CONTROLLING SPECTRAL HARMONY WITH KOHONEN MAPS

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ABSTRACT

The main goal of this research is to find a method to control complex harmony. In non tonal composition, the organisation of the harmonic material has not the clear orientation found in tonal music. The metaphorical isomorphism between timbre and harmony which forms the basis of spectral harmony suggests that timbre recognition and control of spectral harmony are the results of similar cognitive processes.

With musical instruments, timbre recognition is strongly linked to spectral coherence in the sense that, in a comfortable register, the spectral envelope of the steady-state part of the sound is not much altered whatever the note played, but is different from one instrument to another.

Self-organizing artificial neural networks are particularly efficient for pattern recognition and classification. They were used to test the spectral coherence of 48 musical sounds from 14 instruments, mainly winds.

A stochastic modelling of sound spectra is proposed in order to enable comparing spectra of any given sounds regardless of their pitches.

Finally, from a practical point of view, this paper will highlight methods to help composers who are concerned by the need to have a better control over complex harmonic texture.

Semplicemente credetti di aver fatta un'importante scoperta scientifica. Mi credetti chiamanto a completare tutte la teoria dei colori fisiologici. I meiei predecessori, Goethe e Schopenhauer, non avevano mai immaginato dove si potesse arrivare maneggiando abilmente i colori complemantari.[1] [p.417] (Svevo, 1924)

1. INTRODUCTION

In this paper, a method to control complex harmony, in particular spectral harmony, is presented. The notion of spectral coherence of musical instruments is put forward as an essential path in an itinerary linking elements of music, acoustics, psychoacoustics, computing, A.I., mathematics and philosophy.

One of the principal aim of the present research is to help composers, and also music analysts, in their understanding of the harmonic environment in which contemporary music is immersed.

Some knowledge of measure theory are required in the 5[th] paragraph, in which is underlined the stochastic nature of sound. This approach was necessary to test the hypothesis of spectral coherence of musical instruments with Kohonen maps.

2. SPECTRAL HARMONY

Harmony is the science of the formation and organisation of chords[2]. Harmony is inducing time related order onto frequency related notes. The major chord (ex: C-E-G) is *the simplest of*

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[1] I thought I had made an important scientific discovery. I suddenly felt called to complete the physiological theory of colour. My predecessors, Goethe and Schopenhauer, had never dreamed how far one might go simply by skilful arrangement of the complementary colours [p.387] (trans. de Zoete B. 1930).

[2] in Françoise Guerard (ed.), *Dictionnaire Hachette de la langue française*, Hachette 1980, pp. 742. [pt]

chords. It *imitates the euphony of the single tone by omitting the more distant overtones and reinforcing the more immediate* [p.26] (Schoenberg, 1911).

Spectral chords are complex chords incorporating any overtones. They are not directly related to tempered scales. They are modelled on physical property of sound and, in particular, its spectrum. Also called *harmonic timbre*, *it plays a role in identifying instrumental timbre, but only in association with other criterions, in particular, the dynamic criterion* [p. 49] (Chion, 1983)[pt *].

In Occident, musical instruments have been progressively made to produce a well defined pitch corresponding to the fundamental of an harmonic spectrum and made to emphasize the steady-part of the sound, stabilizing it with musical gestures such as bowing or blowing [pp.72-73] (Dufourt, 1999).

This emphasis on the spectral timbre in musical instrument making and playing suggests that the organization of spectral chords could be modelled on sound perception and recognition of western musical instruments. Analysing the spectra of sounds with computer has both led toward *the creation of models for artificial synthesis of natural sources, for instance musical instruments* and *in recasting the interaction of timbre and harmonic function in instrumental composition* [p.169] (Ferneyhough, 2000). This departure from the well-tempered system[3] is not without difficulties.

Helmholtz stressed that the simplicity of the well-tempered system has allowed Europeans to build playable sophisticated instruments and that *the great development of modern instrumental music was possible under the empire of the tempered system* [p.422]. Helmholtz also pointed out the similarity between sounds and chords [p.484] and that *the differences of musical timbres depend on the presence and intensity of partial sounds, but not their difference of phase* [p.163]. (Helmholtz, 1863)[pt]

Without linking explicitly spectrum and harmony, Pierre Schaeffer, founder in 1958 of the GRM[4], put forward the importance in sounds of what he called an harmonic plane linked to the spectrum of sounds [p.207(fig.25) and pp.217-219] (Schaeffer et al., 1952). By the 1970s, the GRM and later Ircam[5] gave the possibility to L'Itinéraire (founded in 1973, ensemble of instrumentalists and composers such as Gérard Grisey, Tristan Murail, Michaël Levinas or Hugues Dufourt) to develop new musical ideas engaging instrumental compositions in new paths where electroacoustics could be included either in performance or/and during the compositional process.

The formalisation of this music practice led to *the exposition of the principles of spectral music* which *illustrate the indissociable relation between music and technique, but* which *replaces also the contemporary creation in the framework of acoustic laws and of the history of knowledge expertise and of the necessary learning of this expertise* [p.154] (Levinas, 1999)[pt]. Although the deduction from the spectrum of musical direction is the initial and most important input of spectral music other aspects of sound making are taken into account. Hugues Dufourt highlights 5 principles:

1. The computer allows to compose sound and to compose at the infinitesimal scale of sound.
2. The harmony mutates in timbre.
3. The form and the material become one.
4. The development of musical possibilities of synthesis and of digital processing of sounds is inseparable from research into the characteristics of hearing.
5. A move from form to structure.

