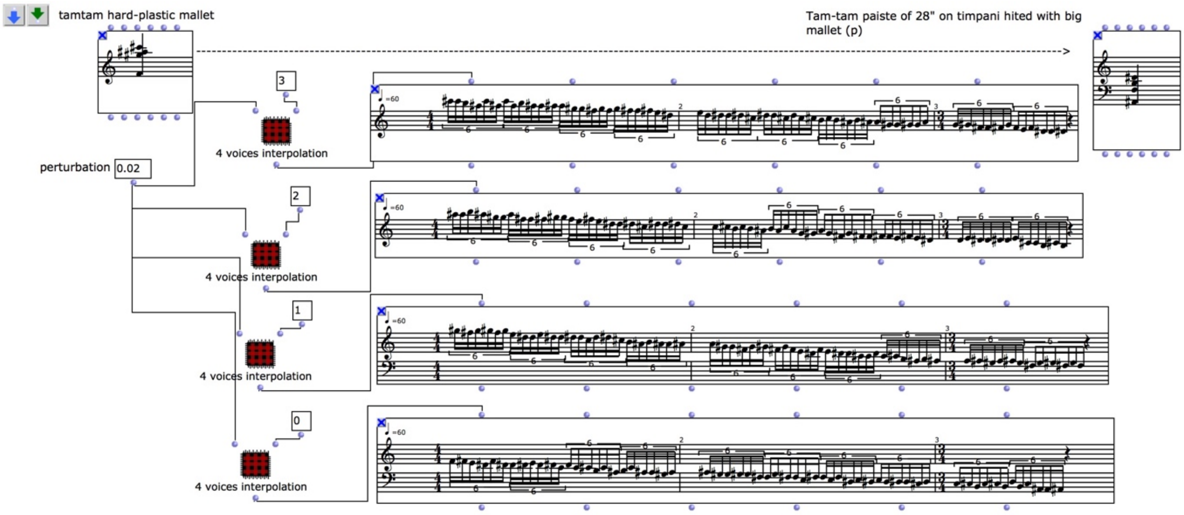

Figure 9. *OpenMusic patch featuring four voices sextuplet interpolation as an elastic* `deformation` *process.*

One other compositional technique used in *Crescencia* is called `sound wandering.` This consists of freezing a spectrum while all the voices are in movement. The idea of this process is related to the concept of `blinking or sound wandering` in SD with the generation of sound material inside a spectrum or sonority. The result is a spectrum freeze within a continuous internal movement. This process has been implemented on the following OpenMusic patch and the result can be seen in bars 135-152.

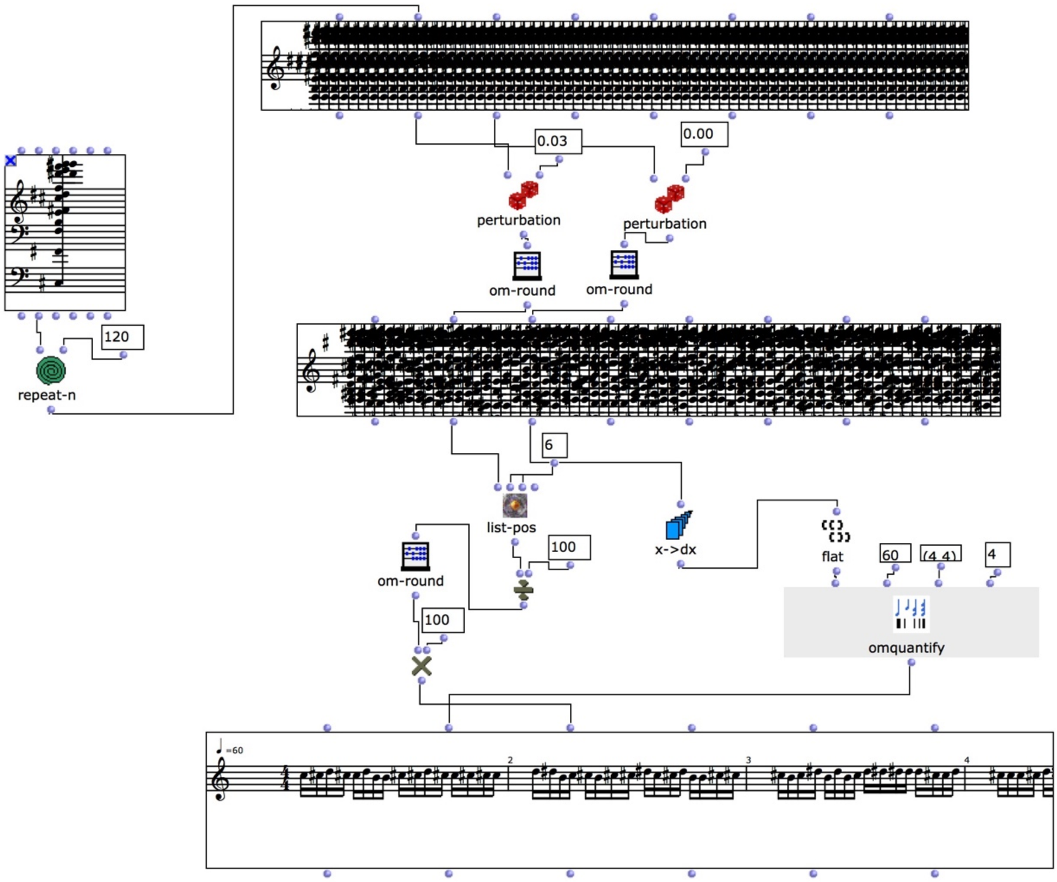

Figure 10. *OpenMusic patch to perform* `sound wandering` *in the* `1st level` *of SD.*

6.2 *Travesía a través de los estados de la palabra*[34] [2nd level of SD]

Collaborative installation work for ARCO,[35] commissioned by the Spanish telecommunications company Telefonica. The installation was open to the public from 27/02/2015 to 02/03/2015 at the La Casa del Lector at Matadero Madrid (Madrid).

In this collaborative project[36] the `2nd level` of SD is used as part of its sound design, and frequency band distribution is organised as a *`glassy system`* with *`burning frequencies`* and *`spectral jumps`*.

6.2.1 Project idea and sound purpose

The brief for the commissioning of this interactive audio-visual installation was to foster connections between Spain and Colombia (guest country for ARCO 2015), and this brief informed many decisions and implied certain constraints on the realisation of this piece. As a result, the two main ideas underlying the different artistic areas of this collaborative work are the language and the physical space that separates both countries and continents: the Atlantic Ocean, the sea. In prior discussions between the collaborators on technical and artistic considerations, it was decided to create an interactive installation in the form of a journey, in which people could navigate throughout the different typographies of the 'word': written word, spoken word and printed word, as a sea of words presented with a number of interactive cutting-edge technologies (from 3D printing to spatial audio). The final piece has three clear zones in which the structure unfolds, as seen in the following plan (Figure 11).

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[34] Journey, Crossing the States of the Word. www.losestadosdelapalabra.com
A 3D game engine recreation of this installation is included in this portfolio (for OS X 10.13 or later).

[35] Feria Internacional de Arte Contemporáneo de Madrid (Madrid International Contemporary Art Fair).

[36] The author was the composer and responsible for sound implementation in this collaborative project. The other involved artists in the project were Chechu Salas artistic director, José María Cira project coordinator, Rómulo Aguillaume video artist, Gorka Cortázar lighting design and PKMN Collective architecture design.

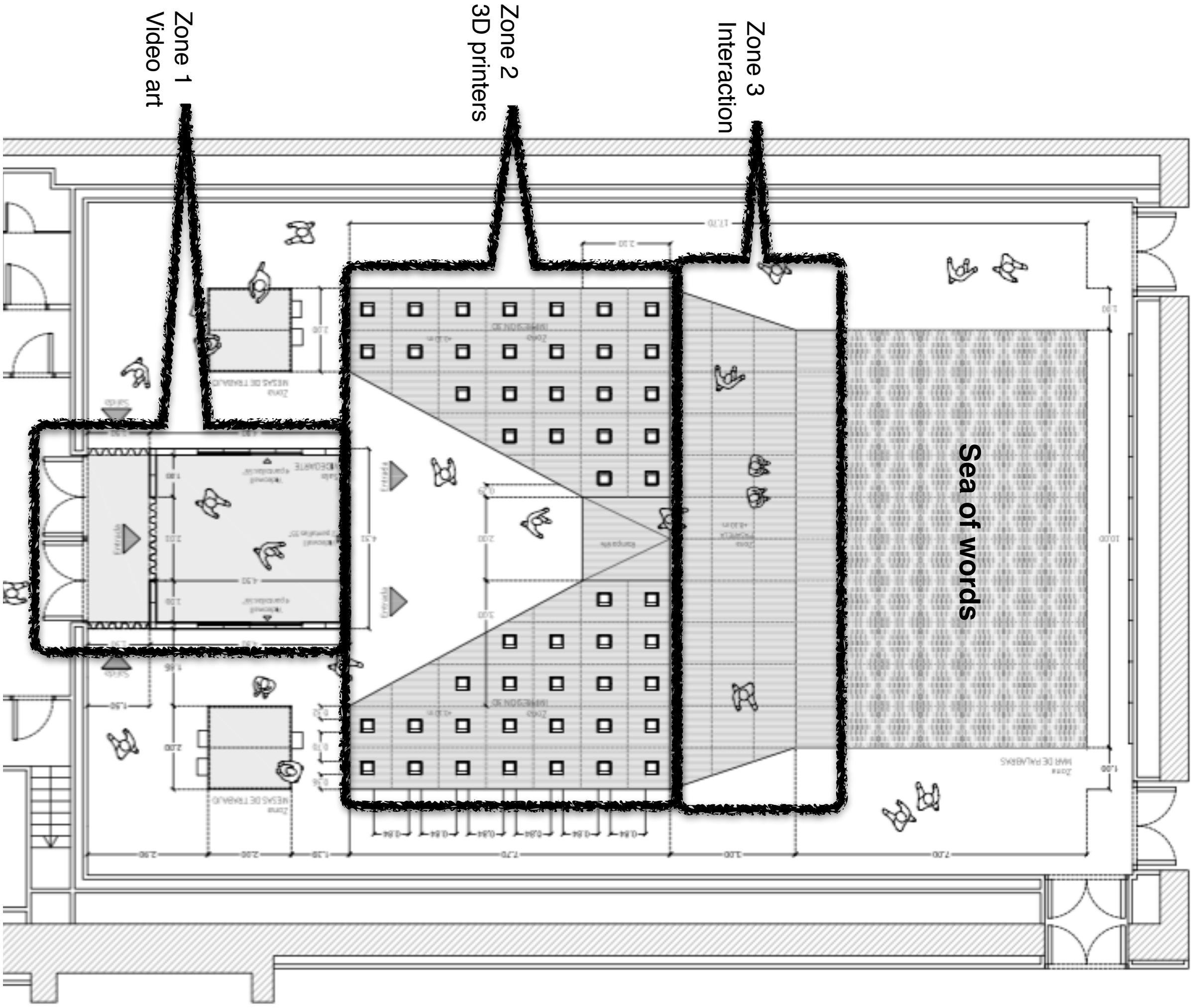

Figure 11. *Plan of Travesía installation.*

Zone 1 is a small black room with video art, in which people from Colombia are recorded reading passages from the books of the Nobel Prize winning author Gabriel García Márquez. These words are captured in Zone 1, analysed via software and 3D printed in Zone 2. In this section, the sound of words (spoken word) in the form of a sound wave is reinterpreted as printed word. In this area, the video soundtrack is played alone without interactive intervention, to make the speech more understandable.

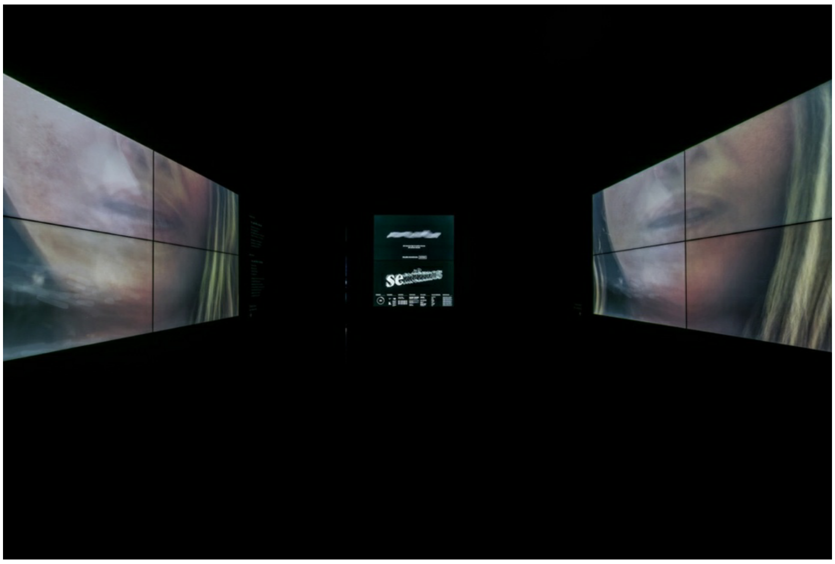

Figure 12. *Picture of Travesía's Zone 1.*

Zone 2 is the space housing fifty 3D printers working simultaneously to print circa 10,000 words during the opening hours of the exhibition.

Figure 13. *Picture of Travesía zones 2 and 3.*

An SD Space was designed and constructed for this area, using as the main sonic material present in the room the sound of the fifty 3D printers. This primary sound source was divided into frequency bands and organised in this space throughout an array of 12 loudspeakers. This aimed to create a pathway in which visitors could walk 'inside the sound'. This spectral image was organised from high frequency bands to low frequency bands, as shown in Figure 14.

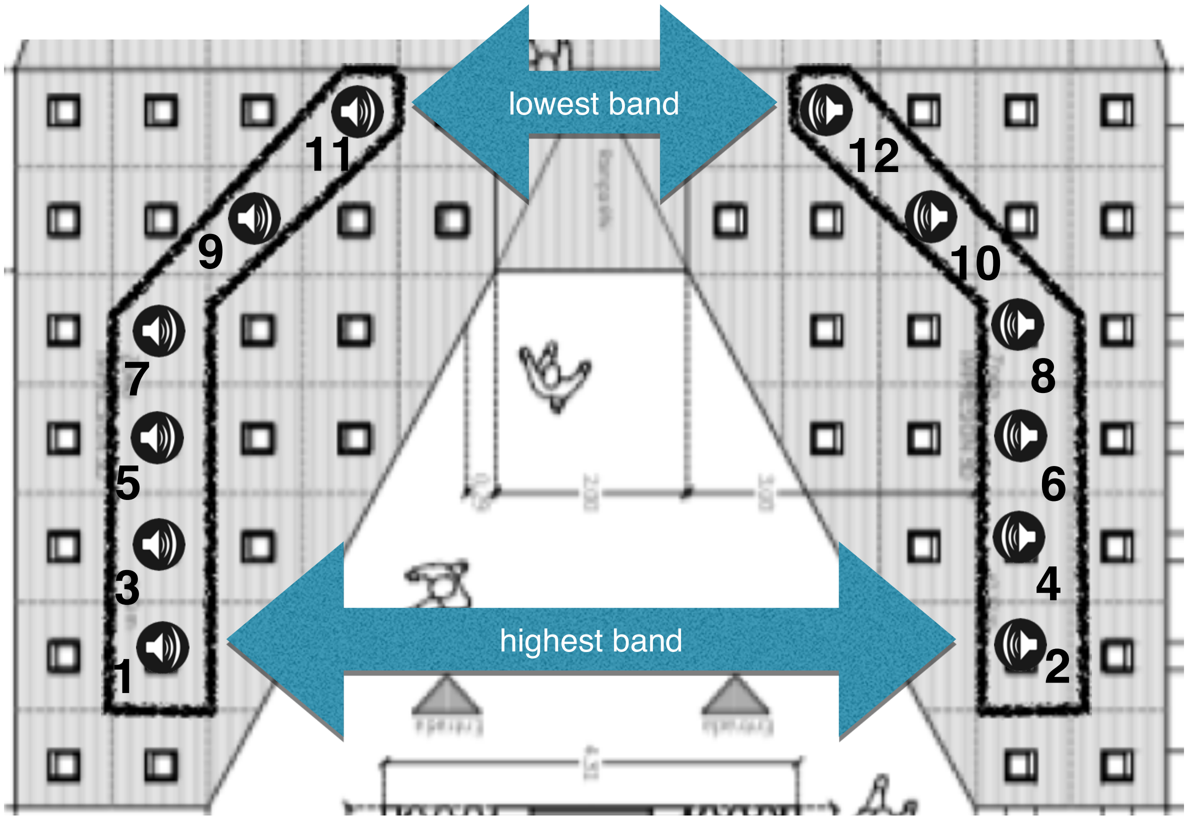

Figure 14. *Scheme of band loudspeaker distribution in zone 2.*

Zone 3 aimed to represent a synthetic sea of words in which the visitors could locate all the words printed during the exhibition. In this final part of the installation, the concept of the physical space between Colombia and Spain and the idea of the shared language merge together. This Zone was primarily interactive. The sound of a recording of the sea was divided into 5 spectral bands. The lowest sounds were played continuously, and the other three bands appeared when people stepped on specific areas near the emerging 'synthetic sea'. At the beginning of the interactive area, these interactive frequency bands sounded like a normal sea, but as the visitor interacts with the space, a method of cross-synthesis turned the sound of the sea into words. Figure 15 shows the distribution of interactive points.

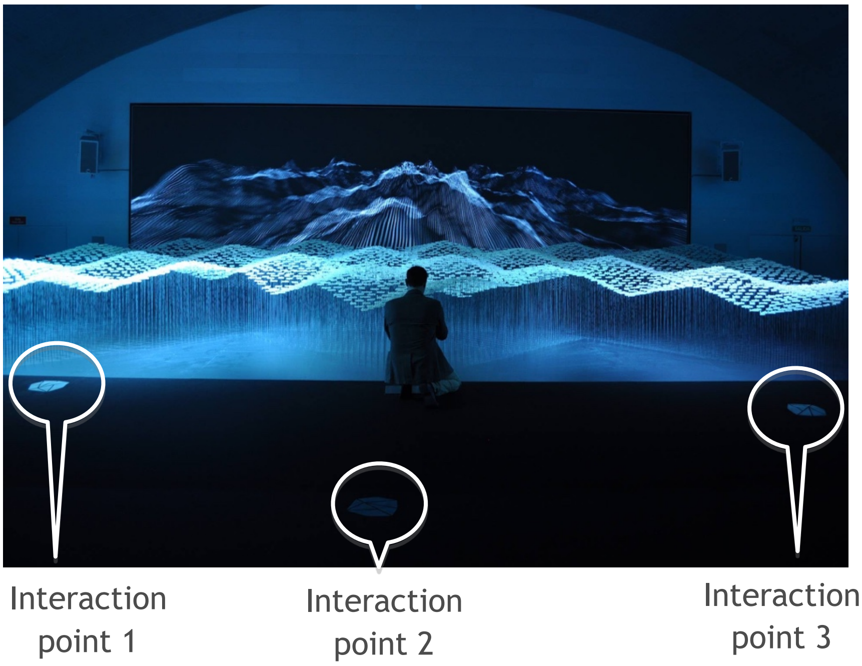

Figure 15. *Picture of interactive areas in zone 3.*

6.2.2 Realisation

On a technical note, all the sounds in *Travesía* are controlled by a single Max patch, in which there is independent control for Zones 2 and 3. There are no volume controls, as in this performance all the inputs and outputs were routed to a mixer controlled by an iPad to make it possible to introduce changes while being inside the installation area.