[pp.181-186] (Dufourt, 1998)

Regarding the second principle, Grisey added:

- *More 'ecological' approach to timbres, noises and intervals.*
- *Integration of harmony and timbre within a single entity.*
- *Integration of all sounds (from white noise to sinusoidal sounds).*
- *Creation of new harmonic functions which include the notions of complementarity (acoustic, not chromatic) and hierarchies of complexity.*
- *Re-establishment, within a broader context, of the ideas of consonance and dissonance as well as modulations.*
- *Breaking out from tempered systems.*
- *Establishing new scales and over time a melodic re-invention.*

[p.2] (Grisey 2000)

3. SPECTRAL COHERENCE

And, just as he [Schopenhauer] *considers the colors physiological phenomena, 'conditions, modification of the eye'* [6]*, so one would have to go back to the subject, to the sense of hearing, if one would establish a real theory of tones* [p.18] (Schoenberg, 1911)

The spectrum of the steady-state part of sound is not enough to characterise it fully, however it represents an important information on sound and can be used for musical purposes, as one of the precursors of spectral music, Jean-Claude Risset demonstrated it in his piece *Mutations* (1969):

[*] *pt* stand for *personal translation.*

[3] or *equal-tempered system*.
For more details on equal-tempered systems see, for example:
Aline Honingh, *Measures of Consonances in a Goodness-of-fit Model for Equal-tempered Scales*, Proceedings ICMC 2003, Singapore.

[4] Groupe de Recherches Musicales (Musical Research Group of Radio France).

[5] Founded by Pierre Boulez in 1969, the Institut de Recherche et Coordination Acoustique/Musique (Acoustics/Music Coordination Research Institute) was conceived originally as the music department of the Centre Georges Pompidou, Paris.

[6] in Arthur Schopenhauer, *Sämtliche Werke: Schtirften zur Erkenntnislehre* (Zweite Auflage; Wiesbaden: Eberhard Brockhaus Verlag, 1948), p.21 [R. E. Carter's note].

" A*n arpeggiated chord is echoed after 4 sec by a gong like sound that has components of the same frequencies as the fundamental chords. Although the gonglike sound is not heard as a chord, but rather as a timbre, one can hear clearly that this timbre is a prolongation, a shadow of the chord harmony.* " [p.20] (Risset, 1991).

The spectrum is not only a useful tool for analysing sounds in the laboratory, but is also a good representation of how the cochlea processes sound to send auditory images to the brain. Steve McAdams stressed that *the initial mapping of the frequency spectrum into the auditory system via the basilar membrane roughly corresponds to a logarithmic scale… This spatial organization of the frequency domain in the auditory system is maintained (to some extent) as far as primary auditory cortex* [p.284]. McAdams has also put forward the importance of spectral fusion (particularly in the case of harmonic sounds) and of the spectral envelope for learning and recognition [pp.285-286]. (McAdams, 1982)

Concerning sounds from musical instruments, Levinas has stressed the importance of *a more systematic classification of families of instruments that could be ordered in terms of spectral coherence* [p.15]. Indeed, this points out the need to control the spectral material to operate what Levinas called "*hybridising" different families of acoustical attacks or ways of acting on the sound-producing body* [p.13]. (Levinas, 1994).

Spectral music techniques are quite explicit, for example see (Baillet, 2000) for an overview of Grisey's techniques, and the main method to control harmony is the *interpolation of timbral structures* [p.93] (Saariaho, 1987). But this method make possible to classify chords only in very specific contexts. The metaphorical isomorphism between timbre and harmony implies that a better knowledge of music instrument classification according to their spectral properties would allow to extend the domain of classification of spectral harmony. A first step in our study was therefore to find a way to classify instruments as sound objects and not for their visual features. Grisey already pointed out the need for a perceptual organisation of the instruments of the orchestra:

"*Between the A played on one violin and an A on another violin, there is a small difference: that of the quality of the instrument and of the instrumentalist. This is the minimum degree of change that we can hope for in an instrumental ensemble.*
We can compare thus the same musical line on all the instruments of the orchestra and establish a more or less arbitrary graduation. For example, the same A on a cello will be closer to the violin than an A on a flute, which would be much more similar to the violin than another A on the Tuba, and so on.
An attentive listening of this kind resists the traditional classification in wind, strings etc..: for example, the low D of a piccolo will be certainly more similar to a contrabass harmonic on the same note than the same D played by a clarinet, a sound of mute trumpet closer to a woodwind than a French horn, etc.. And what can be said about the transients of attack and ways of playing such as the ponticello of strings and the mutes which change so radically the instrumental spectrum?
Are we going towards the realization of a new treatise of orchestration which would classify the timbres and ranges according to their spectrum, of their formants and of their transients and no longer according to their making?
It is hoped that the computer might quickly provide a modelization of the instrumental spectra that will be easier to compare and organise into hierarchies."
[p.373] (Grisey, 1991)[pt]

Spectral coherence can be tracked by analysing the similarities in the pattern of spectra of various instrumental sounds. Artificial neural networks are particularly efficient to test similarities.

4. KOHONEN MAPS AND MUSIC

Amongst artificial neural networks, self-organised Kohonen networks induce topologically ordered computational maps with strong stochastic properties. The many kinds of maps or images of sensory experiences in the brain, in particular *tonotopic projections in the primary sensory areas* are one of the main neurobiological inspirations of Kohonen maps [p.59](Kohonen, 1982).

After initialisation, the elaboration of a SOM (self-organised map) follows 3 processes: competition, cooperation, and synaptic adaptation. In the competition process a topology is featured which is defined by the Euclidian distance. A distance calculus is operated when synaptic weights are adjusted to find the best matching neurone for a given input value. Then, based on neurobiological evidence for lateral interaction, the cooperative process imposes a Gaussian convergent condition in order to limit the influence of a neuron on its surroundings. Lastly, the adaptive process, in two stages, ordering and convergence, allows for synaptic weights to be readjusted when a new input data is presented. An Hebbian process with the learning rate as a feature is introduced and a forgetting term is added such that, overall, adjacent neurons have similar synaptic weight vectors and that, after fine tuning, an accurate statistical quantification of the input space is provided. After initialisation, the 3 main steps of the SOM algorithm can be seen as equivalent to sampling, similarity matching and updating. [pp.443-483] (Haykin 1999)

Recent researches linking Kohonen maps and music, and in particular timbre, are presented by Toiviainen in his paper *Symbolic AI versus connectionism in music research* (Toiviainen, 2000). Since the late 1980s, Marc Leman has conducted several studies exploring harmonic structures using Kohonen maps. Leman with Carreiras and Lesaffre (Carreiras et al. 1999) have presented new methods for the description of harmonic context based on chord decomposition in terms of sub-chords. This research gives good grounds to believe that Kohonen maps are an efficient tool to pursue an investigation of spectral harmony.
From a practical stance, the difficulty with Kohonen networks is to find the best vector representative of the object tested. In the case of the spectrum of the steady-part of musical instrument sounds

(periodic tones), it seemed, at first, that the coordinates of the vectors should be the values of the amplitude of each partial of the corresponding spectrum. However, this implied that only sounds of the same pitch or of harmonically related pitches could be implemented. [7] Here it is assumed that *a periodic complex tone has a pitch corresponding to the fundamental frequency* [p.3486] (Hartman, 1996), although the influence of timbre on pitch [pp.675-676] (Terhardt et al. 1982) should be taken into consideration in the following when analysing resulting Kohonen maps.

In order to test the spectral coherence of musical instruments, the spectra of the sounds[8] of the 39 musical instruments (woodwind, brass and strings) analysed by Gregory Sandell [Sharc database][9] (Sandell, 1994) were used. Only sounds with fundamental pitched at F#3, F#4, C#5, F#5, C#6, F#6, C#7, F#7 were chosen. The result obtained on a Kohonen map shows effectively a grouping of sounds according to their pitch with the exception of the C trumpet muted. The 4 sounds of the C trumpet muted including the lowest note of the trumpet register (F#3) and one of the highest notes of its register (F#5) were clustered showing strong spectral coherence.

One characteristic of the spectrum of the notes of the C trumpet muted, and this at least in the 2 octaves above F#3, is that the fundamental is not the maximal amplitude. Depending on the pitch, the partial with the maximal amplitude can be the 5th or even the 7th. Thus the spectral envelope of the C trumpet muted depends little on the pitch, at least this is what can be concluded from this first experiment with Kohonen map. To avoid issues with pitch and to obtain for all sounds a similar result as obtained with the C trumpet muted, a reconsideration of the traditional (frequency, amplitude) approach to sounds was necessary.

5. STOCHASTIC MODEL OF SOUND

The following model of sound is restricted to harmonic sounds that is sounds with a temporal soundwave presenting a periodicity, however it is hoped that a generalisation to any type of sounds will be possible out of this model.

5.1 Spectrum and linear operator

In spectral music, the spectrum is considered as a representation (frequency, amplitude) of the Fourier transform of a sound signal. In maths, the spectrum of a linear operator is the set of its eigenvalues. Each eigenvalues is associated to one or several eigenvectors defining a linear space associated to the linear operator. If we think of a sound S in term of linear operator, we may write:

$$(1) \qquad S[\psi(f,t)] = \sum_{n=1}^{N} a_n(t)\psi(f_n(t))$$

where a_n is the amplitude of the n[th] partial of frequency f_n,
and ψ is a given function (wave function, usually sine or cos).
A characteristic of harmonic sounds is that the frequencies of the partials of the spectrum are ordered and multiple of the suite $\{1, 2, 3, \ldots, N\}$.
N is linked with perception.

For example:

$$\forall k < N, (f_{k+1} - f_k) \times N < 20000 \ Hz \ ^{10}$$

and

$$\forall k < N, (f_{k+1} - f_k) = Cte = f_0 \ ^{11}$$

The f_n are the frequencies of partials of sounds related to the fundamental of frequency f_o (often coinciding with the pitch of that sound) and :

$$S[\psi(f,t)] = \sum_{n=1}^{N} a_n(t)\psi(f_n(t))$$

The spectral characteristic of a sound is mainly determined by the couple (amplitude, frequency) of each partial or by the function s such that:

$$(2) \qquad s(f_n(t)) = a_n(t)$$

In the following, the temporal increment t will not be considered, although its importance is not denied.

[7] Most psycho-acoustic experiments on timbre differentiation suppose that the pitch of the sounds tested are the same; however in the following paper three tones [B3 (247 Hz), C#4 (277 Hz) and Bb4 (466 Hz)] were used : Jeremy Marozeau, Alain de Cheveigné, Stephen McAdams and Suzanne Winsberg, *The dependency of timbre on fundemental frequency*, JASA 114-5, 2003 pp.2946-2957.

[8] source sounds: McGill University Master Samples (MUMS) http://www.music.mcgill.ca/resources/mums/html/index.htm (site accessed 25/04/2004).

[9] Restricted access for http://www.parmly.luc.edu/sharc/. Data from Sandell Harmonic Archive (SHARC) on the web: http://people.cs.uchicago.edu/~odonnell/Scholar/Data/SHARC/ (site accessed 25/04/2004)

[10] 20,000 Hz is the upper limit in frequency for the human perception of tone (Brian C.J. Moore, *An Introduction to the Psychology of Hearing*, Academic Press, 2[nd] edition, 1982, p. 43).