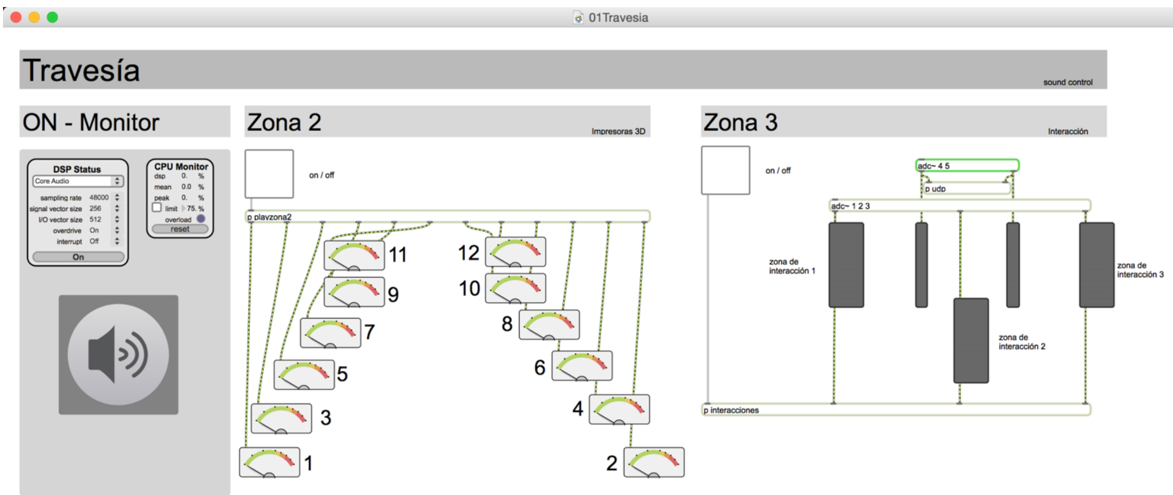

Figure 16. *Main patch control of Travesía installation.*

Zone 2, *burning frequencies*

In this area, there are different *burning frequencies* in a *two-level* SD system. All the sound material is a large loop of 27 minutes, imperceptible to visitors who spent about 10 to 15 minutes inside the installation. Below some of the 3D printers, 12 loudspeakers are placed to mask or enhance the direct sound of the printers, but at other times visitors can hear the direct sound from the printers alone.[37] Due to the fact that all these sounds gradually appear and disappear the effect becomes a *burning frequency*; emphasising some real frequencies emerging from the printers. These *burning frequencies* are processed via AudioSculpt and Pro Tools filters. With Pro Tools 12 dB/octave filters are used to created *overlapping band transitions* and AudioSculpt has been used to obtain *spectral jumps*; bands divided abruptly without transitions. Frequency division in this area is done by selecting equilibrated bands in terms of spectral energy, whereby there is no integer relationship between band limits. As a result, the *surrounding matrix* of loudspeakers reproduces an *asymmetric system*.

Zone 3, interactive *glassy system*

The final space is dedicated to interactive sounds. The real recorded sound of the sea is divided into 4 *glassy bands* and one background sound with a peak filter in 450 Hz. The first glassy band is the sub base (30-150Hz), and each of the other three bands corresponds to different interactive points (150-700Hz, 700-2000Hz, 2000-7000Hz). As in the previous zone, the limits of the different bands conform an *asymmetric system.* Those boundaries have been selected to achieve a well-balanced weight in term of spectral energy. Figure 17 presents interactive block diagram system.

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[37] SD system for zone 2, resonates with Smalley's definition of *Perspectival Space* and *Scale* (Smalley 2007). Notwithstanding, in *Travesía,* it is the listeners or visitors who change their own perception of the space perspective depending on their movements, not just the fixed media sounds.

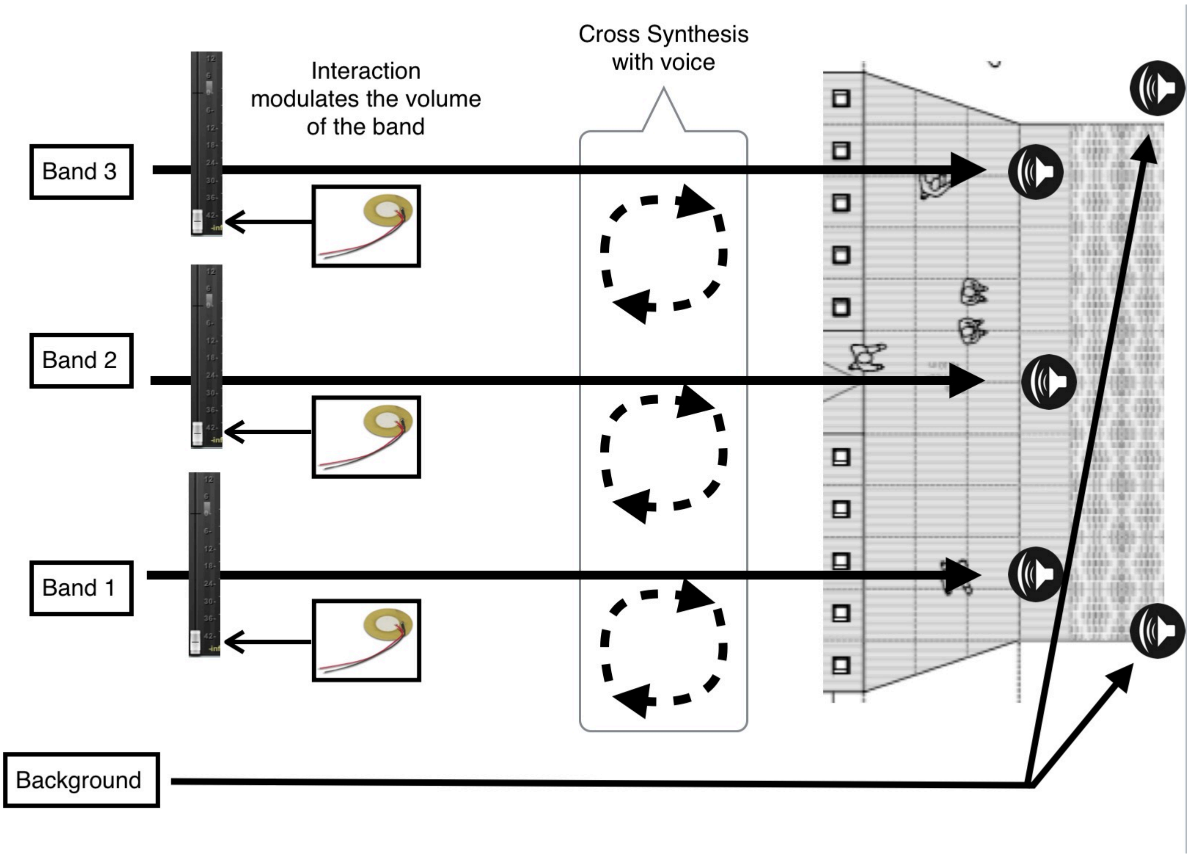

Figure 17. *Block diagram of Zone 3 interaction implementation.*

6.3 *Kantaber* [1st level of SD]

For tuba with amplification ad libitum (12:53min.)

In this work, a `first-level system` of SD is applied to the instrumental writing as well as to instrumental techniques, by preparing a valve slide. Having said this, the piece could be considered a work between `first` and `second-level` when the instrument is amplified. *Spectral position*, *spectral jumps*, *blinking*, and *sound wandering* are the SD concepts investigated in this score.

6.3.1 Concept of the piece

After investigating in depth the mechanical and acoustic properties of the tuba,[38] two types of sound transformation were developed for this instrument: one is related to the implementation of SD inside the tuba (via valve slide preparation), and the other has to do with its unique sound and its variations of spectral energy (split sounds[39]).

Due to the fragile quality of some of the sounds of this piece, amplification is recommended if the piece is played in halls with over 100 seats. In the case of smaller halls where the performer is very close to the audience, such an acoustic reinforcement is optional. It is important to note that when amplifying the performance, the diffusion of the spectral energy of the source material is enhanced, therefore the amplification is not only a functional option but also impacts on the system response and interpretation.

6.3.2 Process

Kantaber is a composition for tuba that explores the possibilities of the instrument to produce split sounds, a peculiarity also found in other woodwind instruments and referred to as cracked sounds,[40] a type of sounding technique very close to multiphonics. In contrast to the instrumental technique of playing and singing at the same time, the sounds

[38] The author (who has played saxophone professionally) spent three months learning the tuba, and studying extended technique books and extensive bibliography for tuba and trombone (Ron 2014; Buquet n.d.; Kennedy 2016; Larson 2013; Dempster 1979).
[39] Split sounds or multiphonics, both denominations are correct as they describe the same phenomenon, in contrast to woodwinds where which each denomination refers to a different technique.
[40] As for example in J. L. Sampson's book about extended techniques for bassoon (Sampson 2014).

investigated in this piece are split sounds, similar to those produced by woodwind instruments with special fingerings. In the case of the tuba, these sounds are produced by special positions of the embouchure and tuning changes.

Split sounds in the tuba are produced by playing a non-real note between two harmonics of a determined fingering. For example, if on a tuba in C we play a G 2 (no valve pressed), and the player lowers the intonation with their lips, there will be a moment in which a kind of multiphonic will start sounding. This technique consists of playing a pitch note that does not exist in the natural harmonic series of a determined fingering to produce an array of sounds that vibrate at the same time. The notation of tuba split sounds is:

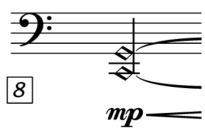

Figure 18. *Notation of tuba split sounds.*

This requires playing between C and G to sound all the additional sounds together:

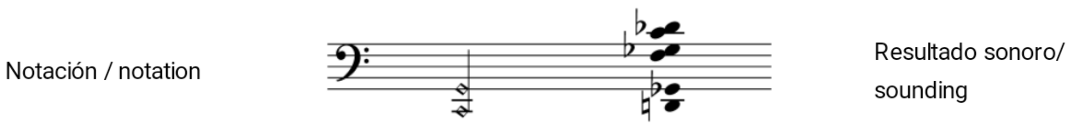

Figure 19. *Sound results of the split sound.*

Split sounds are produced between harmonics of 8th, 5th and 4th. Tuning variation is very small on each split sound; they have to be played with the exact pitch and mouth position to have the appropriate sound. These pristine sounds will be presented slowly from the most essential sounds of air to the most complex from a harmonic point of view. Figure 20 shows an example of how multiphonics are used at the beginning of the piece and the evolution reached at the end.

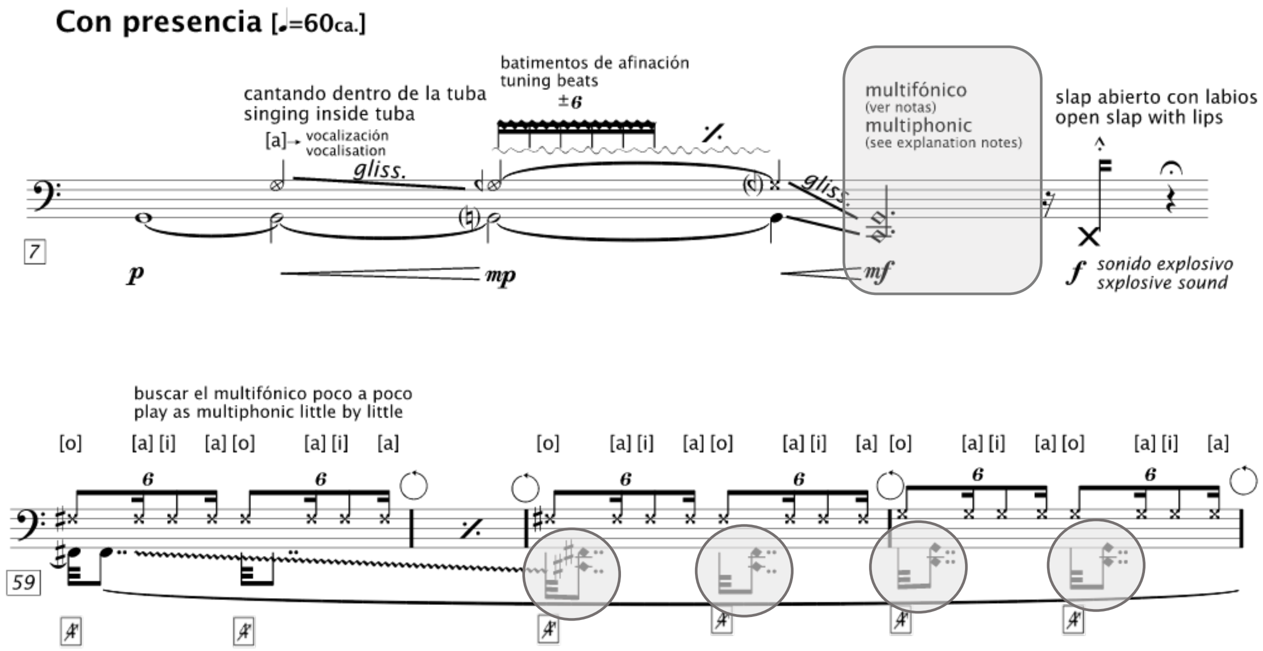

Figure 20. *Evolution of split sounds through the piece.*

Kantaber also investigates how the tuba is able to produce sounds from different parts of the instrument, apart from the bell, to create `spectral position` changes. To achieve this purpose, the tube of the 4th valve slide is open during the entire performance leaving one extreme of the 4th valve slide out of its place, as shown in Figure 21.

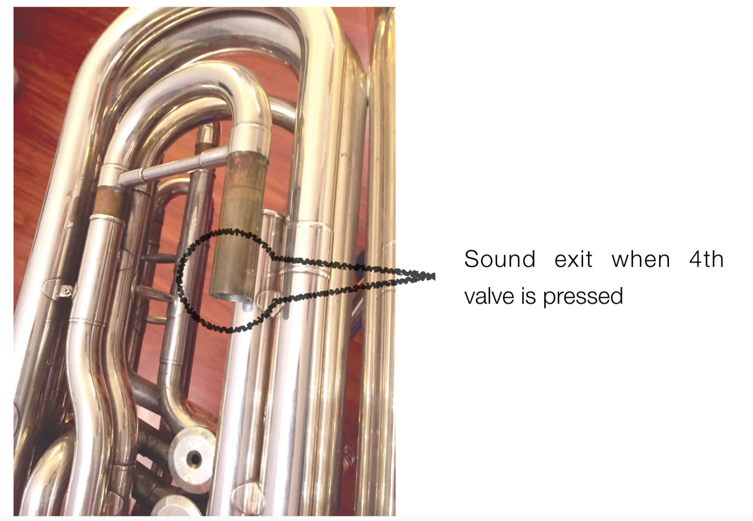

Figure 21. *Valve slide preparation.*

With this technique of preparing the instrument, one sound can be routed to the main output (the bell) or to an alternative output (the prepared valve slide). This alternative sound exit allows the instrument to obtain the same notes with different formants or filtering due to the changes in the physics of the tube. Therefore, with this manipulation, the tuba is able to produce a natural spectral diffusion of the sound by creating *spectral jumps, sound blinking*, and *sound wandering*, with the possibility of further amplification via electroacoustic means.

To amplify the tuba, two near-field microphones are needed: one for the bell of the instrument and the other for the prepared 4th tube that will be open during the entire performance. The microphones will be slightly panned to either side (L and R) of the main loudspeaker system.[41]

Aesthetic goals in *Kantaber*

There are no aesthetic goals in the compositional process of *Kantaber*. The only objective of this piece is to demonstrate that SD techniques can be implemented in a tuba without the use of electronic means, not in a metaphorical way but in a physical intervention of the instrument with effective SD sound. As a result, a circumstantial aesthetic consequence has arisen from this musical approach. The tuba 4th slide preparation has allowed the production of sounds that resemble a didgeridoo when combined with split sounds and vocalisations. This can be seen as an aesthetic achievement in terms of contemporary techniques applied to the tuba and demonstrates that SD compositional techniques are able to create new avenues of musical expression.

[41] This use of microphones has strong connections with the concept of *Microphone Space* from Smalley's *Enacted Space-form* classification (Smalley 2007) adding the parameter of frequency band division.

6.4 *Pronomo's Space [e]* [1st, 2nd & 3rd levels of SD]

Work for Pronomo[42] flute and live electronics in 8 channels (7:56 min.). This work has been composed in collaboration with the flautist.

This piece explores the *1st, 2nd and 3rd levels* of SD and works around the concept of *spectral jumps* and *glassy-systems*.

6.4.1 Characteristics of the instrument

The Pronomo flute is a new and unique instrument developed by the Spanish flautist Julián Elvira.[43] This flute is a new step in the evolution of the Boehm system, which uses small and big holes across the entire range of the flute. This allows the flautist not only to play quarter tones across the entire range of the flute, but also allows for 11,337,408 possible fingerings, increasing significantly the range of possibilities for producing multiphonics.

6.4.2 Concept of the piece

Pronomo's Space [e] explores and implements two key concepts that are employed in electroacoustic SD techniques. Firstly, the concept of *elastic deformation* that refers to changes over time in the range of a determined band of frequencies. This concept is implemented in the Pronomos piece when using a technique known as *serial closing*. This consists of leaving one hole opened and continuously closing the others as usual. This affects the timbre characteristics and the pitch that is compressed in some sort of irregular deformation of the normal fingering scale. The Pronomos flute is therefore playing all the fingering extension, but the band of frequencies that it produces is narrower than normal.

The second key concept are the *Spectral jumps* implemented in this work by using three different partials of a fundamental fingering. These three registers are the three bands in which the piece is developed. However, the behaviour of the same fingering in the bands or registers is different because of the timbral peculiarities of this special technique. This

[42] Pronomo or Pronomos flute, both denominations are correct. www.pronomosflute.com
[43] Julián Elvira is a flute performer who has developed the Pronomo flute with the luthier Stephen Wessel. http://pronomosflute.com/

means that playing the same fingering scale can produce up to three different pitch scales depending on the chosen register, but there are no transitions or common pitches between ranges, so that this instrumental technique is related to `spectral jumps` of SD. Figure 22 depicts this special relationship between fingerings, registers and final pitch.

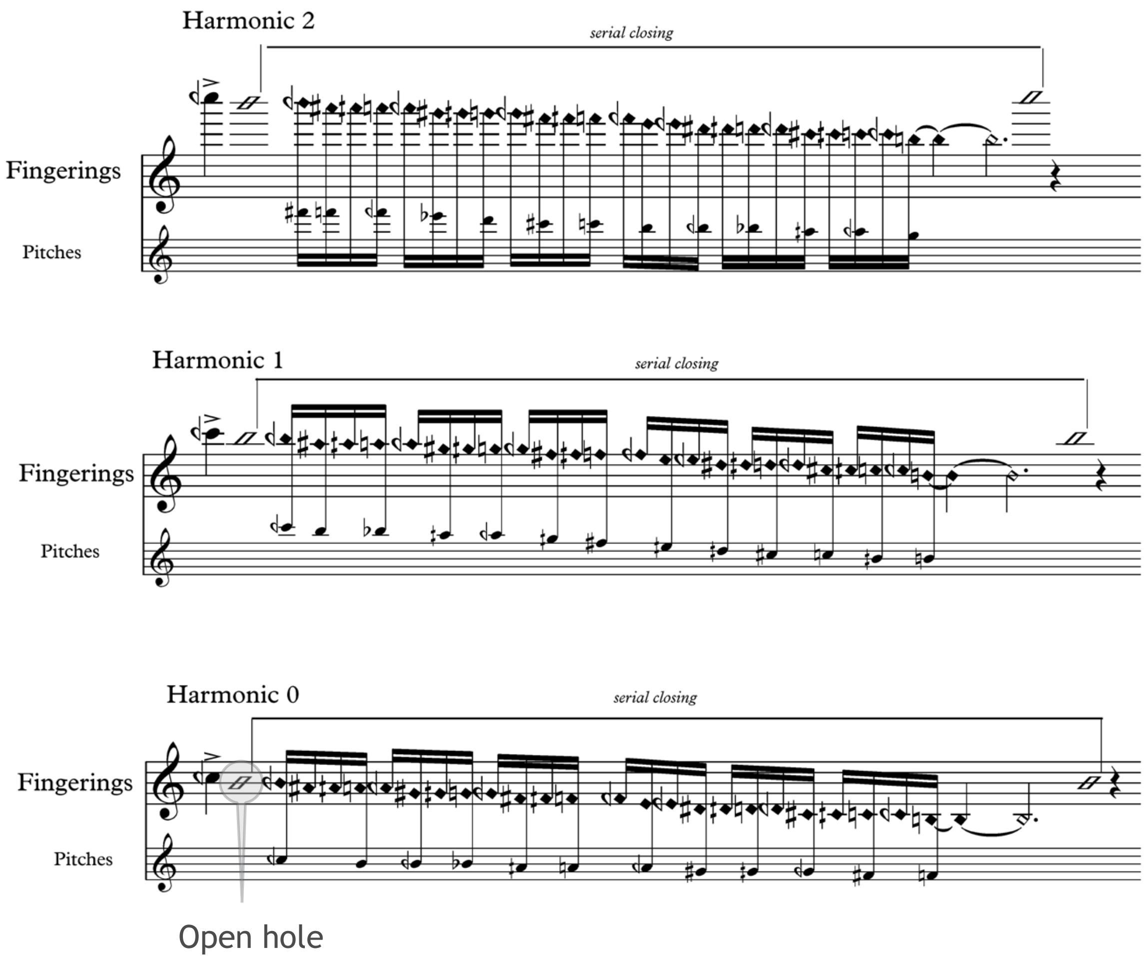

Figure 22. *Example of relationships between fingering techniques and pitch obtained in serial closings.*

6.4.3 Instrumental writing

Writing for serial closings is a combined system of two staves, in which one represents fingerings (diamond notes) and the small stave is for the resulting sound. Figure 23 shows an example of this writing technique.