[11] True only for harmonic sounds.

5.2 Inverse image of a function and Dirac's measure

Some mathematical notions need to be recalled at this point:

$$\forall A \subset [0, a_{Max}],\ s^{-1}(A) = \{ f \in [0, 20000],\ \textit{such that}\ \ s(f) \in A\}$$

where a_{Max} is the maximal amplitude (perceptual threshold).

The function ∂_{A} is defined as followed, for any $A \subset [\,0,\ a_{Max}]$:

$$\forall a \in [0, a_{Max}],\ \partial_A(a) = 1 \ \text{ if a} \in \text{A},\ \ 0 \ \text{ if a} \notin \text{A}$$

Thus, for $f \in [0, 20000]$:

$\partial_{s^{-1}(\{a\})}(f) = 1$ if $s(f) \in \{a\}$ that is if $s(f) = a$,

$\partial_{s^{-1}(\{a\})}(f) = 0$ if $s(f) \notin \{a\}$ that is if $s(f) \neq a$,

5.3 Measure associated to the spectrum

The amplitude a linked to a partial of frequency f , takes its value in [0, a_{Max}]. The values of a are not necessarily discrete, which could be implied in writing:

$$S = \sum_{n=1}^{N} a_n \psi(nf_0)$$

Thus it may be more accurate, with respect to both amplitude and frequency values, to write S as follows:

$$(3) \qquad S = \int_0^{a_{Max}} a[\sum_{n=1}^{N} \psi(f_n) \partial_{s^{-1}(\{a\})}(f_n)]da$$

This puts forward the measure μ defined on the set of amplitudes, depending on N, linked with the function s, and therefore the sound S and such that:

$$(4) \quad \forall \mathrm{A} \subset [0, \mathrm{a}_{\mathrm{Max}}], \mu(A) = \mu_s^N(A) = \sum_{n=1}^{N} \psi(f_n) \partial_{s^{-1}(A)}(f_n)$$

It is easy to check that μ is a finite measure. μ is finite because the number of partials in an harmonic sound is finite. This model could be generalised to non-harmonic sound, although in some cases it might not be trivial to show that μ is finite:

$$\forall A \subset [0, a_{Max}], \mu(A) = \int_0^{20000} \psi(f) \partial_{s^{-1}(A)}(f) df$$

$$\Rightarrow (5) \qquad S = \int_0^{a_{Max}} \int_0^{20000} a\, \psi(f) \partial_{s^{-1}(A)}(f) da df$$

$\mu = \mu_s^N$ is finite ($b_s^N = \mu_s^N([0, a_{Max}])$), it therefore can be considered associated to a probability measure:

$$\forall A \subset [0, a_{Max}], P_s^N(A) = \frac{1}{b_s^N} \mu_s^N(A)$$

P_{s} is the probability that partials for any frequencies take their amplitude values in a set A of amplitudes.

5.4 Bands of amplitudes

For a given set of amplitudes (or band of amplitudes) corresponds an associated set of frequencies.

If K is the number of bands then:

$$[0, a_{Max}] = \bigcup_{k=0}^{K-1} [a_k, a_{k+1}]$$

Thus a representation of S for a chosen K is given by:

$$(6) \qquad S = \sum_{k=0}^{K-1} [\int_{a_k}^{a_{k+1}} a d\mu(a)] \ \text{with} \ \ a_0 = 0,\ a_K = a_{Max}$$

5.5 Partials and bands of amplitudes

A set of frequencies (or partials) can be associated to a given amplitude band such that

$$(7) \qquad Q_s([s(f) \in A]) = \partial_{s^{-1}(A)}(f)\ .$$

If for $p \in \{1, \ldots, N\}$ and $Q_s([s(f_p) \in [\alpha_k, \alpha_{k+1}]]) = 1$, then:

$$s^{-1}([\alpha_k, \alpha_{k+1}]) = \{ f_{p_k}, p_k \in \{1, \ldots, N\}$$

where $[\alpha_k, \alpha_{k+1}]$ is a band of amplitude, thus:

$$s^{-1}([0, a_{Max}]) = s^{-1}(\bigcup_{=0}^{K-1} [\alpha_k, \alpha_{k+1}]) = \bigcup_{k=0}^{K-1} \{ f_{p_k}, p_k \in \{1, \ldots, N\}$$

It seems that the number of partials but also their actual frequency in a band of amplitude represent an important factor in the spectral characterisation of the timbre of an harmonic sound. The actual importance of the harmonic structure is not crucial in the final results suggesting that this model of representation of harmonic sounds could be generalised to any sounds

5.6 Examples

In the Sharc database, the amplitude of the partial are proportional to the maximum amplitude which is given the value 0 dB. In this example, partials with amplitude value inferior to –70dB are not considered. [12]
Thus a_{Max} = 0 *dB* and instead of [0, a_{Max}] , the amplitude range is written:

$$\bigcup_{A \subset]-70dB,0dB]} A =]-70dB,0dB]$$

If we choose K = 7 and A such that the length of all A corresponds to 10dB and that together they form a partition of [-70dB, 0dB], then we have:

$$]-70dB,0dB] = \bigcup_{k=1}^{7}]-10kdB,10(k-1)dB]$$

Let's now consider the note C#5 (or Db5), it corresponds to the production of a sound on an instrument such that its fundamental is f_0 = 554.37 Hz and that its spectrum has 18 harmonic partials below 10,000 Hz.[13]

5.6.1 Trumpet in C

In the case of the trumpet in C (fig.1), the 2nd partial [1108.74Hz or C#6] has the maximum amplitude.

For k=3 (as an example), the 8th , 9th and 10th partials are in the amplitude band]–30dB, -20dB].
This can be written:

s^{-1} (]-30, -20]) ={8 f_0 , 9 f_0 , 10 f_0 }= {4435 *Hz*, 4908.933*Hz*, 5543.7*Hz* }.

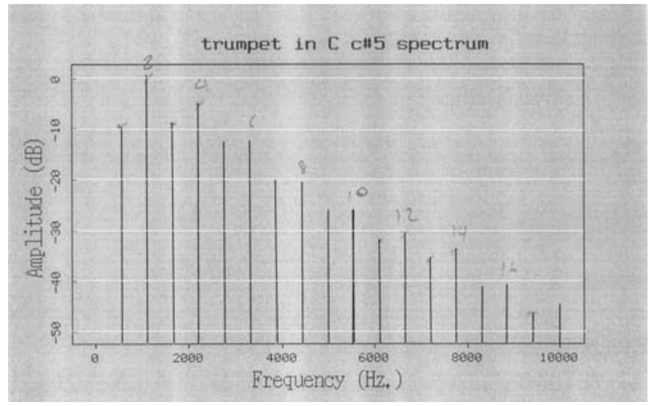

Figure 1: Spectrum of Trumpet in C playing a C#5
[from SHARC database]
Exact values in dB for partials 7 to 12:
-19.9345, -20.632, -26.1757, -25.8422, -31.8845, -30.26280

5.6.2 Trumpet in C (muted)

In the case of the trumpet in C (muted) (fig.2), the 12th partial [6625.44Hz or Ab9] has the maximum amplitude.

For k=3 (as an example), only the 5th partials is in the amplitude band]–30dB, -20dB].
This can be written:

s^{-1} (]-30, -20]) ={5 f_0 }= {2771.85*Hz*}.

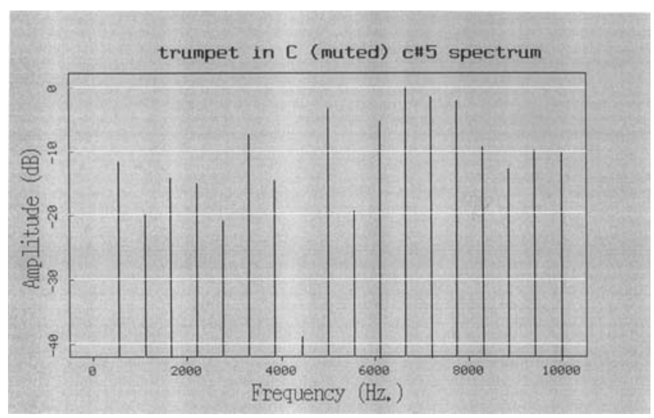

Figure 2: Spectrum of Trumpet in C (muted) playing a C#5
[from SHARC database]
Exact values in dB for partials 2 to 10:
-19.81690, -14.26650, -15.17010, -20.80340, -7.54688, -14.59810, -38.87510, -3.35428, -19.34910

[12] They have usually very little signification due partly to perceptual threshold and partly to accuracy in the measurement of sound.
See for example:
Keith Dana Martin, *Sound-Source Recognition: A Theory and Computational Model*, PhD thesis, MIT 1999. (particularly pp. 90-92).
[13] In the SHARC database, all the note's harmonic are in the range 0-10 kHz (Sandell, 1994).

These two examples are an illustration that the spectrum can be represented by a suite of frequencies related to band of amplitudes instead of a suite of amplitudes associated to the partials arranged according to increasing values of frequencies.

6. SPECTRAL HARMONY AND KOHONEN MAP

The pseudo-inversion process described mathematically can be computerised and may be useful for other data than the spectrum of the steady state of harmonic sounds. However our goal is to investigate how AI can be useful for music composition and, in particular, how AI can help to manage complex harmony, in particular, spectral harmony.

Kohonen maps are thought to be "able to preserve the topological relations while performing a dimensionality reduction of the representation space" [p.82] (Kohonen, 1997). The space of frequencies is the representation space thus the hypothesis of the spectral coherence of musical instruments can be checked. 48 sounds corresponding to 14 instruments were chosen: alto flute (3), bass flute (14), Eb clarinet (4), Bb clarinet (5), bass clarinet (1), bassoon (1), C trumpet (5), Bach trumpet (5), C trumpet muted (4), alto trombone (2), contrabass (1), contrabass martelé (1), contrabass muted (1), contrabass pizzicato (1). The spectra of these 48 sounds have between 8 and 56 partials.

For the first experiments using the pseudo inversion, the dimension of the space of frequencies was 35. The space was partition into 7 regions corresponding to 7 bands (see 5.6):

For each k in $\{1, 2, 3, 4, 5, 6, 7\}$, $card\,(s^{-1}(]-10k dB, 10(k-1)dB]) = 5$.

If in a band, the number of frequencies was inferior to 5, the remaining coordinates were given the value 0. If in a band, the number of frequencies was superior to 5, the frequencies most relevant according to psychoacoustics were kept, for instance the local maxima of the spectral envelop (also known as formants). [pp.286-288 & pp.308-311] (McAdams, 1994)

The sound vectors were then inputted in the Kohonen networks and a resulting Kohonen map was obtained. On the map (fig.3), we can see that the bass flute sounds form a separate region from trumpet and clarinet. Some sounds tend still to cluster according to pitch, for example trumpet and clarinet for C#5. However, at that pitch and during the steady-state portion a confusion of the 2 instruments is possible. Overall, the results are convincing enough to be exploited in spectral harmony, however improvements could be made, in particular through psychoacoustics tests.