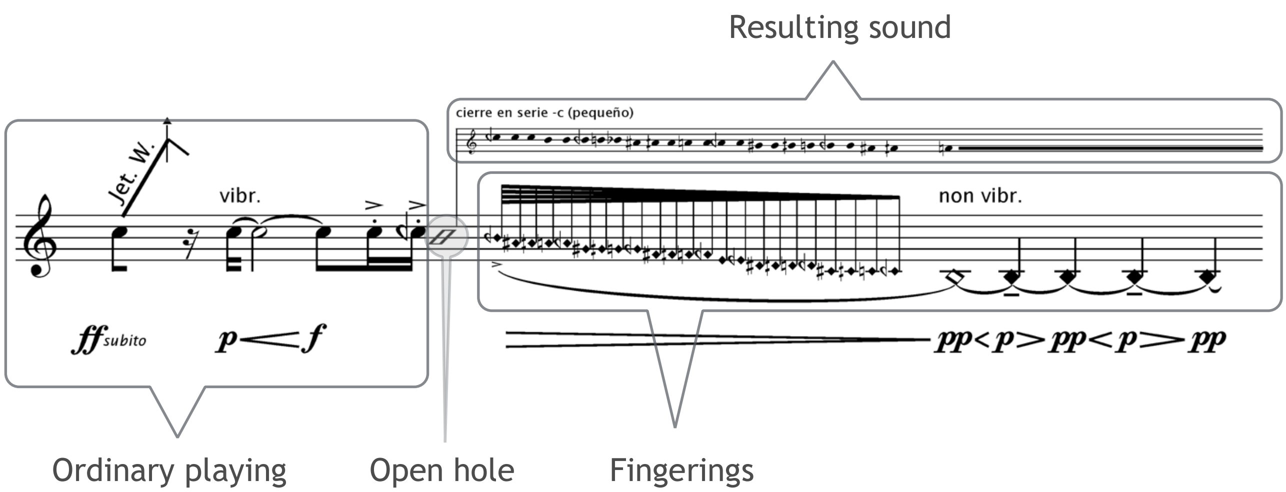

Figure 23. *Example of serial closings writing.*

The other challenge is writing to indicate which partial or register the flautist should play, and the indication of changes between these three different registers or partials. It is not possible to use traditional pitch notation because the fingering used in this work does not match the resulting sounds. Figure 24 shows the solution for this problem and the symbols for register changes.

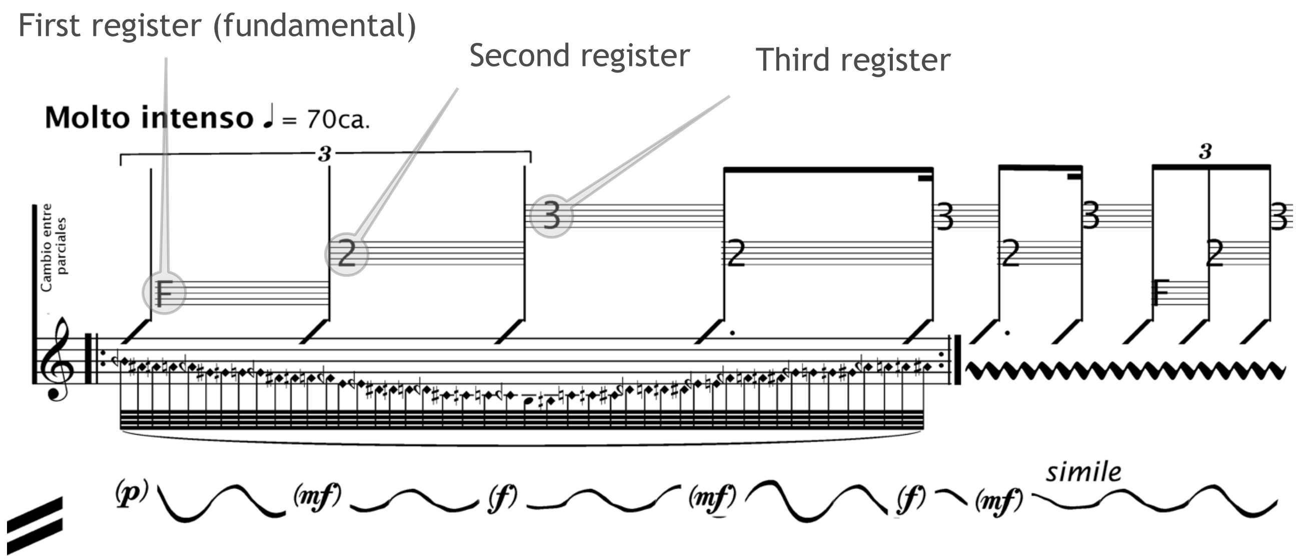

Figure 24. *Example of register changes writing.*

6.4.4 Live electronics

The live electronics of *Pronomo's Space [e]* implement two main processes. The first one is in the `second-level` of SD and is implemented as a *`glassy-system`* with *`spectral jumps`* using FFT filtering, applied to the first part of the piece and the improvisation. As Figure 25 shows, the sub-patch for this section is implemented in Max using FFT filtering inside a *poly~* object to divide the spectral content into each band.

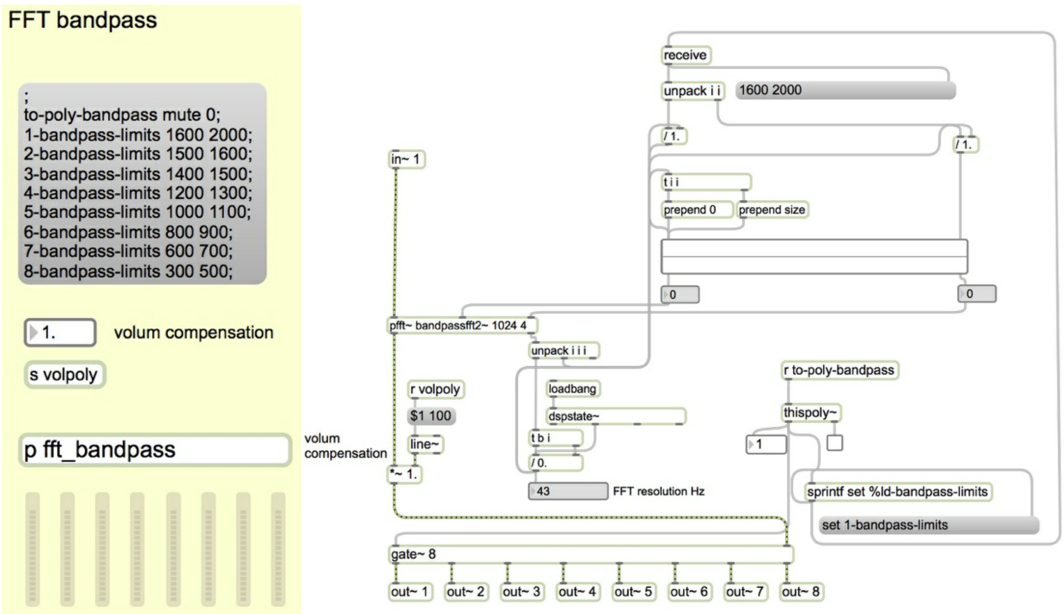

Figure 25. *FFT filtering implementation.*

The second process can be classified as the `third-level` of SD in which the flute sound is moved throughout the performance space using *Ambisonics*[44] and concatenative synthesis[45]. Concatenative synthesis creates a corpus organised in a two-axis graph in which each bin is located according to its amplitude (dB) and its frequency (Hz). This organisation of binaries creates a cloud of sound that is mapped to the performance space (concert hall) using *Ambisonics*. With this procedure, each bin is allocated to one determinate point of the performance space. The corpus is formed by several instrumental recordings of *Pronomo's Space*, and this corpus is read using real-time audio-descriptors, a technique named

[44] *Ambisonics* is a technique used for spatialising sound in a full-sphere (3D) that allows the encoding of movements or point locations of virtual sources (Malham & Myatt 1995) and decoding using different arrays of loudspeakers (Malham 2012).

[45] Concatenative synthesis is an extension of granular synthesis but with a corpus or library of sound instead of a sample. An IRCAM patch called CataRT has been used in this work as explained in (Schwarz et al. 2006) and (Schwarz 2006).

Descriptor-Based Spatialisation (Einbond & Stravinsky 2010), therefore the result of the electronic part becomes an acoustic shadow of the flute sound spread across the performance space. The implementation in Max of the spatial Ambisonics module uses ICTS tools[46] (Schacher 2010). Figure 26 shows the control of this second process in the main patch.

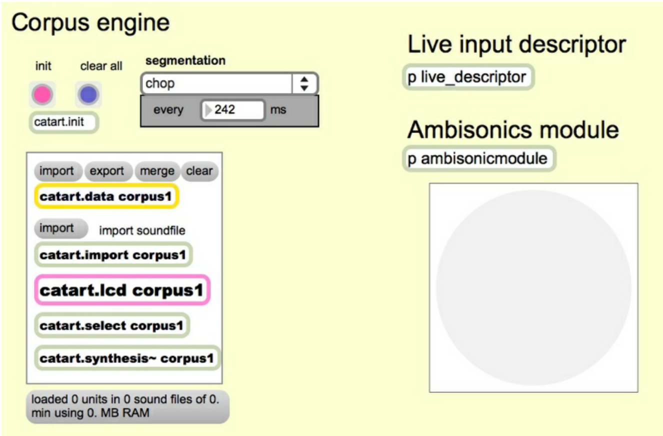

Figure 26. *Corpus engine and Ambisonic spatialisator*.

[46] ICTS tools include objects for Max Msp in order to work with high order Ambisonic encoders and decoders.

6.5 *Time Folds II* [1st & 2nd levels of SD]

For alto flute, bass clarinet, cello, double bass, marimba and Helmholtz resonators (7:09 min.).

This work implements Helmholtz resonators in toms using surface-loudspeakers, and investigates `1st` and `2nd level` of SD techniques in a `glassy system` with `transitions` between `neighbour bands`, enhancing 4 marimba notes as `burning frequencies`.

6.5.1 Concept of the piece

Time Folds II is a work that is composed in analogy to the construction of the *Dragon Curve*. This fractal can be implemented using several techniques. The most common technique is folding a strip of paper in half to the right and repeating the fold again. If the strip is opened out again, undoing each fold to become a 90-degree turn, the resulting sequence would be the second iteration of the *dragon curve*. This fractal can be implemented as a *Lindenmayer system*[47] as well. These two ways or processes of construction have been used in this work to organise and compose the musical material and the spectral content divided into bands of frequency in order to introduce this spectral content into the Helmholtz resonators.

6.5.2 Formalisation

The shape of the *Dragon Curve* has been mapped and scaled into the frequency band division of the instrumental writing, and the Lindenmeyer system has been mapped to time division. To achieve this purpose, a Max patch has been developed to implement the curve production, and a MIDI section has been used to translate this shape into musical content. Figure 27 shows the Max patch implemented to visualise the fractal with its correspondent Lindenmayer representation.

[47] *'Lindenmayer systems — or L-systems for short — were conceived as a mathematical theory of plant development. […] The central concept of L-systems is that of rewriting. In general, rewriting is a technique for defining complex objects by successively replacing parts of a simple initial object using a set of rewriting rules or productions.'* (Lindenmayer & Prusinkiewicz 1990)

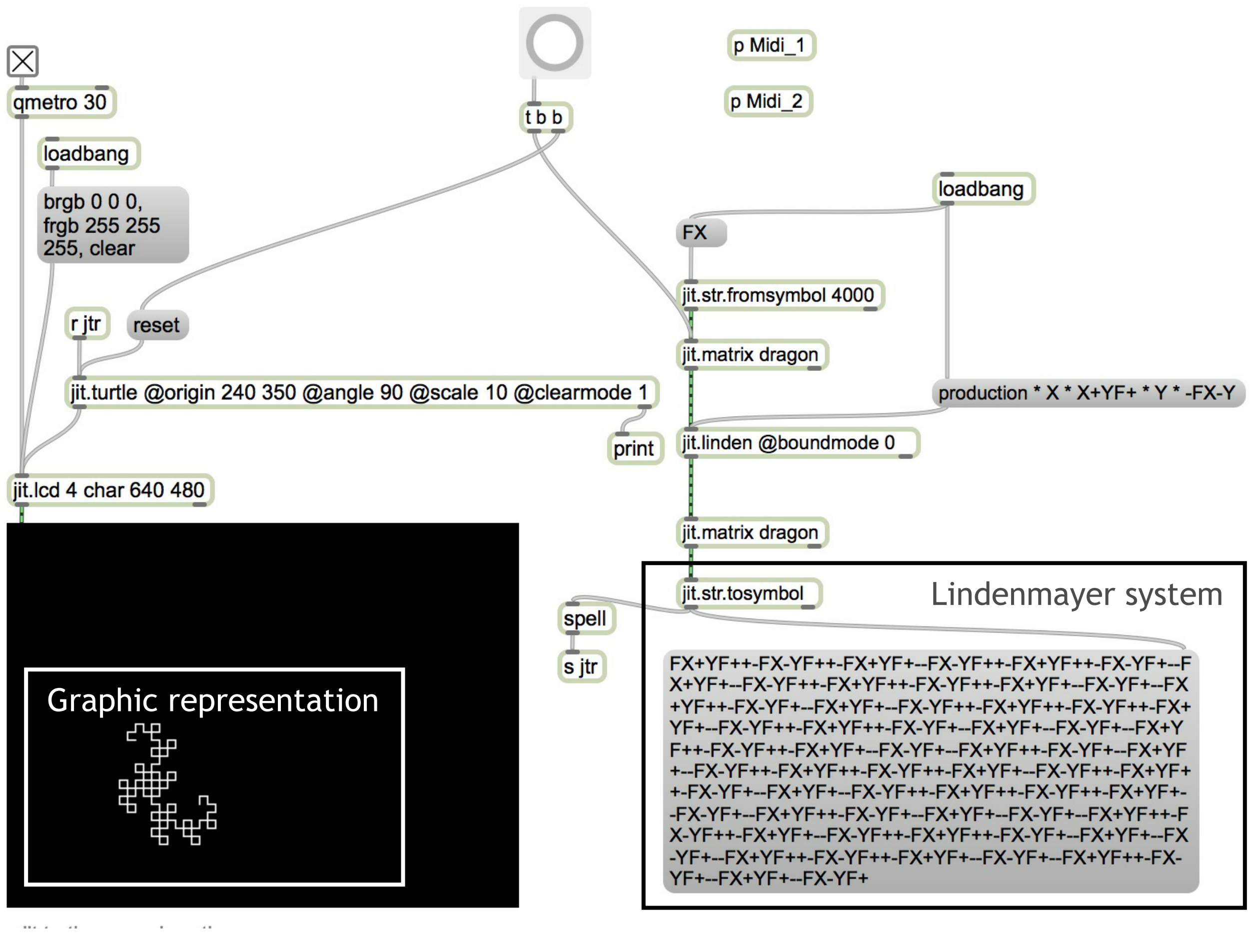

Figure 27. *Dragon curve implementation in Max MSP as a Lindenmayer system.*

Figure 28 shows an example of musical mapping in which right and left turns (represented by + and - in L-system representation) are grouped to create a continuous changing rhythm. At this point in the score, the value of each symbol has been mapped to a 16^{th} note.

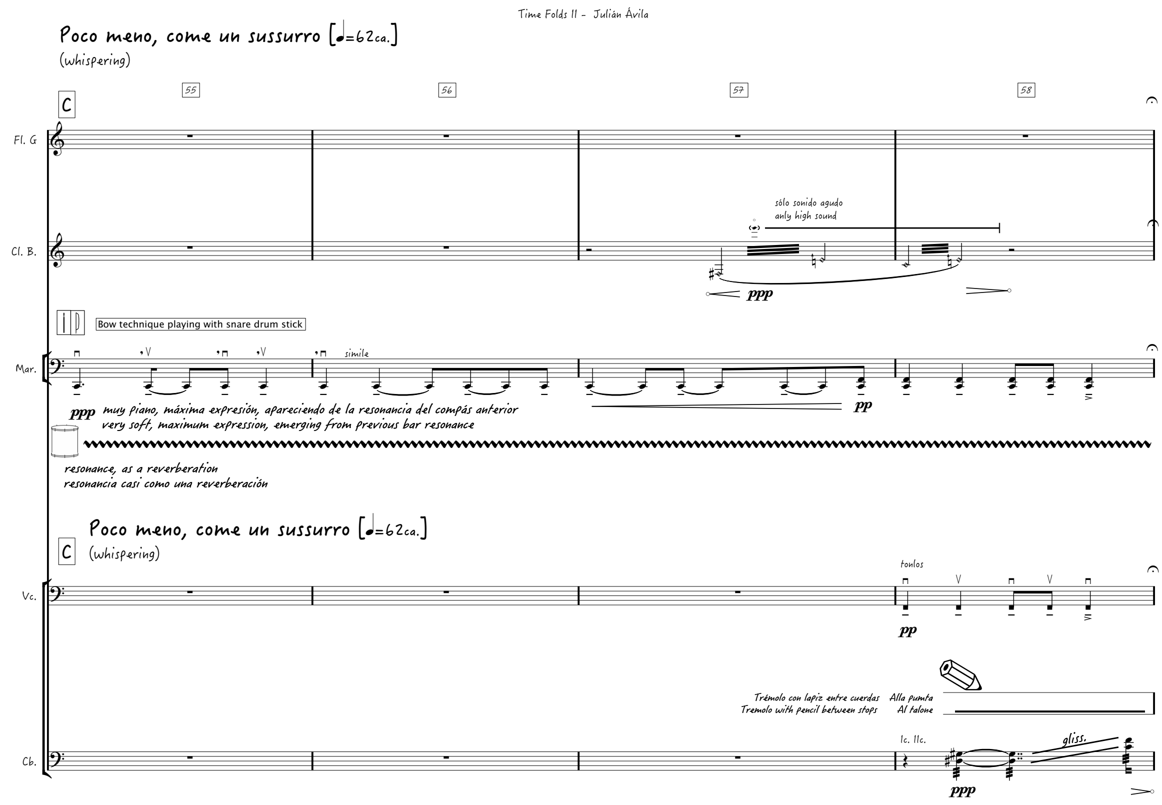

Figure 28. *Lindenmayer turns mapped to marimba part.*

6.5.3 System implementation

Time Folds II uses physical containers as a Helmholtz resonator, in order to achieve a physical filter without the use of digital or analogue filtering. In this case, 4 toms with attached surface-loudspeakers (a type of contact loudspeaker also known as vibra-speaker) constitute the resonator system. Depending on the tom size and pitch tuning, the sound will be filtered in a different band of frequencies. The system has been tested with pink noise and analysed with a spectrograph[48] (Figure 29).

[48] Smaart v.7 software and ECM8000 measurement microphone.