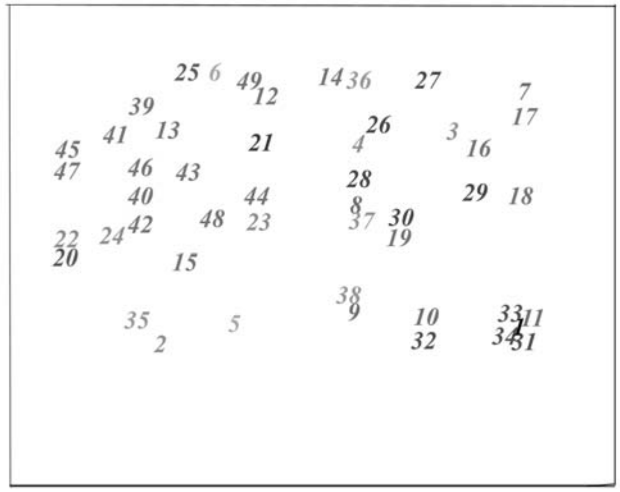

Figure 3: Kohonen map of musical instruments

1 : silence ; 2, 3, 4 : alto flute [F#4, C#5, F#5]; 5, 6 : alto trombone [F#4, C#5]; 7 -11 : Bach trumpet [F#4, C#5, F#5, C#6, F#6]; 12 –14 : bass flute [F#3, F#4, C#5]; 15 –19 : Bb clarinet [F#3, C#4, F#4, C#5, F#5]; 20 : bass clarinet [F#3]; 21 : bassoon [F#3]; 22-25 : contrabass [F#3] (normal, martelé, mute, pizzicato); 26 –30: C trumpet [F#3, F#4, C#5, F#5, C#6]; 31 –34 : C trumpet muted [F#3, F#4, C#5, F#5]; 35 –38 : Eb clarinet [F#4, C#5, F#5, C#6]; 39 –49 : bass flute [C3, C#3, D3, D#3, E3, F3, G3, G#3, A3, A#3, B3]
NOTE: This Kohonen map was obtained after the sound vectors were 'amplitude low pass filtered'(k>4). C trumpet muted sounds have very few low energy partials, hence they cluster with silence on this map.

7. MUSICAL APPLICATION

Even as a child I was fascinated by the idea opened up by Goethe in his Theory of Colors[14] *(1810), which places the birth of colors within the confines of light and shade. The tensions created by transitional spaces fascinated me most of all as parameters with which it was possible to create musical forms.* [p.97] (Saariaho, 1987)

Ligeti's piece *Atmosphère*s (1961) is a model of how to transpose electro-acoustic music technique to the orchestra. It shows that harmonic concepts developped in electro-acoustic music can be transposed in acoustic music although it requires new writing techniques [pp.198-206]. Ligeti advocates the use of computer for composition and believes that A.I. can help in understanding the influence of *a cultural constellation* on compositions but he does not believe important the automation of the composition process [p.196]. (Ligeti, 1981)

[14] J. W. von Goethe, *Scientific Studies*, D. E. Miller, ed. and trans., Suhrkamp, New York (1988)

Using artificial neural networks, Bharucha and Todd have highlighted the failure of *rule-based model of music* to *account for the acquisition of the rules they postulates* [p.46]. Indeed they were able to put forward that *a net trained on the Western major and minor scales seems to assimilate some Indian ragas to the western scales, sometimes shifting the tonic* [p. 47] (Bharucha et al., 1989). However the use of Kohonen maps to control harmony using the spectral coherence paradigm has the potential to help the composers to organise the harmonic material of their composition as long as they are aware in which context they compose.

A method used to control the harmony of *Interstice* (Maintenant, 2002) was to consider that each sound vector (see paragraph 6), represents a local harmonic field. According to what Bregman calls sequential integration (Bregman, 1990)[15], to move from one point to another, on the Kohonen map, is metaphorically isomorphic to modulate to corresponding remote or not remote harmonic field, depending on the move.

Interstice was composed during summer 2002 as a commission for Camilla Hoitenga with some funding from the Bliss trust/PRS foundation. It is a 21 mn music theatre piece in 3 parts (the duration of part 2 may vary) for a flautist and a guitarist:
1. bass flute solo (with tape at the end)
2. music theatre (involving domestic objects)
3. duo bass flute - electric guitar. (fig.4&5)

It was inspired by *Les Immatériaux* [16] (extract, fig.5), a poem by Michel Houellebecq (Houellebecq, 1997). The second part is influenced by Kagel's concept of music theatre (Kagel, 1970). The first and third parts are written according to the classical process of theme and variations. However all the harmonic material is spectral, and its frequential organization relies upon readings of Kohonen maps. Each of the 48 sound vectors provide an harmonic field and the harmony evolves according to paths in the Kohonen maps.

Interstice was premiered the 3 April 2003 at the Alte Feuerwache in Cologne, by Camilla Hoitenga[17] (bass flute) and Wilhelm Bruch[18] (electric guitar), theatre direction by Franz-Josef Heumannskämper. It can be argued that many parameters have contributed to the success of the premiere but one thing is certain: most of the harmonic material was drawn from information derived from the spectrum of sounds of musical instruments, and organised with the help of Kohonen maps.

15 particularly chap 2 pp. 47 – 211.
Note that Ligety calls 'fusion' a similar notion whilst refering to Koening's experiments in electronic music, in 1957 [pp. 181-188] (Ligeti, 1981).