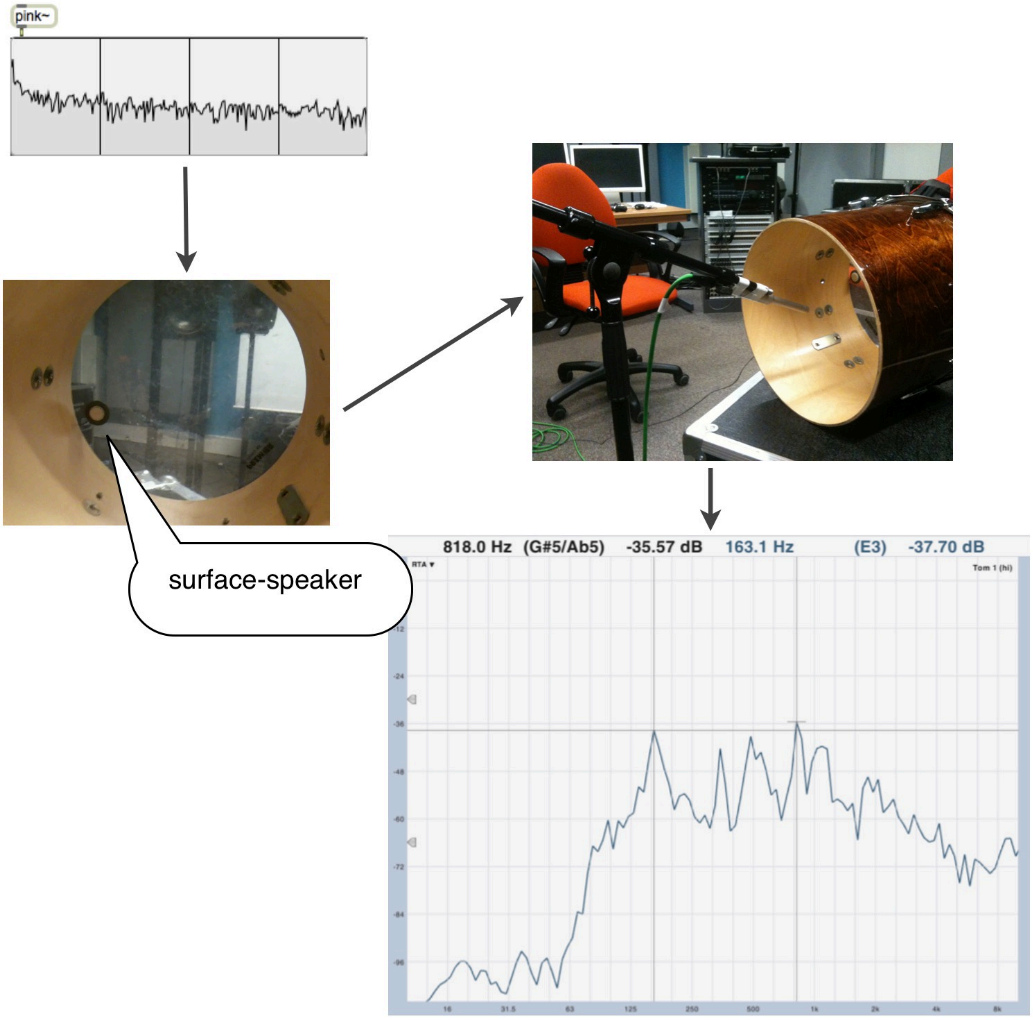

Figure 29. *Frequency response measurements of toms.*

This system has been applied to low notes of the marimba throughout its amplification using contact microphones. Figure 30 shows the 4 notes in the marimba with a contact microphone amplified inside each tom.

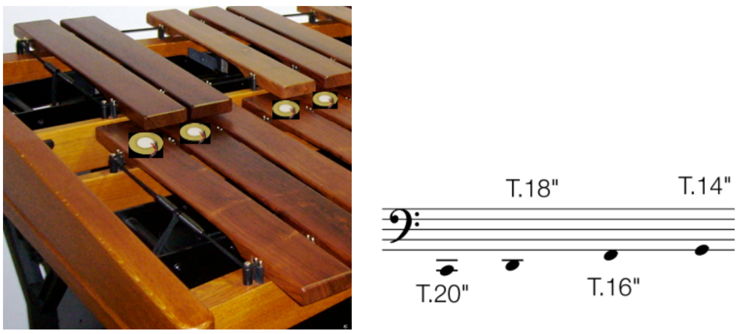

Figure 30. *Piezzo microphones installed in marimba to be amplified in 4 different toms.*

6.5.4 Musical writing

The sound result of the Helmholtz resonator is somewhat similar to a filtered reverberation of the sound introduced in the system. It is for this reason that each time the marimba performer plays one of the notes amplified (C, D, F and G), there is a special notation in the score to describe in which tom it is sounding and the resonance that it produces. The score extract (Figure 31) shows the notation for the resonators in the notes C and G whose amplification is routed to the 1st tom (the lowest) and the 4th tom (the highest) respectively.

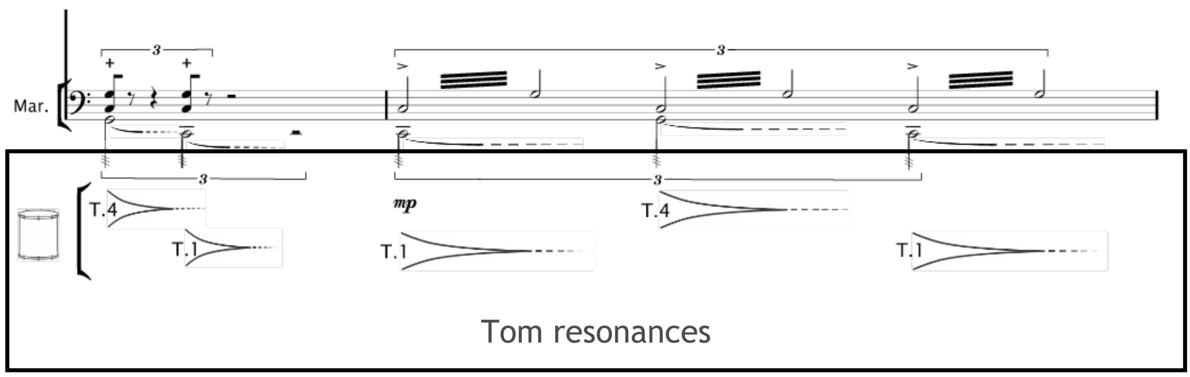

Figure 31. *Example of tom resonances writing.*

6.6 *Unfold* [1st & 3rd levels of SD]

Work for alto flute and electronics (14:12 min.)

In this work, the `third-level system` of SD is applied to the spatial implementation of the electronic part, whilst the instrumental writing uses techniques related to *`spectral jumps`*.

6.6.1 Concept of the piece

Unfold is a work that is informed by the construction of a *Dragon Curve*, using similar methods as seen in *Time Folds II*. In *Unfold*, these fractal shapes have been used to determine the trajectories of the fixed media sound materials that are distributed across space in a surrounding ring of 8 loudspeakers.

All the instrumental sound material is derived from a gesture related to *`spectral jumps`*. As seen in a fragment of the piece below, the overflow of partials generated via low fingering techniques in the alto flute, provides the following instrumental band divisions.

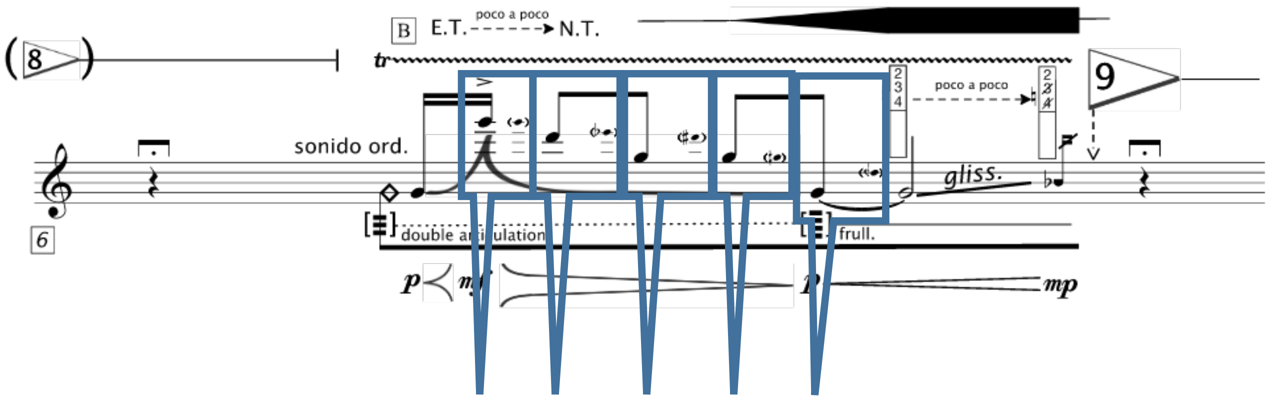

Figure 32. *Five band divisions as `spectral jumps` inside a low G fingering*

6.6.2 Space formalisation

The shape of the first three iterations of the *Dragon Curve* has been mapped and scaled into sound trajectories using an iPad app (*Tweak*[49]) to control X and Y positions and to link the spatial movement with the sound content. With this system, the use of superimposed trajectories not related to sound was avoided; e.g. when creating trajectories with the use

[49] Tweak is an OSC iPad app that allows the user to send MIDI parameters from a X and Y grid.

of a mouse interface not following sound material envelope. Figure 33 shows a smooth automatisation of Cue 10 in Reaper[50] using this technique for iteration 3.

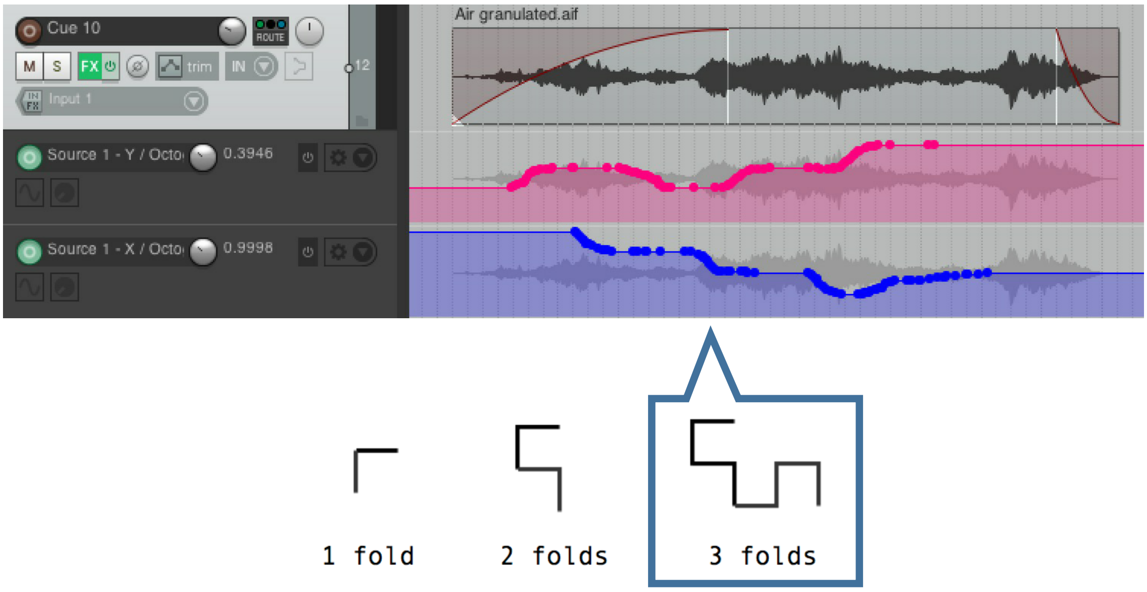

Figure 33. *Example of Dragon Curve spatialisation mapping.*

6.6.3 System implementation

Two different systems were developed to perform *Unfold*. As a result, we can observe advantages and disadvantages of each one. The first one is a Qlab[51] patch that easily allows the user to adjust small details during rehearsal. Since Qlab is not commonly used by the electroacoustic community, there was a second implementation of the same tool using Max 7, to facilitate the performance of this piece. The next two pictures show both patches, the first one is the Qlab version and the second one is the Max 7 implementation.

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[50] Reaper is a multitrack channel recorder similar to Pro Tools.
[51] Qlab is a software for scenic arts show control very common in theatres and stage productions generally.

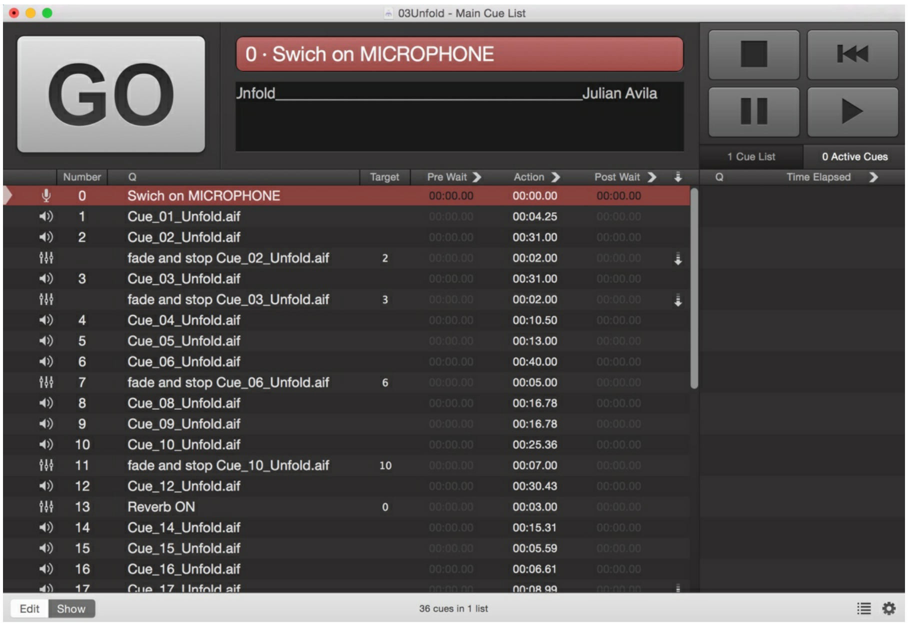

Figure 34. *Qlab implementations of the electroacoustic part.*

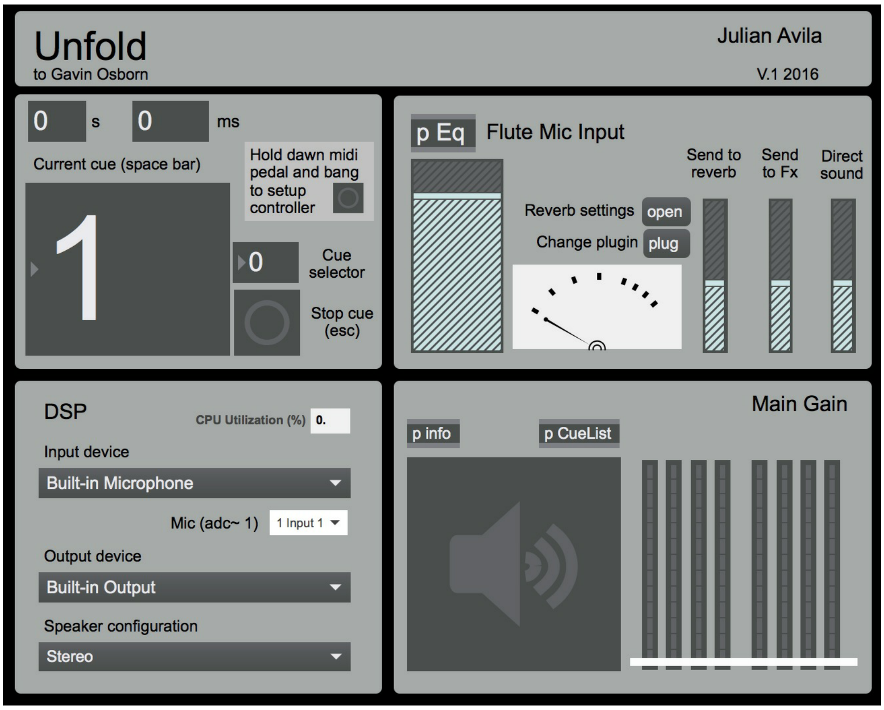

Figure 35. *Max MSP implementation of the electroacoustic part.*

6.7 *Garabatos* [1st, 2nd & 3rd levels of SD]

Piece for clarinet, cello, percussion and electronics (8:52 min.).

A tribute to Cervantes, the work was written to commemorate the 400th anniversary of his death. This piece is included in *Sound Spaces for Cervantes Project*, developed by staff of the CSMCLM[52] conservatory and was premiered during the *New Music Festival* at Gheens Science Hall Rausch Planetarium, University of Louisville (Kentucky, 9th November 2016). This project was co-funded by the Erasmus + Programme of the European Union.

Garabatos works on the 1st, 2nd and 3rd levels of SD using *burning frequencies* as an implementation of formant filters in an *asymmetric* and *disordered* SD system with frequency *holes*.

6.7.1 Concept of the piece

As Cervantes is one of the most important writers in the Spanish language, this work commemorates the 400th year of his death by using as a metaphor the sound that Cervantes listened to when he was writing his novels: the sound of a quill pen writing on paper. In a way, it is a tribute to the sound-field which Cervantes experienced while he was writing.

Given that *Garabatos* is the first of a concert-length set of pieces based on the life and work of Cervantes, it is the action of writing itself that provides the main sound base, a way of recognising Cervantes' status as the leading Spanish-language author.

6.7.2 Sound material

The main sound source of the whole piece is the sound of a quill pen writing the word “Cervantes” on paper. In *Garabatos*, this sound is repeated over and over again in different approximations of the real sound. The work traces a process from the most distant approximation of the real sound to the sound of writing “Cervantes” on paper placed on the timpani head. The image is simultaneously projected on a screen[53].

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[52] Conservatorio Superior de Castilla La-Mancha (Castilla La-Mancha Conservatory).

[53] The idea of using the sound generated by the action of writing is close to the concept of Smalley’s *Source Bonding* from *Space-form* (Smalley 2007), as at the end of the piece this sound recreates a mental image of the pen writing on a paper.

This structure has the aim of getting closer and closer to the real sound of the writing action. The origin of the sound that has been sounding throughout the piece is only disclosed at the end.

6.7.3 Relationship of SD elements to time and structure

The levels of SD in *Garabatos* are used to modulate tension and drive the expectation of the listener. The 1st level of SD is broadly used throughout the piece as is the 2nd level of SD. Both levels of SD have been applied at the same time or separately. The 3rd level has been used only to focus attention on the sound trajectories and to demarcate section changes in the piece. Figure 36 shows the use of SD levels over the piece.

Cue number	Bar	Fixed media	Live process	Levels of SD 1st	2nd	3rd
1	2	X	X	X	X	
2	4	X	X	X	X	
3	6	X	X	X	X	
4	8		X	X	X	
5	11		X		X	
6	15		X	X	X	
7	16	X				X
8	18		X	X	X	
9	39	X		X		
10	41	X		X		
11	48	X				X
12	49		X	X	X	
13	62	X			X	
14	65	X				X
15	66	X	X	X	X	
16	70	X	X		X	
17	71	X		X	X	
18	74	X	X		X	
19	75	X		X	X	
20	77	X				X
21	90		X	X	X	

Figure 36. *Use of SD levels and processes in Garabatos.*

First level of SD

The `first-level` of SD has been implemented in *Garabatos* using the timpani and bass drum as a Helmholtz resonator filtering frequencies and amplifying a small range of frequency content. The instrumental technique used was scribbling on a paper placed on the timpani head and modulating the sound with the tuning pedal. In this way, there is an enhanced band of frequencies as a type of instrumental *`burning frequencies`*. Figure 37 shows this technique in a rhythmic writing.

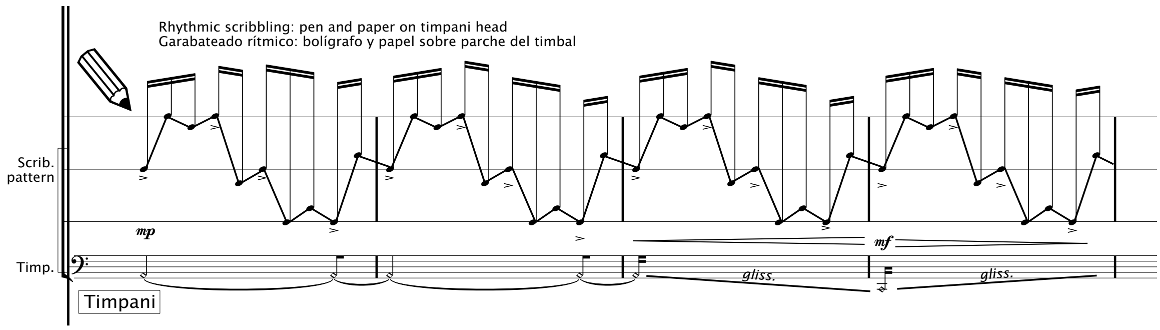

Figure 37. *`First-level` of SD applied in Garabatos.*

A range of derivative material has been used as a gradual approximation of this sound, for example, using shoe brushes on the bass drum or superball mallets. Figure 38 shows two different approximations of the former sound.

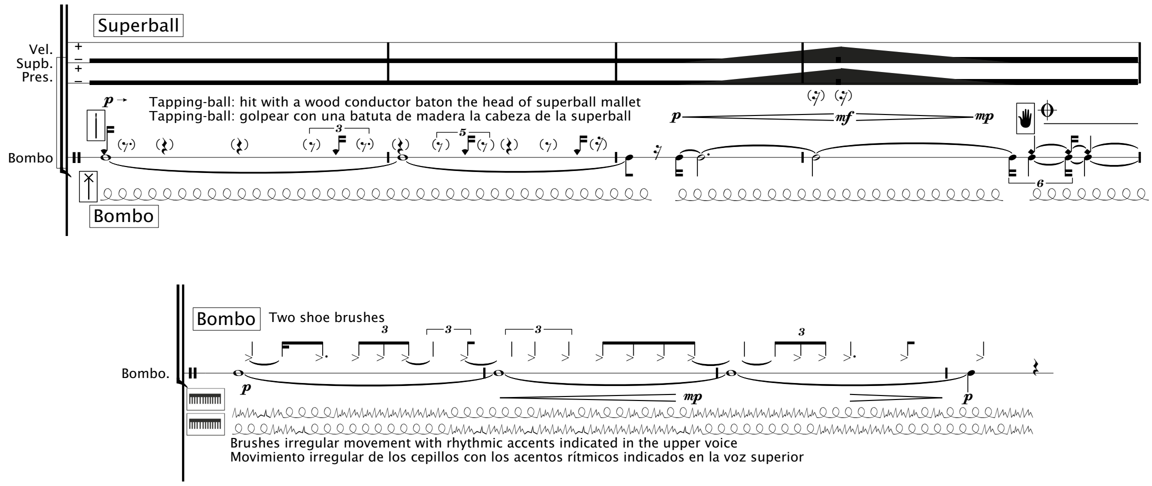

Figure 38. *Two approximations of sound in Figure 37.*

Second-level of SD

The `second-level` of SD has been implemented as a metaphor for vowel sounds. In this level, formants[54] of a masculine voice have been used to filter live sound creating a sort of `asymmetric, disordered` SD system with frequency `holes`.

Vowels used for the formant filters have been extracted from the full name of Cervantes, Miguel de Cervantes Saavedra. With this sound process, the instrumental sound has been filtered and modified to sound as the vowels contained in the word. The sound writing of the full name of Cervantes is also the ground sonic material recorded for this piece. Figure 39 shows this filtering process applied to the bass drum with vowel changes and fundamental changes as a PAF filter.[55]

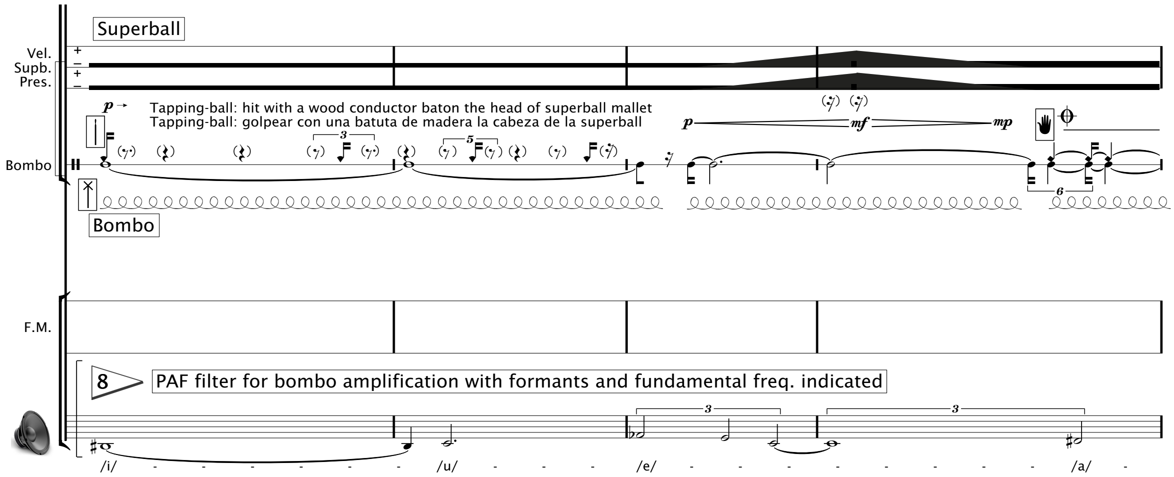

Figure 39. *PAF filter for bass drum live sound.*

Third-level of SD

The `third-level` of SD has been used in the fixed media parts. This implementation has been done using PAF filters and spatialising the sound with Ambisonics. The fixed media elements of *Garabatos* are encoded in Furse-Malham 3rd order Ambisonics: recordings are

[54] Vowel formants are the regions in which the first partials of the human voice saying a vowel are located. These formants have a band range in which the partials are usually located depending on the range of the voice (e.g. bass, soprano, etc.).
[55] PAF: phase-aligned formant synthesis algorithm developed by Miller Puckette (Puckette 2006). A modification of this synthesis generator algorithm has been used as a formant filter. Live filters have been implemented with FFT band-pass filters and fixed media sound has been filtered with modified PAF filter. In the score, all formant filters are notated as "PAF filter".

decoded for the loudspeaker array during the performance allowing for any disposition of surrounding loudspeakers.

The decision to use the `third-level` of SD in the fixed media parts only, responds to the fact that it is very risky to implement this level of SD with low frequencies and live processing. Low frequencies are omnidirectional and even if PA or loudspeakers near the instruments are facing the public, feedback problems could easily present. As this work was composed to be premiered in a planetarium with loudspeakers behind the screen, this option was adopted as a solution.

3rd level of SD has been implemented in *Garabatos* alone (without other levels of SD). The 3rd level parts are distinguishable from the others and facilitate trajectory appreciation by the listeners. It is this distinctive aspect in level 3 (trajectory implementation) that has driven the musical decision. In addition, 3rd level sections have the function of demarcating sections but also making a join between them. Figure 40 shows the macroform of *Garabatos* and the use of the 3rd level of SD.

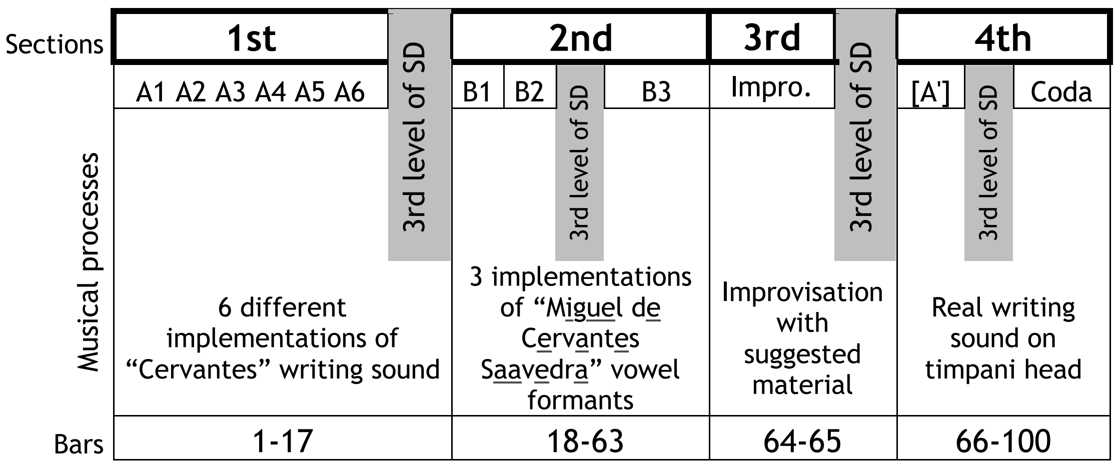

Figure 40. *Sections of Garabatos and use of 3rd level of SD.*

Implementation of 3rd level sections

First: writing sound recordings with different PAF filters spatialised with intuitive trajectories recorded with an XY pad.

Second: spatialisation of SD instrumental material played before (bars 46-47). This part adds the spatial component to instrumental material.

Third: SD material on timpani (as a Helmholtz resonator) spatialised with intuitive trajectories recorded with an XY pad.

Fourth: segmented cello bow recording technique with low-pass filtered and spatialised in an anti-clock revolution around the audience.

The macroform in *Garabatos* has been implemented by changing the level of SD used in each part. This technique resembles a zoom-in and zoom-out inside levels of SD that modulates listeners' attention. In addition, changes between SD levels in *Garabatos* are linked to musical repetition, so macroform is conducted by SD level changes and musical repetitions. These repetitions are not literal and SD levels are not always applied in the same way. This non-literality of repetitions appeals to the subjective perception of time and memory, two crucial aspects of musical form.

6.8 *Worstward* [1st & 2nd levels of SD]

For bass clarinet and live electronics (10:47 min.).

This piece investigates the 1st and 2nd level of SD with *spectral jumps*, *elastic deformations* controlled by hyperbolic paraboloids[56] as well as *elastic deformations* applied to instrumental writing. The electroacoustic part allows the performance in stereo, quadraphonic and octophonic arrays implementing a system of *spectral jumps* in the *surrounding matrix* with *system impurities*.

6.8.1 Dutch-UK network

This piece is part of the Dutch-UK Network[57], a project between the Institute of Sonology at the Royal Conservatory of The Hague and the NOVARS composers' community. In this project several composers, inspired by the Phillips Pavilion for the Brussels universal exposition in 1958, have created new pieces for bass clarinet and electronics. In this work, Le Corbusier, Varèse and Xenakis worked together with Philips technicians to create a multimedia show.

All the pieces composed were premiered by Marij van Gorkom after a writing process involving several working sessions with the performer.

> *[…] Scientific improvements and progress in beauty are interlocking factors. As it throws new light in Nature, Science makes its possible for music to go forward by confronting our senses with barely-understood harmonies and unknown sensations. On the threshold of Music, Science and Art work hand in hand.[58] (Varèse, Edgar; Stockhausen, Karlheinz; Maderna, Bruno; Boulez, Pierre; Berio 1963)*

6.8.2 Philips Pavilion and the relationship with the work

This work is inspired by the Philips Pavilion (hereinafter PP) in two different ways. The first is the shared interest in formalising space for generating space-form music. This first

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56 Hyperbolic paraboloids are curves created by superposing lines. These structures were used in the Philips Pavilion as a main architectural structure.

57 www.dutch-uk.network

58 Message from Edgar Varèse to the promotors of the Electronic Music Studio in Brussels.

common point is obvious because the PP is considered the first multimedia show and sound spatialisation was one of the technologies used in the project as well as one of the foci of this work.

The second point of inspiration is the use of hyperbolic paraboloids. These structures were designed by Iannis Xenakis and used as the main structure for the PP as well as for formalising glissandi in *Metastasis* (Xenakis 1967) for orchestra. *Worstward* takes this idea and implements it to control spectral band limits creating `elastic deformations` of the spectral bands. To implement these structures, Iannix[59] software has been used in combination with Max, not only for generating sound but also for controlling limits of the band filters.

> *It is possible to produce ruled surfaces by drawing the glissandi as straight lines. I performed this experiment with Metastasis (this work has its premiere in 1955 at Donaueschingen). Several years later, when the architect Le Corbusier, was collaborator I was, asked me to suggest a design for the architecture of the Philips Pavilion in Brussels, my inspiration was pin-pointed by the experiment with Metastasis. Thus I believe that on this occasion music and architecture found an intimate connection. (Xenakis 1972, p.10)*

6.8.3 Split sounds and sound material of *Worstward*

Worstward considers the option of making a live spectral division of the bass clarinet sound. This means that a very rich sound (spectrally speaking) was needed in order to give material to each frequency band. After considering various instrumental techniques, split sounds[60] were chosen as the best clarinet sounding technique to cohabit with SD band division.

The production of this sound is relatively easy, nevertheless it is difficult to notate due to the fact that one single fingering can produce a huge amount of different sounds. To notate this special technique, and after studying the notations used by other composers (Iannis Xenakis, Klas Tortensson, Tomás Marco, Jos Kunst, Takayuki Rai and Arne Mellnäs), it was decided to create a more concise notation. Figure 41 shows the notation used in *Worstward* for the split sounds[61].

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[59] Iannix is a software inspired in Upic, a type of graphic interface for producing synthetic sounds from line pictures.

[60] Split sounds seem to be firstly used in *Échange* a piece for bass clarinet and ensemble of Iannis Xenakis. *These "split sounds" are produced by means of embouchure only and work best in the lowest register. No special fingerings are needed.* (Sparnaay 2012)

[61] Split sounds in *Kantaber* (see chapter 6.3.2) are very similar to these ones but the technique and

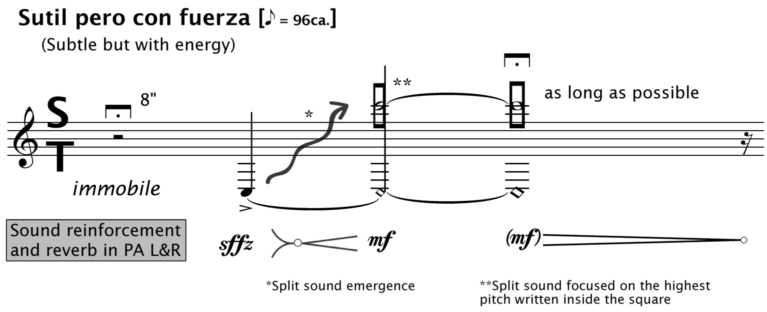

Figure 41. *Split sounds notation for bass clarinet.*

Notation provides information on the low fingering (diamond note head) and the focused note in the high register (normal note head). This pitch is the most perceptible one. The square notates that the high note is not the only one sounding since there are other surrounding notes. Although it seems that the high "C" is a partial that it is not possible to obtain from a low "C" fingering as it is an even harmonic, it is possible to produce it as a split sound.

These types of sounds are by nature an instrumental mode of spectrally divided sound with `spectral jumps`, as they contain a low frequency isolated from a cluster of partials in the high register and could be changed individually as if a hypothetic band limit were changed creating a sort of instrumental `elastic deformation`. This idea is applied extensively at the end of the piece with a continuous change of fundamentals and high focused notes. For this reason, this piece is considered inside the `1st level` of SD, because a SD idea is translated to an instrumental technique. Figure 42 shows the score writing of this idea.

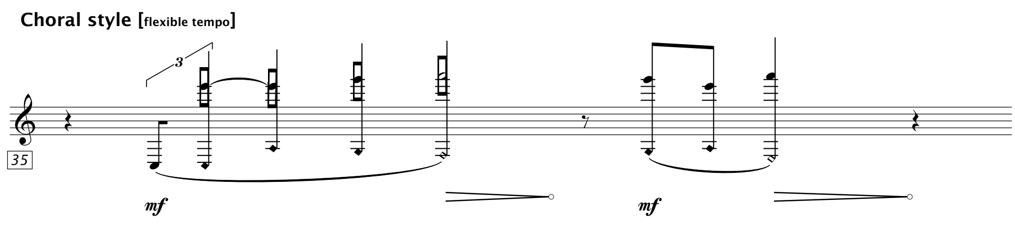

Figure 42. *Split sounds with changes in fundamentals and focused notes.*

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production of split sounds in the tuba is very different than in bass clarinet. For this reason, the notation is also different.

6.8.4 Electroacoustic implementation

There are two processes working separately or in series during the piece. The first is a spectral band division that is controlled by hyperbolic paraboloids. The other is a Fourier Filter[62] in which spectral bands change amplitude weights in a continuous form swapping from one value to the next.

These two processes are complementing each other: spectral band division makes it possible to route a portion of sound to each loudspeaker and elastic deformations are controlled by Iannix software changing the limit of spectral bands. Katja's Fourier Filter adds a degree of mutation to the live sound of the clarinet, generating infinite downward spectral glissandi and implementing a `jump rate` on the spectral energy of sound.

Processes are applied live or to fixed media cues depending on the searched sound result and looking for the best solution in each point of the score. Final sound output roots one or more spectral bands to each loudspeaker depending on the `surrounding matrix` configuration that can be set up for stereo, quadraphonic or octophonic systems. The main block diagram of sound processing in *Worstward* can be seen in Figure 43.

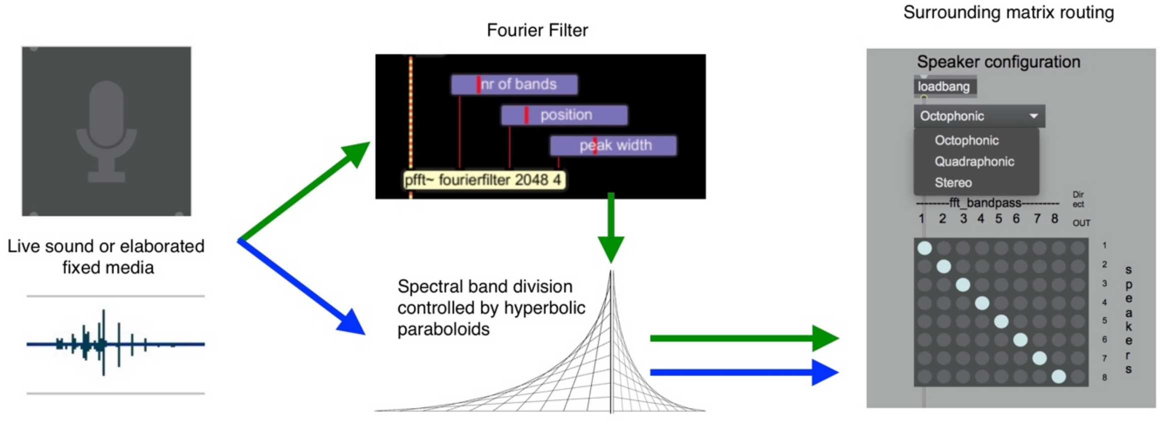

Figure 43. *Block diagram of sound processing in Worstward.*

Iannix control (hyperbolic paraboloids) over FFT band filter limits creates a sort of continuous `elastic deformation` with `spectral jumps` that converge in the low or high range of frequencies creating an `impurity system`. This superimposed control

[62] This filter is designed and explained in http://katjaas.nl/fourierfilter/fourierinmax.html *Wosrtward* patch implements a version of this as adapted to the needs of the piece.

generates ascending and descending live electronics gestures.[63] Figure 44 illustrates some hyperbolic paraboloids designed in Iannix for *Worstward*.

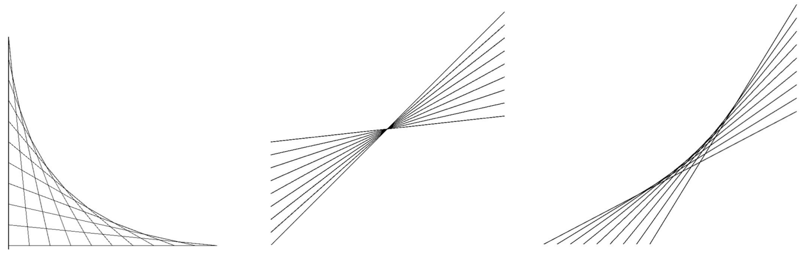

Figure 44. *Example of hyperbolic paraboloids designed for Worstward ('X' axis represents time and 'Y' axis represents frequency).*

[63] Implementation of `elastic deformations` controlled by hyperbolic paraboloids generates a concept that resemble Smalley's description of *Diagonal Forces, Planes* and *Levitation* (Smalley 2007). The main differences are that the technique developed for *Worstward* always links spectral content to space, and the motion is created by an external agent (hyperbolic paraboloids) not by the spectral content of the live clarinet sound.

6.9 *Low* [1st & 2nd levels of SD]

Guided improvisation for double-bass flute, bass clarinet, tuba and live electronics (15 min.). In this work, 1st and 2nd levels of SD are investigated through *elastic deformations, disordered* and *asymmetric systems, burning bands*[64] with smooth *transitions*.

6.9.1 Concept of guided improvisation

As mentioned in the previous chapters, this investigation implements SD techniques in different musical genres. Improvisation is one of them. In this case what is presented to performers is a known material on which to improvise and in consequence there are a huge number of variables controlled by the composer. However, the final result is in the performers' hands. As in jazz improvisation where harmonic material is fixed, in *Low* the timbral material is fixed, for that reason the work is referenced as "guided improvisation".

The piece requires instruments and loudspeakers to be set up in a triangle formation around the public. In this way, loudspeakers create a *surrounding matrix* and the performers within form part of this *surrounding matrix*. The electroacoustic performer is placed in the middle of the public since their function is to modulate instrumental sound into a concrete band of frequencies inside SD. The work is structured into contrasting sections in which electronic means modulate instrumental sounds and sections without electroacoustic manipulations. There is another layer of structural contraposition that corresponds to those sections in which each performer improvises without taking into account the other performers, and sections in which players must interact each other. This organisational technique creates a modulation between ensemble sound and atomised sound from individual instruments in which the perception of spatiality is enhanced.

All the elements of this piece are formalised using the information of turning folds of a dragon curve generated as a Lindenmayer system.[65]

---

[64] *Burning band* is a derivate concept from *burning frequency* but applied to a range of frequencies.
[65] Information about Lindenmayer systems and dragon curve is found in chapter 6.5

6.9.2 Material proposed for improvising

The sound material of *Low* is extracted from *Kantaber*, *Unfold* and *Worstward*.[66] Ideally the work is intended to be programmed in the same concert as these three-solo works.[67] If this is not possible, performers must have played the solo pieces before and be well acquainted with the sound and instrumental techniques required.

This piece uses 8 types of timbral materials that are organised according to frequency content. This material classification gives the piece a structure in the frequency domain that is changing and evolving in the time domain. Figure 45 shows the correspondence with the Lindenmayer folding sequence (three "+" or "-" signs in any combination), and its correspondence with timbric material.