16 Also the name given to an event/exhibition curated by Jean-François Lyotard and Thierry Chaput (Centre Georges Pompidou, Paris 28/03 – 15/07/1985)

17 Camilla Hoitenga has collaborated with and performed pieces written for her by composers such as Karlheinz Stockhausen or Kaija Saariaho

18 Wilhelm Bruck has worked extensively with Mauricio Kagel, also with Helmut Lacheman and Giacinto Scelsi.

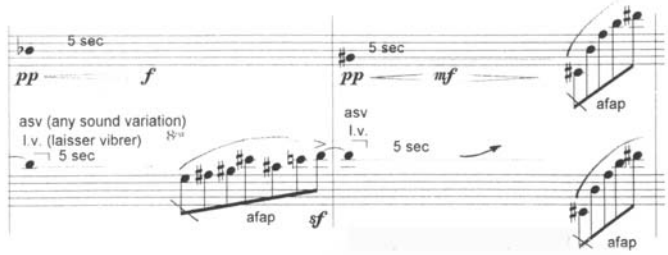

Figure 4: Extract of *Interstice* for bass flute and electric guitar[19] [Development 3A, p. 2]
(both written in treble clef sounding an octave lower)
The first group of notes [E5 to D6] correspond to the bands of amplitudes]-50*dB*, -40*dB*] and]-60*dB*, -50*dB*] of a F#5 of an Alto Flute.
The second group of notes [C#3 to D#5] correspond to the local maximum (possible formant) of the bands]-10*dB*, 0],]-20*dB*, -10*dB*],]-30*dB*, -20*dB*],]-40*dB*, -30*dB*],]-50*dB*, -40*dB*] of a C#5 of a trumpet in C
[the 3rd note is a F4: 10th partials (see 5.6.1 fig.1) 4 octaves below [20]]

Figure 5: Extract of *Interstice* for bass flute and electric guitar [Development 3 Coda, p. 4]
The first group of notes [G#2 to D4] corresponds to the band of amplitudes]-10*dB*, 0] of a C#5 of a trumpet in C (muted)
[the first 2 notes correspond to partials 6 and 9 (see 5.6.2 fig.2)
5 octaves below]

19 Bass flute and electric guitar are both written in trebble clef sounding an octave below.

20 By transposing the spectrum, the spectral envelop is not preserved. However the goal, here, is not to synthesize sounds but to establish new ways to control spectral harmony for composition purpose.

This approach to composition is maybe experimental but it does not rely on chance, it relies rather on mathematical modelling, psychoacoustics and A.I.. To make sure that my processes were fully exposed, I did not modify any of the harmonic fields imposed by the spectra of musical instruments. The only manipulation I did was to transpose frequencies 4 or 5 octaves below. This suggests that harmonic properties can be related to topological properties. Mathematically, this may be justified by the existence of *the spectrum functor*, which is *a contravariant functor from the Ring category* [including the space of frequencies] *to the Topology category* [including Kohonen maps] [p.73-74] (Lafon, 1974)[pt].

8. CONCLUSION

The metaphorical isomorphism between timbre and harmony together with the use of Kohonen maps have enable us to exert some control on spectral harmony. Further improvements and developments will be necessary to be able to elaborate a new harmonic system comparable to the highly organized tonal system, however any information on complex harmonic material need to be given consideration and those given by Kohonen maps seem to have some validity. There is a large field of knowledge to explore involving concepts drawn from music, psychoacoustics, physics, mathematics, neurology, A.I..

In the same way, impressionist painters benefited from scientific knowledge on light and from using photography, modern composers can develop their musical material benefiting from scientific knowledge on sounds and from using digital technology. Nevertheless the use of technology in music highlight several fundamental problems concerning art and technology. Heidegger recalled that technique should benefit to mankind and that technique should not take us over. He also mentioned that *Technikon means that which belongs to techné . We must observe two things with respect to the meaning of this word. One is that techné is the name not only for the activities and skill of the craftsman but also for the arts of the mind and the fine arts. Techné belongs to bringing-forth, to poiésis; it is something poetic*. [p.318] (Heidegger, 1954)

Kohonen maps are essentially a result of modern technology, their manipulations and interpretations are not obvious, however their topological properties provide encouraging possibilities to help controlling spectral harmony and to the development of modern music. It is hoped that the present research will lead to software integrated in compositional tools such as the ones described by Eric Métois (Métois, 1997) or Gérard Assayag (Assayag et al., 1997).

REFERENCES:

Aliprantis, C. and Burkinshaw, O. (1990). *Principles of Real Analysis*. Academic Press.

Assayag G., Agon C., Hanappe, P. and Fineberg, J. (1997). Problèmes de quantification et de transcription en composition assistée par ordinateur. In Genevois, H. and Orlarey, Y. (eds). *Musique et Mathématiques*. Aléas-Grame (pp.145-160).

Baillet, J. (2000). *Gérard Grisey, fondements d'une écriture*. L'Harmattan.

Bharucha, J. and Todd, P. (1989). Modeling the perception of tonal structure with nets. Computer Music Journal Vol.13, No.4 (pp.44-53) (also in Todd, P. and Loy, D. (eds). *Music and Connectionism*. The MIT Press 1991).

Bregman, A. (1990). *Auditory Scene Analysis, the perceptual organization of sound*. The MIT Press.

Carreras, F., Leman, M. and Lesaffre, M. (1999). Automatic harmonic description of musical signals using schema-based chord decomposition. Journal of New Music Research, 28 No.4, (pp.310-333) http:www.swets.nl/jnmr/images/28.4_Carreras(k).jpg, (k)=1, 2 or 3 . (site accessed 25/04/2004)

Chion, M. (1983). *Guide des Objets Sonores*. INA & Buchet/Castel.