<table>
<tr><th>Folding sequence</th><th>Correspondence with timbric material</th><th>Frequency band</th></tr>
<tr><td>+--</td><td>Air sounds</td><td rowspan="3">Above instrument register range</td></tr>
<tr><td>-+-</td><td>Split sounds (multiphonic sounds)</td></tr>
<tr><td>+++</td><td>Harmonic playing (playing harmonic series inside same fingering)</td></tr>
<tr><td>++-</td><td>As high as possible (very high register)</td><td>High end register</td></tr>
<tr><td>+-+</td><td>Quick passages</td><td rowspan="3">Register range</td></tr>
<tr><td>--+</td><td>Trill tremolo sounds</td></tr>
<tr><td>---</td><td>Sustained notes</td></tr>
<tr><td>-++</td><td>As low as possible (low end register)</td><td>Low end register</td></tr>
</table>

Figure 45. *Correspondence between timbric material and folding sequence.*

These types of material are present in the three solo pieces mentioned before in many different ways and form the base sound material of *Low*. Those ranges of different playing

[66] See chapters 6.3, 6.6 and 6.8 respectively.
[67] As happened at the premiere performance.

techniques are used in *Low* as a reservoir of timbral material. In this way, performers see in the score a small portion of material that they already know and use this as a suggestion for improvising during a determined amount of time. Figure 46 shows an example of flute material proposal for minute 1'00" to minute 1'20". The first 10 seconds correspond to the +-- sequence (air sounds), and next 10 seconds correspond to the -++ sequence (as low as possible sounds).

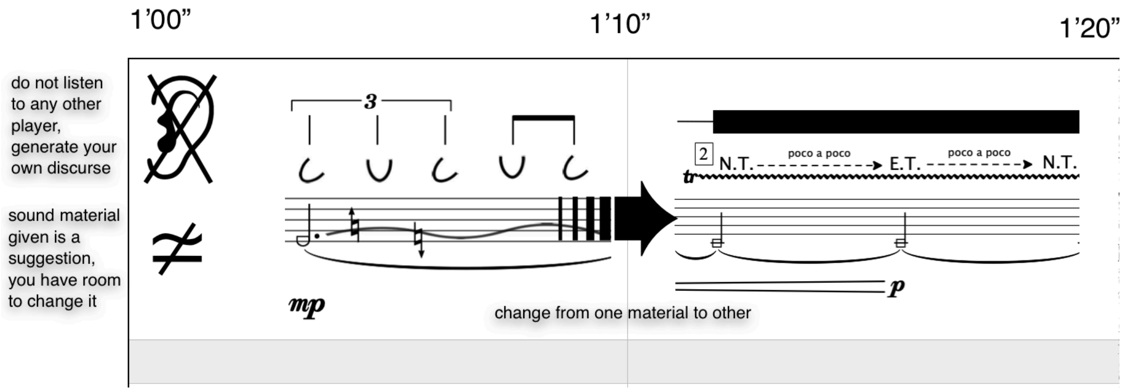

Figure 46. *Example of sound material proposal for improvising in double-bass flute part.*

6.9.3 Electroacoustic processes

The electroacoustic part of *Low* consists of a process of convolution between the three different instruments and a source sound that is spectrally divided into 3 frequency bands.[68] There are three convolution processes that convolve one instrument with its source sound band. These source bands are pink noise, material derived from a granulator[69] and the different instrument input. This means that it is possible to convolve the flute sound and the clarinet sound apart from convolving any of the three instruments with source materials or any parallel process. As band division is implemented in the patch with third order Butterworth crossover filters[70], smooth `transitions` between bands are obtained. During a live performance band limits are manipulated without attending to the symmetric division of bands. The piece comprises therefore a study of `elastic`

[68] This three-band convolution actuates as a frequency band attractor that enhances a portion of the spectral content the performers are playing. This process resonates with the concept of *Gravitation Space* in the paper *Space-form* (Smalley 2007).
[69] A version of *Geiger Granular* from Nobuyasu Sakonda has been modified and implemented in this patch.
[70] 3rd order Butterworth crossover filter is a filter with 12dB of attenuation each octave below the frequency cut. These filters were used in passive loudspeaker cabinets up to 90'.

deformations and *disordered* and *asymmetric systems*. In addition, and owing to in-performance manipulation by the electroacoustic player, the piece works on the basis of *burning frequencies*. These are a result of selecting the same band of frequencies for all the instruments in the performance patch.

The electroacoustic performer only changes the sound of the players in the sections in which performers are playing the same material and interacting with each other (these sections are notated inside a highlighted square in the score). The electronics in this piece have the function of homogenising timbre or separating the timbre of the instruments depending on the configuration of the band and source sound selected. The electronic part in the score only indicates if electronic processes are affecting the sound or not.

The source materials for the granulator should be chosen freely by the electroacoustic improviser taking in to account the sound material proposed in the instrumental parts in each section and collaborating with the players for achieving the written nuances. In the sections in which the electronics are not processing sound, instruments should be amplified only.

Figure 47. *Low improvisation patch for the electroacoustic performer.*

6.9.4 Structure formalisation

The structure of *Low* is formalised by using the fold sequence of a dragon curve. This curve is constructed as a Lindenmayer system and structures several layers of information as well as organising sound material. In the next four steps the different layers of formalisation are described:

1. Score minimum unit division: the piece is 15 minutes long and has been divided into small sections of 10 seconds. These sections are the minimum unit of the piece and represent the minimum amount of time in which one determinate timbre could be developed and could be considered a "bar". These sections structure all the pages of the piece, each page contains one minute of music divided into 2 staves of 3 sections each.

2. Playing and non-playing sections: the first decision is made by applying the folds sequence to playing and non-playing sections. In this layer, right turns represented by "+" signs have been mapped to playing sections and left turns represented by "-" signs have been mapped to non-playing sections. Each fold sign has been mapped in sequence to each section of 10 seconds. The complete code generated by Max for the 9th iteration of the dragon curve and its simplification follows:

```
FX+YF++-FX-YF++-FX+YF+--FX-YF++-FX+YF++-FX-YF+--FX+YF+--FX-YF++-FX+YF++-FX-YF++-FX+YF+--FX-YF+--
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FX+YF++-FX-YF+--FX+YF+--FX-YF+
```

A filtering process is applied to obtain only right and left folds (+ and -):

```
++-  -> +
```

```
+--  -> -
```

`FX` -> eliminate

`YF` -> eliminate

Final list of folds:

```
++-++--+++--+--+++-++---++--+--+++-++--+++--+---++-++---++--+--+++-++--+++--+--+++-++---++--+---++-++-
-+++--+---++-++---++--+--+++-++--+++--+--+++-++---++--+--+++-++--+++--+---++-++---++--+---++-++--+++--
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--++--+--+++-++--+++--+---++-++---++--+---++-++--+++--+--+++-++---++--+---++-++--+++--+---++-++---++--
+--+
```

3. Tutti parts and atomised playing: in *Low,* there are 2 different ways of improvising. The first is as an ensemble performance, consequently players should interpret the music by listening to each other and interacting as in a typical improvisation session. The other type of playing is as an individual player, even if there are other performers playing at the same time. Each player should focus on his or her own improvisation without interacting with the other performers.

These sections are structured after the playing and non-playing sections. When all the instruments coincide in a non-playing bar they start a section in which all of them will play the same type of timbral material and the improvisation will be an interaction between them. Those sections are indicated in the score inside a highlighted square. When the music arrives at another general non-playing bar, the improvisation goes back to an atomised playing mode.

4. Timbrical material: the last step in the formalisation process is the mapping to each section and instrument of its respective timbre. In order to achieve this, the previous simplified folding sequence has been divided in blocks of three folds and has been assigned to each different timbrical section (see Figure 45).

Figure 48 shows the second page of *Low* with the formalisation structure presented in this section superimposed in different colours. The red colour is superimposed playing and non-playing sequence and blue colour is superimposed by the timbrical material.

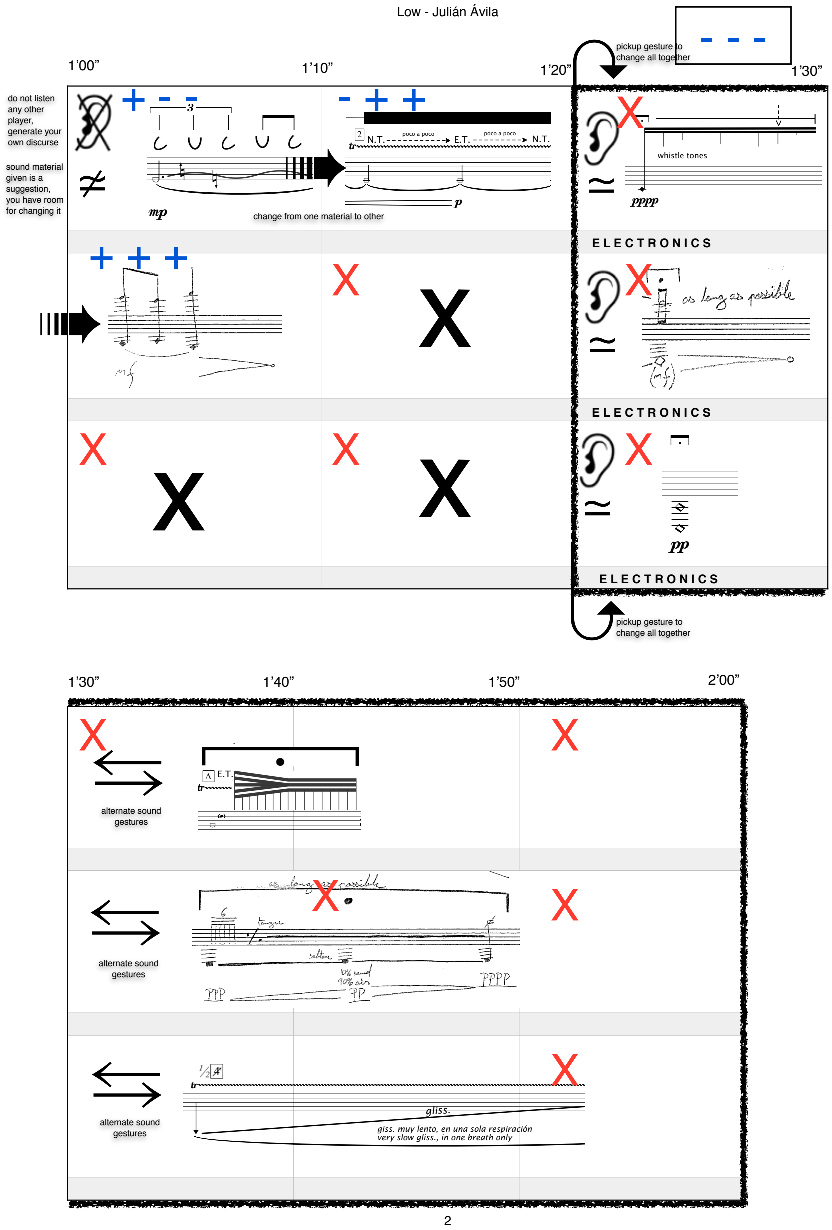

Figure 48. *Lindenmayer formalisation superimposed on page two of Low.*

6.10 *Cuasicristal III* [1st level of SD]

Work for flute, alto saxophone, violin, viola, cello and piano (7:57).

This piece is the third part of a cycle of pieces that uses quasicrystals as a musical metaphor. *Cuasicristal III* (Ávila 2017) explores the concept of `burning frequencies` in the field of instrumental composition.

6.10.1 Concept of the piece

Quasicrystals are atomic structures that occur in metal alloys that repeat their structure again and again, but sometimes this repetition is not exact. This structure behaviour has been used as a metaphor for non-exact repetition in music. In *Cuasicristal III*, there is only one source material repeated 8 times throughout the piece. Notwithstanding, this repetition organises the piece structure but musical repetition is blurred by the use of SD techniques that try to work in the field of "quasi-repetitions".

The `burning frequencies` in electroacoustic spectral diffusion techniques enhance some frequencies that are present in a determinate sound. In this work, all of the material for the strings is composed before starting the process of score writing. In this way, this source material is the main source for the entire score and metaphorically speaking is the quasicrystal structure of the piece. This ground material is ordered by strings, so each four strings of each string instrument have their own specific material. Figure 50 shows all the map material together.

Figure 50. *Picture of source map material.*

Once the material is organised, the compositional process consists of choosing these materials and reorganising them in the final score, therefore this final choice is, by analogy to SD electroacoustic techniques, the process of `burning frequency` enhancement.

Afterwards, it is the string trio that will create the enhancement of frequencies, whilst the other ensemble instruments enhance and introduce timbrical richness to the ground material. In this piece, the acoustic instruments are therefore assuming the function that usually belongs to the electronic part.

6.10.2 Ground material

The ground material consists of self-similar harmony and rhythm calculated in OpenMusic and derived from a division into two golden sections of the total range that is used inside one string. This material is organised as multiple rates of self-similarity that are reflected in the ground material map. Figure 51 shows the OpenMusic patch used to calculate all the material, and an example of IV string material correspondence.

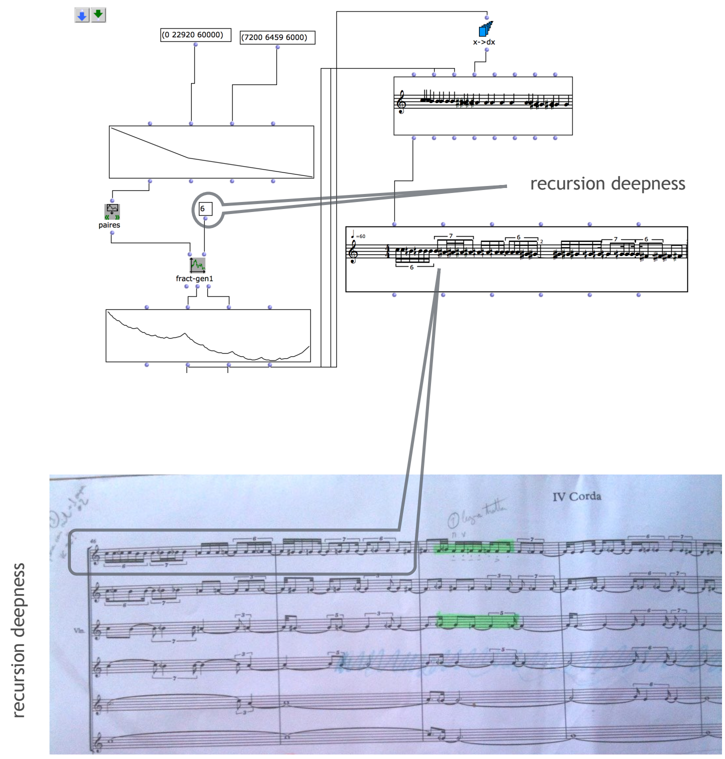

Figure 51. *Open Music patch for instrumental material formalisation for violin IV string.*

6.10.3 Score formalisation

Cuasicristal III is structured into seven repeats of the source material plus one "quasi-repetition" but using different enhancing frequencies inside the recursion depth of the material. These eight repetitions are presented with different timbrical realisations and are preceded by an introduction. This form can be compared to with a traditional passacaglia or chaconne but the main difference is that even though the score repeats over and over again the same source material, it is impossible to perceive this repetition. For that reason, these procedures are more closely related to `burning frequencies` structure and SD techniques organisation than to perceptual musical repetition. Figure 52 shows the macro formal structure of the piece. Note that as the repetition is not perceived by listening to the piece, different letters are chosen for each section.

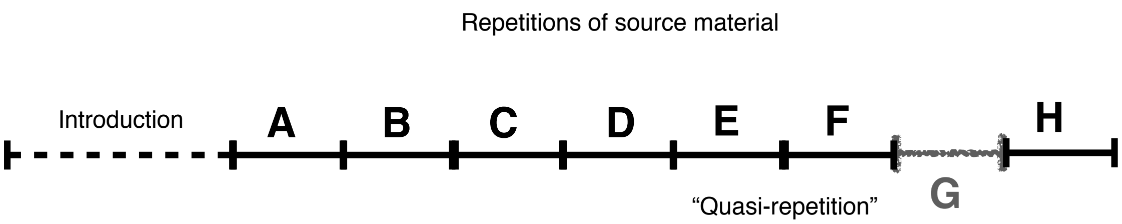

Figure 52. *Macro structure of Cuasicristal III.*

6.10.4 SD at Quasicrystals service

One of the research questions of this thesis is investigating to what extent SD processes could cohabit with other compositional and structural ways of organisation. In *Cuasicristal III,* there is a subordination of the SD techniques to the concept of quasi-repetition. That means that SD has been used as a compositional technique and macroform is superimposed by another idea.

Cuasicristal III uses its macroform repetition as a metaphor of quasi-repetitions in quasicrystals but achieves different levels of similarity between sections implementing the concept of `burning frequencies` in a 1st level of SD.

7. Conclusions

This portfolio of musical compositions emerges from research into, and the construction and implementation of a Spectral Diffusion system and its vocabulary and grammar. The work has been informed by a variety of existing research and resources.

The submitted compositions illustrate a number of strengths and weaknesses deriving from the implementing of both Spectral Diffusion and Spectral Energy in the compositional process. A well-defined methodology for this implementation is proposed, starting with the definition of the three levels of Spectral Diffusion techniques and a suitable vocabulary (informed by biophysics and spatial audio and form terminology). The vocabulary is gradually employed as the portfolio and research evolves. These levels of SD were applied across a diverse range of compositions and musical genres within this portfolio, not only to evaluate the potential and limitations of the techniques but also particularly to develop a unique and personal compositional voice, whilst at the same time demonstrating the potential for musical expression, from which others can benefit.

More specifically the investigative process has resulted in several compositional milestones.

SD techniques have a positive impact on compositional focus and creative constraints: working under the limitations of organising material through spectral division and spatial band allocation, requires the composer to restrict her/himself to those compositional artefacts.

SD implementation has demonstrated excellent adaptation and success across genres and musical forces in the context of this portfolio. This ranges from instrumental pieces (solo, ensemble and symphonic music), to fixed media, mixed media, sound installation and improvisation music.

The research undertaken has determined a number of suitable sound sources and scenarios for the successful implementation of this technique, especially for determining the needs of spectral content found in sound materials in the second and third level of SD. There is an inherent need for having live sound sources with broad spectral occupation.[71]

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[71] It can be noted that the final pieces of this portfolio (e.g. *Worstward*) have handled this question with greater accuracy than the first ones (e.g. *Pronomo's Space [e]*).

SD systems work particularly well alongside non-audio processes and structured systems of formalisation, such as fractals or self-similar structures. Examples of this can be found in *Low, Unfold, Time Folds II and Cuasicristal III*. This basically means that SD could also be controlled by alternative macro formal structures –not only mathematical ones– without losing its potential for generating musical expression. This may include SD as the main process for determining the whole structure of a piece, as well as for controlling all levels of formalisation.[72]

A difficult aspect of this research was to find a suitable vocabulary across spectral analysis and sound diffusion in spatial audio and form. Therefore, the author had to amalgamate new terminology which involves existing vocabulary in spectral taxonomy and spatial form with non-musical vocabulary (e.g. in spectral diffusion biophysics) for the purpose of navigating the methodologies and musical thinking behind this portfolio of works.

The first level of SD is probably the most open-ended and conceptual level out of the three, as it is often applied as a different metaphor in instrumental music contexts.[73] This may also apply to any other type of external structure mapped on to musical parameters though. For example, there is an infinite number of ways of implementing the same fractal structure to a piece. However, it is key for the composer to identify which options work better for each need.

The second level of SD is far more concrete than the others, as each spectral band is always routed to a spatial source (e.g. a loudspeaker). As a consequence, composing with this level implies an extensive use of *elastic deformations* and, in general, the use of techniques that allow spectral changes on each spectral band, as a way to avoid a static sound image in the *surrounding matrix*. This level has a good balance between the use of computational resources used and the efficient diffusion of the sound image.

Finally, the third level of SD is, technically speaking, the level with more variables available for implementation and mapping. This level is a clear extension of the second one because it adds sound virtualisation and it widens its range for potential implementation, since this process could be applied to a variety of different technologies.[74] It is particularly suitable

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[72] As happens in *Kantaber*, *Garabatos*, *Pronomo's Space [e]*, *Travesía*, and *Crescencia*.
[73] As can be seen in *Crescencia* and *Cuasicristal III*.
[74] Not all the technologies available have been used in this research as this was not a part of the enquiry. Technologies used have been the most convenient for each case in terms of computational resources and sound result.

for the formalisation of musical trajectories, as this is one of the main features that distinguish it from the others.