Dufourt, H. (1998). L'espace sonore, "paradigme" de la musique de la seconde moitié du XXème siècle. In Chouvel, J.-M. and Solomos M.(ed.). *L'espace: Musique/Philosophie*. L'Harmattan (pp. 177-186).

Dufourt, H. (1999). Pierre Schaeffer: Le son comme phénomène de civilisation. In *Ouir, entendre, écouter, comprendre après Schaeffer*. INA & Buchet/Castel (pp. 69-82).

Edgar, G. (1990). *Measure, Topology and Fractal Geometry*. Springer-Verlag.

Ferneyhough, B. (2000). Shaping sound. In Kruth P. and Stobart H. (eds). *Sound*. Cambridge University Press (pp. 151-172).

Grisey, G. (2000). Did you say spectral? Contemporary Music Review 2000, vol.19 part 3 (pp. 1-3) (In Fineberg J. (ed). *Spectral Music*. CMR vol.19 part 2&3).

Grisey, G. (1991). Structuration des timbres dans la musique instrumentale. In Barrière J.-B. (ed.). *Le timbre métaphore pour la composition.* Christian Bourgois / Ircam (pp. 352-385).

Hartman, W. (1996). Pitch, periodicity and auditory organization. Journal of the Acoustical Society of America 100 (6) (pp. 3491-3502).

Haykin, S. (1999). *Neural Networks, a comprehensive foundation*. Prentice-Hall.

Heidegger, M. (1954). The Question Concerning Technology. In Krell D. F. (ed). *Basic writings: Martin Heidegger*. Routledge 1978/1993 (pp. 311-341) (Reproduced form *The Question Concerning Technology and Others Essays*. Harper and Row (1977). English Translation by Lovitt. W. from *Vorträge und Aufsatze.* Günther Neske Verlag. 1954).

Helmholtz (von), H. (1863). *Théorie Physiologique de la Musique Fondée sur l'Etude des Sensations Auditives*, Editions Masson (1868)/ Editions Jacques Gabay (1990, reprint). French translation by Guéroult G. (1868) from *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik.* Braunschweig: Friedrich Vieweg und Sohn. 1863.

Houellebecq, M. (1997). Les Immatériaux. In *La Poursuite du Bonheur.* Flammarion (or In *Poésie*. J'ai lu 2001, (p. 166)).

Kagel, M. (1970). *Atem*. Universal Edition.

Kohonen, T. (1982). Self-organized formation of topologically correct feature maps. Biological Cybernetics 43 (pp. 59-69).

Kohonen, T. (1997). *Self-Organizing Maps*. Springer-Verlag.

Lafon, J.-P. (1974). *Les formalismes fondamentaux de l'algèbre commutative*. Hermann.

Levinas, M. (1994). Transients of attack and hybrid sounds: toward a new mixity. Leornado Music Journal, Vol.4 (pp. 13-15).

Levinas, M. (1999). Le frisson de Mallarmé. In *Le Compositeur Trouvère, écrits et entretiens (1982-2002)*. L'Itinéraire/L'Harmattan 2002 (pp. 149-155).

Ligeti, G. (1981). Musique et technique, expériences personelles et considérations. In *Neuf Essais sur la Musique*. Editions Contrechamps 2001 (pp. 181-209).

Maintenant, F. (2002). *Interstice*. Self-Edition, PRS copyright.

McAdams, S. (1982). Spectral fusion and the creation of auditory images. In Clynes M. (ed). *Music, Mind and Brain, the neuropsychology of music*. Plenum Press (pp. 279-298).

McAdams, S. (1994). Audition: physiologie, perception et cognition. In Richelle M., Requin J. and Robert M.(ed). *Traité de psychologie expérimentale.* Presse Universitaire de France (part 1, pp. 283-344).

Métois, E. (1997). *Musical Sound Information*. MIT Thesis.

Risset, J.-C. (1991). Timbre analysis by synthesis: representations, imitations, and variant for musical composition. In De Poli, G., Piccialli, A. and Roads, C. (eds). *Representations of Musical Signals*, The MIT Press (pp. 7-43).

Rudin, W. (1973). *Functional Analysis.* McGraw-Hill.

Saariaho, K. (1987). Timbre and harmony: interpolations of timbral structures. Contemporary Music Review, Vol.2 No1 (pp. 93-133).

Sandell, G. (1994). *SHARC Timbre Database.* Electronic publication: http://www.parmly.luc.edu/sharc/.

Schaeffer, P. and Mole, A. (1952). Esquisse d'un solfège concret. In Schaeffer, P. . *A la Recherche d'une Musique Concrète.* Edition du Seuil (pp. 201-228).

Schaeffer, P. (1966). *Traité des Objets Musicaux*. Edition du Seuil (1966/1977).

Shoenberg, A. (1911). *Theory of Harmony*. Faber and Faber. Translated by Carter, R. E. (1978) from *Harmonielehre*. Universal Edition 1911, 3rd ed. 1922.

Svevo, I. (1924), *La Coscienza di Zeno*. L. Capelli / Studio Tesi (1985). English translation by de Zoete B. (1930). *Confessions of Zeno*. Putnam & co ltd (1948).

Terhardt E., Stoll G. and Seewann M. (1982). Pitch of complex signals according to virtual-pitch theory: tests, examples and predictions. Journal of the Acoustical Society of America 71 (3), pp.671-678.

Toiviainen, P. (2000). *Symbolic AI versus connectionism in music research.* In Miranda E. R. (ed). *Readings in Music and Artificial Intelligence.* Harwood Academic Publishers (pp. 47-68).