The composition process of a piece using SD techniques is very malleable. This is due to the fact that the levels of SD can work together or separately and in any combinatorial set between them. This trait gives large compositional freedom in terms of thinking and planning a new piece and it is probably one of the reasons why the possibilities for adaptation of SD to different scenarios and musical genres are so ample.

Future work

Beyond the scope of this portfolio but certainly a future implementation of SD, which the composition community could benefit from, would be to programme a general tool for applying first and second levels of SD to a sound input. A type of plugin or standalone program could be developed to share with other composers for alternative applications in the creation of new pieces, formalising new structures or transforming sound.

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9. Annex A

Audio example of levels 2 and 3

A sample audio file is included in the USB drive. It exemplifies the 2nd level of SD and the 3rd level of SD. The sound example is created for an octophonic ring of loudspeakers. This audio includes examples of the infinite possibilities that 2nd and 3rd levels of SD can produce. This audio sample is included in the annex in order to clarify aural differences between the 2nd and the 3rd level of SD.

10. Annex B

Works composed before starting this PhD but related to it

10.1 Score of *Koch's Space*

Score and recordings are included in the USB drive.

10.2 Score of *Blau*

Score and recordings are included in the USB drive.

11. Annex C

Works composed during this PhD exceeding maximum permitted duration

11.1 *El Mar La Mar* [2nd level of SD]

For 8 channels fixed media (6 min.)

In this piece, the `2nd level` of SD is used by juxtaposing *`glassy systems`* and *`disordered systems`*.

11.1.1 Concept of the piece

This work implements the `second-level` of SD through a ring of eight loudspeakers, employing traditional filters similar to those used in analogue devices. The basic concept is to take a mono recording of a sea water /maritime environment and spread its rich frequency content in bands across the loudspeaker surround sound system, so that the entire loudspeaker system works as an array of spatially distributed frequencies, conforming the entire sea spectra. One of the aims of the piece is not only to change the sound, but especially its perception by the listener, in order to create different representations of the sea in space.

This piece does not follow traditional acousmatic composition in which an important part of the compositional process consists of generating and organising new sound material deriving from an original source. Rather, the source material of this piece (the sea sound) is not transformed via such traditional methods. However, it does make use of SD techniques to create the illusion that these transformations exist. The aim of this type of compositional technique is to highlight the SD process and lead the listener's attention towards it.

11.1.2 Realisation

A Max patch has been implemented to split one channel recording into eight different spectral bands using a process similar to that used in Rob Hordijk synthesisers[75], in which

[75] Rob Hordijk synthesisers are handmade analogue and modular instruments.

two hi-pass filters are used to create a band pass filter. Here, the output of each filter is directly routed to one of the loudspeakers. The idea of implementing this filtering method in Max is to create a filter typology that resembles analogue sound in order to contrast with other SD systems explored in other pieces of this portfolio (created using FFT techniques). In addition, these filters allow an overlapping of frequencies between bands, creating *spectral transitions* between *neighbour bands*. Figure 53 shows the basic idea using this filter in Max for *El Mar La Mar*.

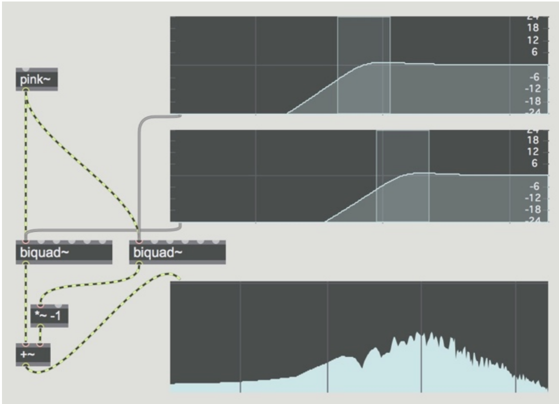

Figure 53. *Band filtering process in El Mar La Mar inspired by the Rob Hordijk filter.*

Apart from developing this special type of filter, other features have been implemented to explore different changes in *ground states* as well as a new modulation of elastic deformations. Changes in *ground states* have been developed with the object *matrix~* allowing fast changes in the routing of bands to different loudspeakers, and *elastic deformations* have been programmed as independent LFOs[76] that control band limits as well as the Q factor[77] of each filter. Figure 54 shows the patch used for performing these processes in communication with Pro Tools[78] through Soundflower[79] as if it were an external VST[80] plugin created especially for this piece.

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[76] Low frequency oscillator.
[77] Quality factor of filters.
[78] Avid DAW software with random data access.
[79] Soundflower is a Mac native app that allows 64 audio channels communication between audio software.
[80] Extension for external plugins for DAW and other audio software.

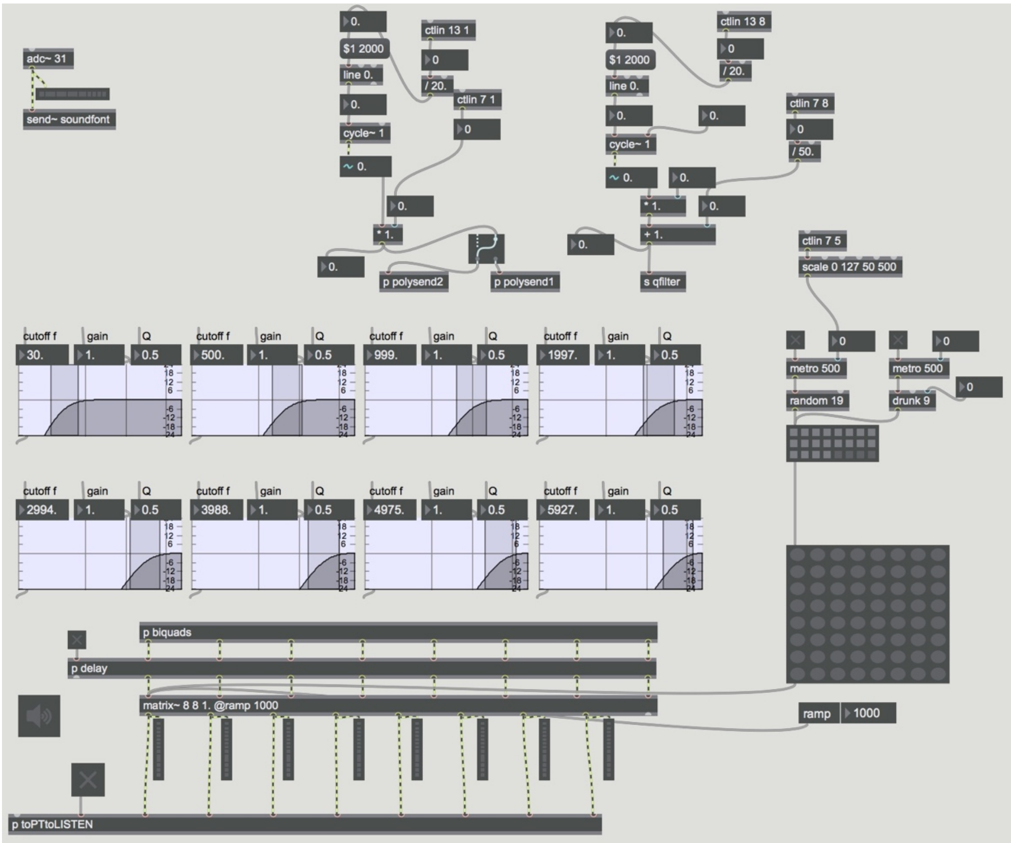


Figure 54. *Max MSP patch for performing SD in El Mar La Mar.*

These processes have been organised throughout the piece by constructing a crescendo-like tension shape, moving from more static SD processes to more dynamic ones. There are two large sections plus one introductory part. The introduction has the role of disrupting the inertia of silence and initiating the sound of sea (no SD processes are applied to this section). The first section investigates *glassy systems* and changes between different *ground states*. The second section works around *elastic deformations* of previous *glassy systems* and introduces an increasing degree of change in the *disordered system*. Figure 55 shows overall formal structure.

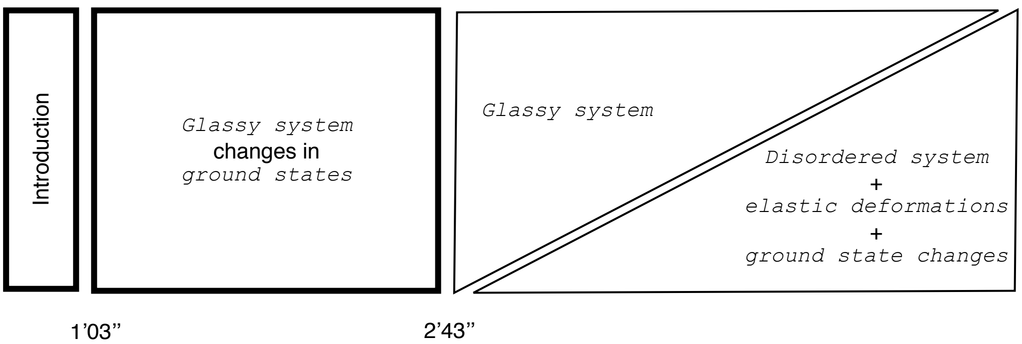


Figure 55. *Macroform of El Mar La Mar.*

12. Annex D

Article published in OM Book III

Koch's Space

Julián Ávila

When we listen to a sound, our brain analyses its characteristics. This process of extracting sound information in our brain always includes a description of spatial hearing; that is, for any sound we hear, or brain determines its location so there is no "non-spatial hearing" [2]. This behaviour could be an anthropological phenomenon with practical application in life; but if source location is such an important element for our brains, it seems reasonable that it should also be considered by composers.

Space is one of the most important elements in my music, and it is handled and composed in the same way I work with other elements related to time, structure, process, or the vertical and horizontal organisation of sound. For this reason I try to balance both space and time (which in other disciplines are closely related concepts, for instance in physics, which could be said to search for a "theory of everything"), a concern similar to the connection that Karlheinz Stockhausen made between pitch, rhythm, and structure; or later to spectral techniques.

An important issue is how to relate the two basic elements of time and space in order to write music. In my music, fractals and self-similarity are highly useful tools to control the processes that take place in a work. They allow me to apply the same idea in different compositional strata without losing unity. The main goal is to choose a system applicable to all the elements included in the composition of a space-time field.

Main idea of *Koch's Space*

Koch's Space is a work written and conceived from a spatial vision of sound. This spatiality has informed the characteristics of the electronic and acoustic space, as well as the structure of the score and sound materials.

The performance space is organised as a *topographic filter*[1] in which the sound is spatialised using a light held by the performer. The illuminated area

[1] A topographic filter is a filter that depends on spatial location of the signal. For instance, location could control cut-off frequency, Q factor, or any other filter parameters.

represents the place that is excited by electronics, and sound filtering responds to different iterations of a fractal structure, the Koch curve.[2]

The score is divided into three pages located on three stands, positioned in a semicircle (centre, left, and right) around the interpreter. The work is performed in darkness and it is the interpreter, playing with a head lantern switched on throughout the performance, who illuminates the staves.

The light is captured by photocells that allow electronic spatialisation using Max, behaving as if it were the result of the illumination. The sound material is generated in the form of an increasing and decreasing process of constructing the Koch curve so that each performer's movement, from left to right or from right to left, corresponds to an iteration in this process. In this way the work attempts to "fractalise" not only sound material and temporal process, but also the concert space and the electronics.

This work is closely related to the topic of *spectral diffusion*.[3] Even though *Koch's Space* is not a "spectral diffusion piece," as it is more related to topographic filtering and spatial processes, it begins a compositional practice that moves in this direction and in which research is currently open.[4]

Spatial development

There is only one sound source in this piece, the saxophone, along with its spatialisation through the topographic filter, a "shadow" sound. This filter works as a shadow of the direct sound of the saxophone, meaning that the public hears the direct sound coming from the stage – where the saxophonist is positioned – as well as the filtered amplification coming from a surrounding array of speakers. The filtered sound is spatialised precisely to the location that the performer lights up in order to view the score.

The first step in the compositional process was the implementation of Koch's fractal shape in its first, second, and third iterations. These curves have been calculated as *BPC* objects in OpenMusic using the OMChaos library and exported to an interpolation table in Max. Figure 1 shows the fractal shape

[2] The Koch curve, also known as Koch Island or Koch Snowflake, "is a mathematically defined coastline with triangular promontories whatever the scale of magnification. [...] The Koch fractal is the prototype of an extensive family of fractals based on the repetition of a simple geometrical transformation"[3].

[3] Spectral diffusion is the main topic of my Ph.D. research at NOVARS, University of Manchester, *Spectral Diffusion and Spectral Energy in Electroacoustic Composition: Sculpting Space in Time Informed by Applications in Biophysics.*

[4] Spectral Diffusion and Spectral Energy research employing spectroscopy measurements has been widely applied in the field of biophysics, using the Fourier Transform as its main analytical tool. Studies of spectral diffusion in proteins [1] have identified behaviour, which composers can observe and reinvent in the language of spectromorphology [6] and space-form [7] in electroacoustic composition. This work with proteins may well be transposed and placed under the umbrella of spectral analysis of aesthetics and music composition with computers, with a special emphasis on spectral and physical space.

implementation that will be the main source for all the other patches. The function *make-w* is used to define the horizontal and vertical translation and angular shifting of the first iteration in order to build iterations 2 and 3.

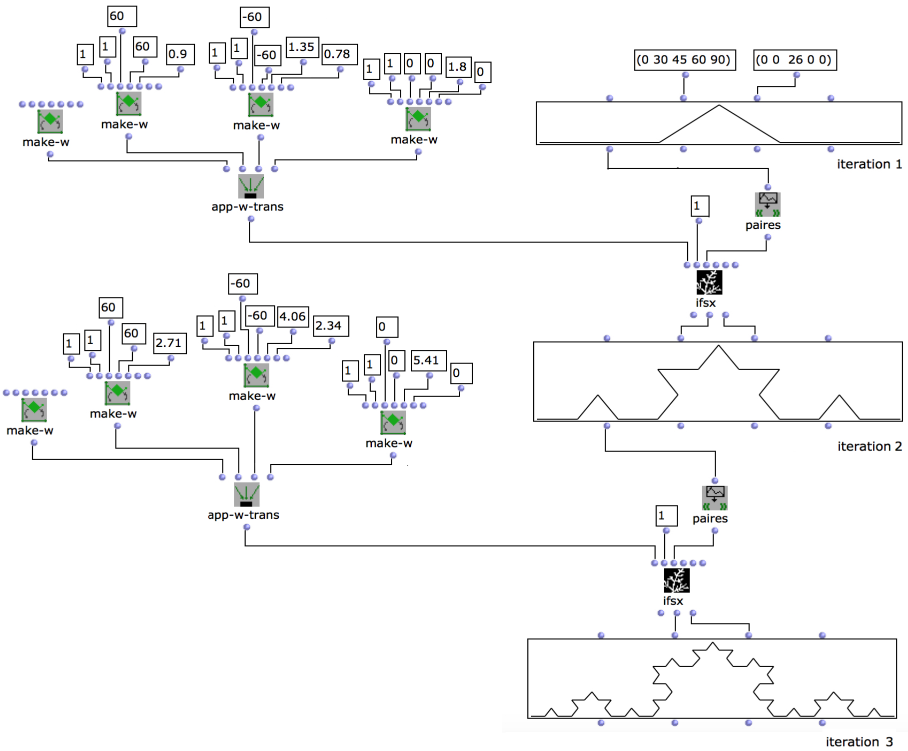


Figure 1. Implementation of Koch's fractal iterations.

Usually a filter graph is defined in dB (in the vertical, y-axis) as a function of frequency (in the horizontal, x-axis). The filter used in this work is an FFT-based band-pass filter[5] in which all the frequencies outside the band are completely attenuated, so there is no need to graph the level. This makes it more convenient to present how the filter evolves throughout the space: the band-pass graphs show a frequency range on the y-axis and represent space as an azimuth angle (in degrees) on the x-axis: hence the name "topographic filter." In other words, the band-pass filter limits vary depending on the amplified sound position inside the performance space.

The shape of this topographic filter is derived from Koch's fractal curves. In order to keep the band-pass limits well-defined as a function of space, and

[5]The use of an FFT-based filter helps avoid a slope (dB/octave) at the cut-off frequency that exists in traditional filters, as well as a change of phase in the filtered signal.

to avoid holes in the frequency bands, the original curves are transformed by taking the absolute value of the x-increment as shown in FIGURE 2.

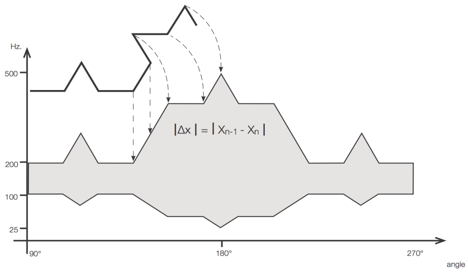


Figure 2. Shape filter for iteration 2.

FIGURE 3 shows the original fractal shapes (iterations 1, 2, and 3), and the corresponding transformed shapes for the topographic filter. The high-cut frequencies are scaled between 200Hz and 500Hz, and the low-cut frequencies are an inversion of the same shape scaled between 25Hz to 100Hz (see FIGURE 2). The outcome of this patch is then exported to MAX to modulate the limits of the band-pass filter depending on the position of the performance illumination.

The three iteration curves produce three different filters that are applied to different sections of the piece. FIGURE 4 complements FIGURE 2, showing the topographic filters that correspond to the first and third iterations.

The topographic filters then have to be spread and "located" around the audience in the concert space in order to achieve a spatial sound structure that changes when the light of the performer is pointed towards a specific direction in the hall.

As a many concert halls have the configuration of an "Italian" theatre, the spatial distribution of the filtering process is organised in a similar way (even though other kinds of configurations are possible). The surrounding matrix of speakers[6] cover the left, right, and back areas of the hall, whilst the stage is reserved for the saxophone sound alone. So the direct sound will come from the front, and the fractal-shaped filters will spread over the left, right and back, as shown in FIGURE 5.

From space to score

There exist many examples of music that has been composed and afterwards spatialised or distributed in space. However, in this case, the aim of giving the spatial design equal importance to other musical element leads the compositional process towards an organisation of all the elements around the space. The

[6]The number of speaker depends on the hall size, but at least four are needed to implement the filter distribution in the room.

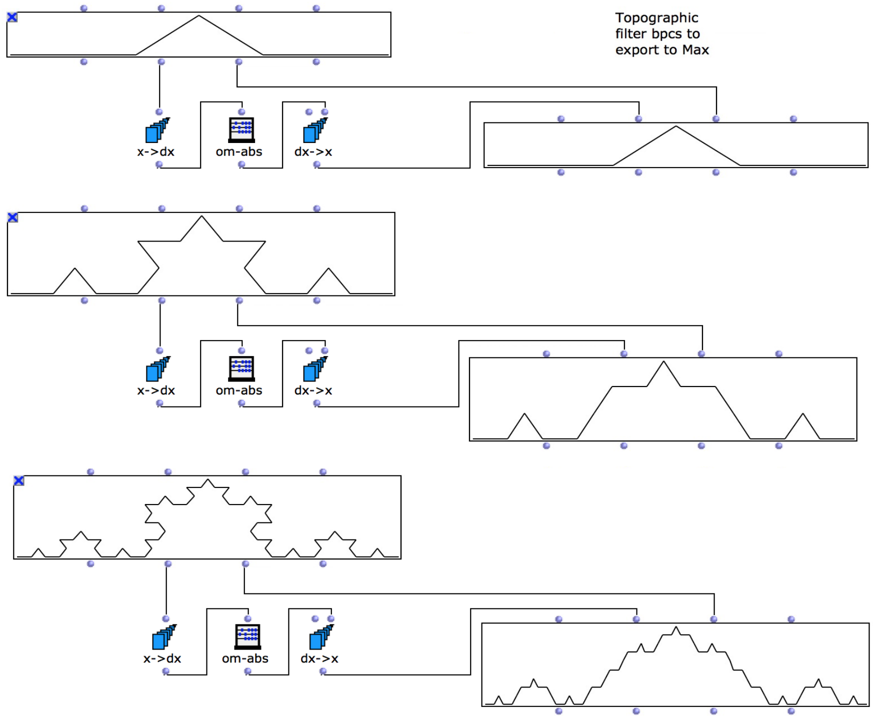


Figure 3. Fractal transformation for filter shapes.

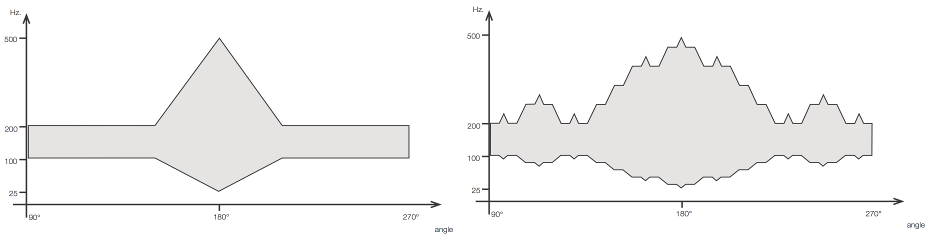


Figure 4. First and third topographic filters.

organisation of the score is therefore conditioned by the spatial form: as the topographic filter is divided into three "sections," the fractal curve that shapes the sound material is divided into the same three parts and distributed in three score pages.

The musical process consists of 12 constructions and deconstructions of the fractal states, as well as mixtures or deformations between fractal iterations. Each complete fractal shape is distributed across the three score pages (each one placed on one stand), and the score of *Koch's Space* is read horizontally

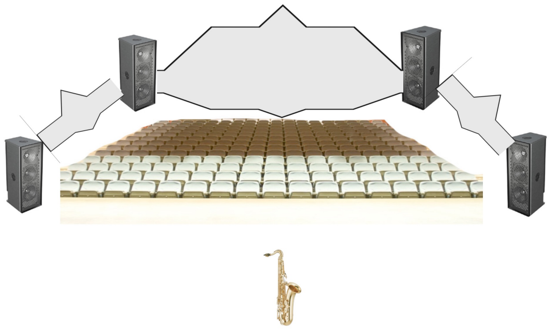


Figure 5. Topographic filter spatial distribution for the second iteration.

across the pages, rather than from the top to the bottom of each page. The first iteration (corresponding to the first stave of each page) is read from left to right, but the second iteration is read from right to left, and so on. Reading the score in this way will produce movements of the lighting during the performance, which are tracked to control the amplified sound filtering and spatialization processes. FIGURE 6 shows the correspondence between the topographic filter and the disposition of the score.

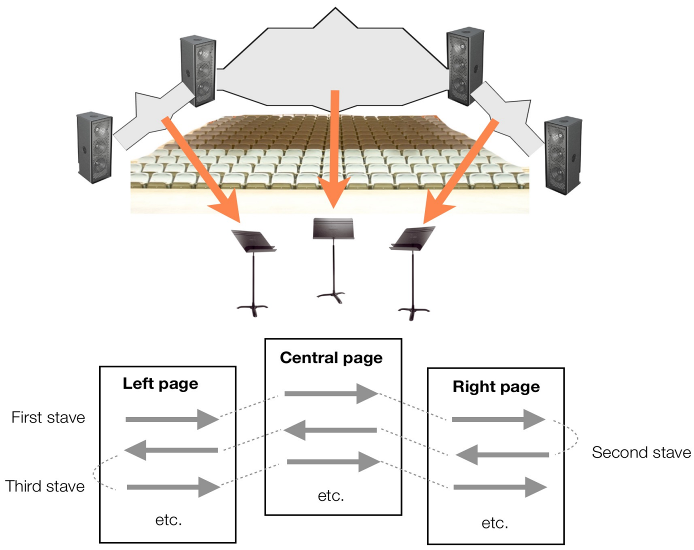


Figure 6. Relationship between space design and score structure.

Register and ranges

A characteristic of the Koch curve (and also of Koch's snowflake[7]) is the relationship between the limits of the perimeter and area of the fractal shape. When the number of iterations approaches infinity the length (L) of each segment of the curve tends toward 0, while the perimeter (P) of the whole shape tends toward infinity:

$$L_\infty = \lim_{n\to\infty} \frac{1}{3^n} = 0 \qquad P_\infty = \lim_{n\to\infty} \frac{4^n}{3^{n-1}} = \infty$$

In other words, whilst the area of this shape is finite, the perimeter is infinite. This peculiarity is implemented in this work to define pitch range limits and register. The perimeter of the shape is applied to the pitch range (scaled to fractions of an octave) and the length of the small segments of the curve is applied to the register or starting note (also scaled within an octave). FIGURE 7 shows the first nine numbers that determine the perimeter and segment length of each of the first nine iterations of Koch's fractal and their scaling within an octave range.

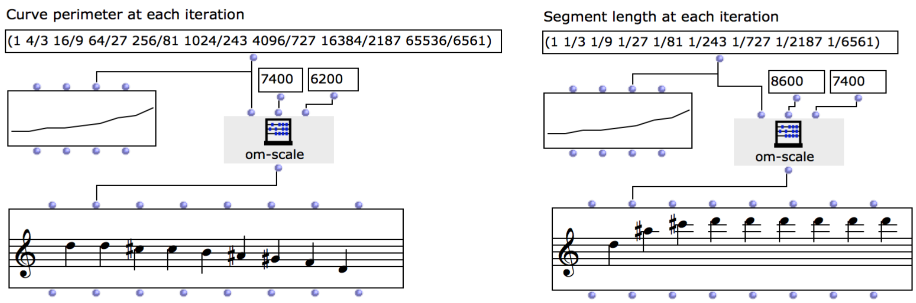


Figure 7. Range calculation patch.

Generation of musical material

To generate the material for the saxophone score, the inversion of Koch's curve has been mapped to musical content in four different ways:

- Direct mapping.
- Mixing one curve iteration for pitches and another for rhythms.
- Interpolation between two different curve iterations.
- Superposition of curve iterations for use in different layers.

[7]Koch's snowflake is similar to the fractals presented in this chapter, but applied to the edges of an equilateral triangle [4].

Direct mapping is the simplest translation between Koch's fractal and musical material, consisting of resizing the x-axis according to time and scaling the y-axis according to register. This correlation between fractal and music is used in sections 3, 6, and 9. FIGURE 8 shows the patch for section 6. Note that the *align-chords* function is used to group nearby points from the *BPC* into chords. FIGURE 9 shows the corresponding score extract.

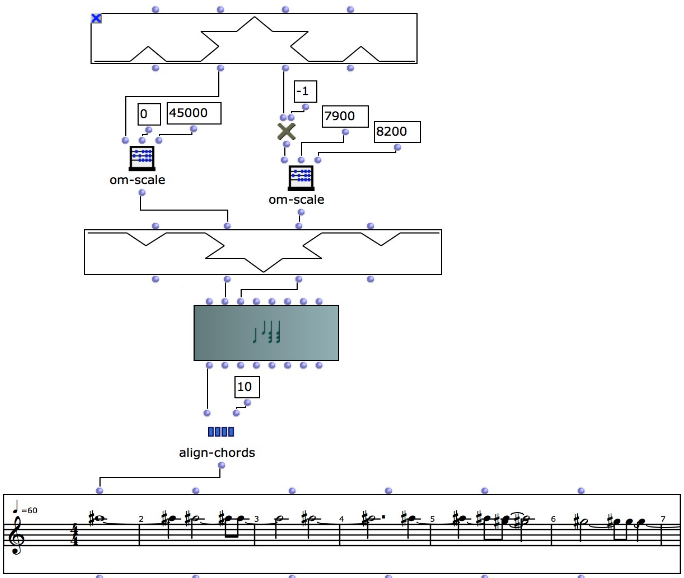


Figure 8. Patch for section 6 and example of musical transcription.

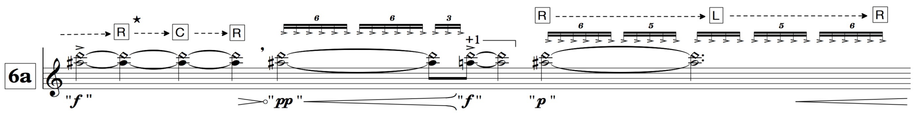


Figure 9. Score extract from Section 6.

Mixing uses different iterations for mapping rhythm and notes in order to obtain more rhythmical content within an iteration. This rhythmical information is used not only for repeated notes, but is translated into music using many different strategies. In fact, this internal subdivision is used to change any parameter within the same note, for instance timbre, dynamic, etc. The example in FIGURE 10 uses values from the first iteration inside the rhythm of the second iteration of the curve, using the *x-transfer* function. FIGURE 11 shows the corresponding score extract from Section 4.

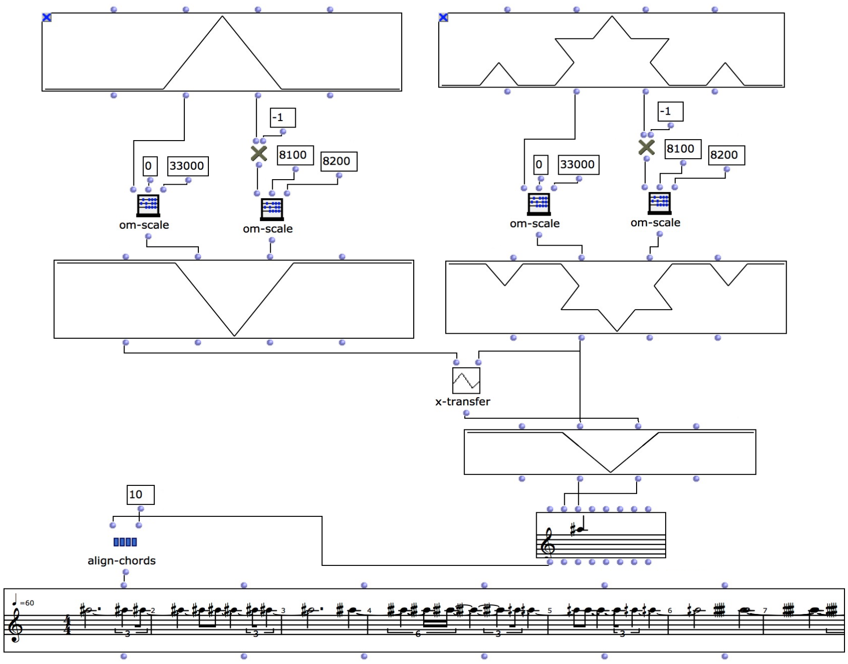


Figure 10. Patch for Section 4 (mixing).

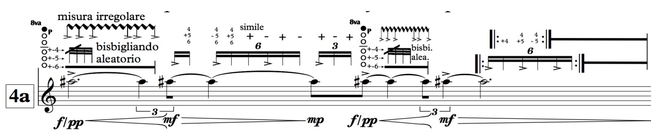


Figure 11. Score extract from Section 4.

Interpolation allows one to obtain a shape "between" two iterations (see FIGURE 12). This method is used to generate additional material from the three iterations used for this piece; the only requirement is that the two curves be scaled within the same range. As different iterations have a different number of points to define their shapes, the *om-sample* function is also used to resample both *BPC* objects before connecting them to *bpf-interpol*.

Superposition allows the use of points of two different fractal iterations for the same section (see for instance the patch and score of Section 7, FIGURES 13 and 14). In this case, lower notes are used as fingerings to produce non-ordinary harmonics in contrast to the same notes produced with normal fingering. Due to the complexity of iteration 3, the function *omquantify* is used here to avoid small rhythmical subdivisions, as well as *align-chord* to group coincident points in a chord, and *merger* to mix both shapes into the final *voice* object.

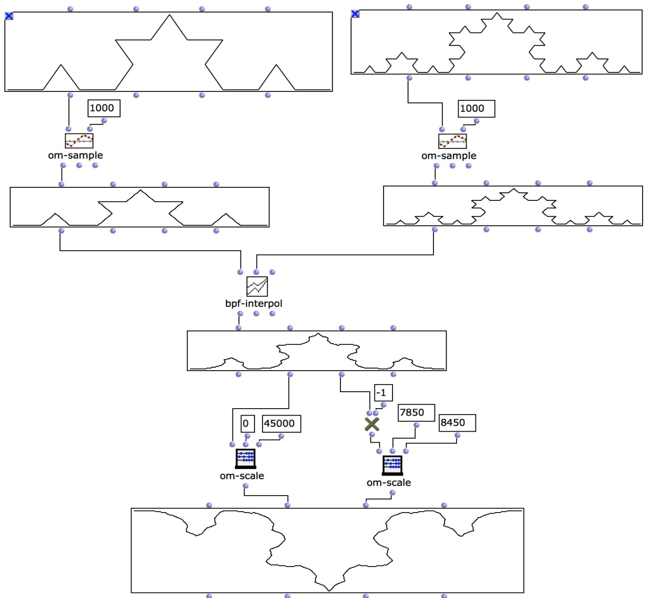


Figure 12. Patch for Section 8 (interpolation).

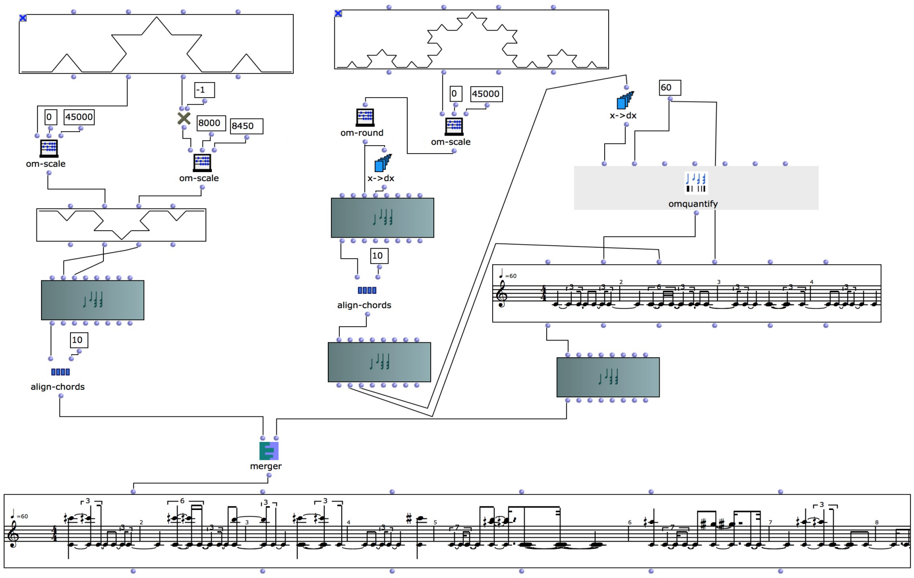


Figure 13. Patch for Section 7 (superposition).

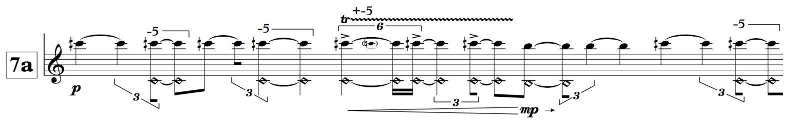


Figure 14. Score extract from Section 7.

These four methods for mapping material are combined to compose the structure of the piece. Sections 1 to 9 comprise a process in which the fractal grows little by little – from the simplest shapes to the most complex. Section 9 contains the shape that corresponds to iteration 3 of the fractal – the furthest stage of the fractal used in this piece – and after this point iterations decrease down to the first one again. TABLE 1 shows how the musical material is organised to create the macro-structure.

System design

The live electronic system in *Koch's Space* works in a similar way to procedural audio – for instance as used in game engines – in which it is not possible to know in advance the exact final result of the sound, but the behaviour of the sound is clearly defined. MAX is used to handle live interactions, and ARDUINO serves as an interface between the photocells and MAX. No score follower or event trigger is used; the system reacts to the performance and leaves the performer absolutely free to take control of the electronic system with her or his movements. FIGURE 15 shows a diagram of the different parts of the system.

On stage

This chapter points out the importance of space and describes a methodology to work in time-space composition balancing these two basic musical elements. I try to make no separation between time and space elements, so that almost all the elements in this work have properties in both fields. In fact this particular treatment of space is not only a compositional idea: the performance also puts forward relationships between sound and space, intensified by the visual effect of illumination which takes an important role in the transmission of the musical idea.

Spatiality in music is not a new invention. There are numerous ancient examples, such as Ancient Greek theatre; the works of Alessandro Striggio, Giovanni Gabrieli, Thomas Tallis; the 17th-century *cori spezatti* [5] in San Marcos of Venice; and 20th-century examples such as Karlheinz Stockhausen's *Gruppen* (1955-57) or Luigi Nono's *Prometeo* (1981-85), to name just a few. But today's technology allows us to think differently about spatiality in music, so that new methods can be implemented as a potential basis for new music. The initial idea of *Koch's Space* was developed through recent compositional tools, and most important, the idea of space has transcended the score or the compositional process to be present in the performance. The process is complete.

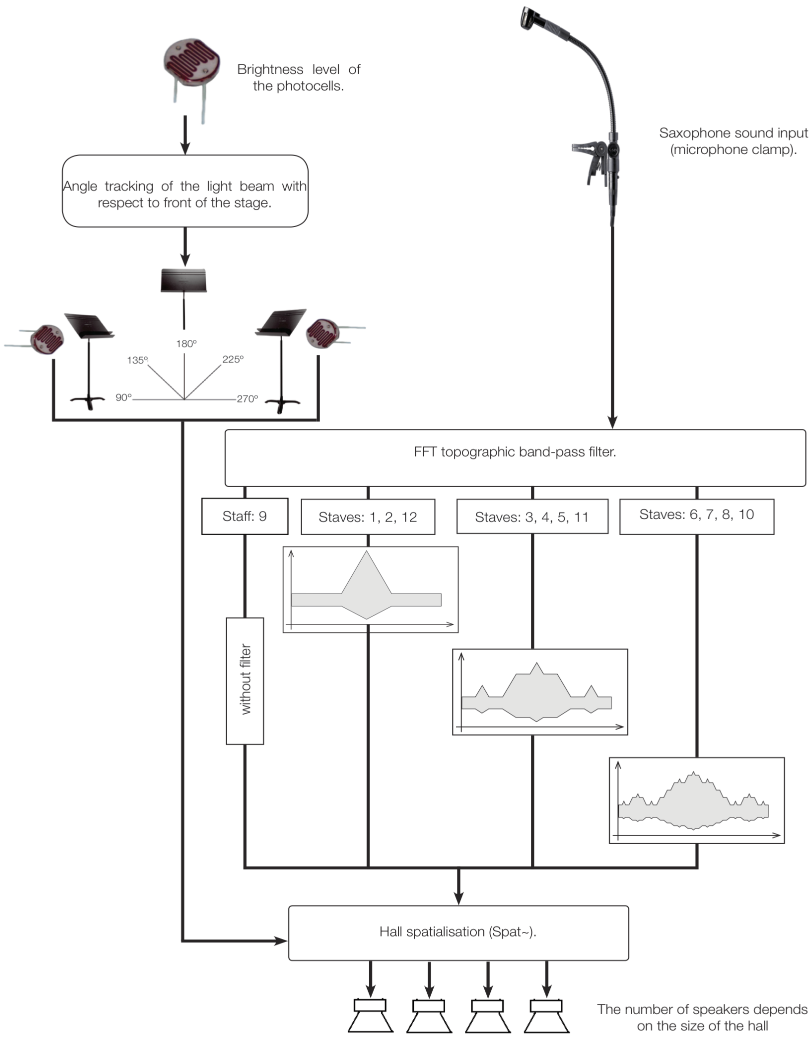


Figure 15. Block diagram of the live electronic system.

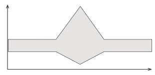
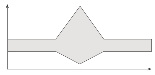
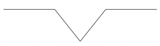
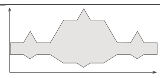
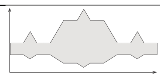
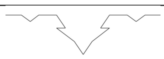
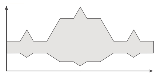
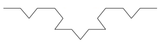
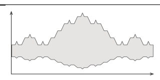
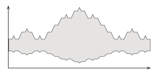
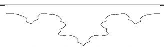
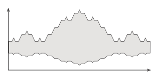
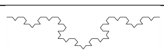
Section /staff	**Direction**	**Iteration**	**Filter**	**Pitch range** (MIDIcents)	**Duration** (seconds)
1	→	Rhythms: K1 Pitches: K0		7400	25”
2	←	Rhythms: K2 Pitches: K0		7400	25”
3	→	 K1		7400-7350	33”
4	←	Rhythms: K2 Pitches: K1		8200-8100	33”
5	→	 Interpolation K1-K2		8200-8000	33”
6	(←→←)	 K2		8200-7900	45”
7	→	K2 and K3		8450-8000	45”
8	←	 Interpolation K2-K3		8450-7850	45”
9	→	 K3	(no filter)	8600-7400	60”
10	←	Same as section 6 (different musical realisation)			
11	→	Same as section 3 (different musical realisation)			
12	←	Same as section 1 (different musical realisation)			

Table 1. Overall structure of *Koch's Space*. *Direction* indicates the reading direction (i.e. spatial movement) of the section. *Iteration* indicates the curves used to determine the rhythm and pitch material. *Filter* is the “topographic filter” used in the section.

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