Composing for light-responsive proteins

An overview of sonification practices and a summary of
The Chromochord Installation

Francisco Castillo Trigueros

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Preface

In this two-part paper I will give an overview of sonification practices in science and art and present my application of sonification in The Chromochord.

The first part, which covers the theoretical and practical issues concerning sonification, encapsulates the research I conducted when beginning to work on The Chromochord. It should give the reader a context from which to understand the artistic and didactic decisions described in the second part. It should also provide the reader a general understanding of the history of the field. Although most of the research cited has been derived from scientific, or analytical applications of sonifcation, the conclusions are relevant to artistic applications as well.

Part One:

Overview of Sonification

1. What is Sonification?

Sonification is the practice of transforming data or information into sound in a "systematic, objective, and reproducible" way.[1] Sonifications make use of *intentional* sounds, which are purposely designed to communicate information and stand in contrast to *incidental*, non-engineered sounds that occur as a result or byproduct of the normal operation of a system.[2] These intentional sounds, which can be created or selected in various ways, are then organized systematically to portray the information being displayed. Thus, sonifications translate relationships in data or information into a designed sound structure with the goal of making such relationships comprehensible.[3]

1.1 Listening

A sub-category of auditory display (the practice of communicating any information through the use of sound) sonification harnesses the capability of the human auditory system to support communication with electronic and mechanical systems and to "explore complex data."[4]

1.1.1 Perceptual Abilities

The auditory system offers unique perceptual abilities that sonifications use in order to be effective:

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[1] Bruce N. Walker and Michael A. Nees, "Theory of Sonification" in *The Sonification Handbook*, Ed. Thomas Herman, Andy Hunt and John G. Neuhoff (Berlin, Germany: Logos Verlag, 2011), 9.

[2] Ibid., 11.

[3] Ibid., 9.

[4] Thomas Hermann, "Taxonomy and Definitions for Sonification and Auditory Display" in *Proceedings of the 14th International Conference on Auditory Display, 2008.*

- **Unconstrained user orientation**. Listening, unlike visual perception, doesn't require specific user orientation, reducing physical, visual, and attentional restrictions. This attribute is often used by auditory displays that use alerts and warnings.[5]
- **Sound location**. The ability to locate sounds, enabled by the capacity of the auditory system to detect interaural time differences, allows the possibility of data to be mapped in a three-dimensional space. Additionally, the capacity to "compare two streams of data displayed binaurally could be capitalized upon, for example in scanning paired data sets for correlations."[6]
- **High temporal resolution**. As Alice Eldridge points out in her article Issues in Auditory Display, the superior temporal resolution of the auditory system "suggests that fast-changing or transient events that may be blurred or entirely missed visually could be detected in the simplest of auditory displays."[7] Furthermore, this sensitivity to temporal characteristics also allows the listener to discern periodic from aperiodic events.[8]
- **Schemas or pattern recognition**. Albert Bregman's *Auditory Scence Analysis* listening model describes the perceptual capacity to hear and recognize acoustic patterns, even when subject to radical transformation, and can be useful for using sound in pattern recognition tasks or data

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[5] Alicia Eldridge, "Issues in Auditory Display" in *Artificial Life*, Vol. 12, Issue 2 (Cambridge, MA: The MIT Press, 2006), 259-274.
[6] Ibid., 260.
[7] Ibid.
[8] Ibid.

mining.[9] Additionally, the perception of schema can allow the comparison of repeated instances of patterns.[10]

- **Integration and segregation of acoustic stimuli**. According to Bregman's *Auditory Scene Analysis* model, the auditory system also has the capacity to segment, segregate, and integrate sounds. These capacities facilitate the grouping and streaming (or *stream segregation*) that allow perception of simultaneous grouping cues, which can be effective when displaying highly dimensional data.

In combination, these capabilities of the human auditory system can be used to facilitate the interpretation of complex streams of data through a variety of sonification techniques. Thus, sonification can serve as a useful alternative or compliment to visual display, especially when data sets are "not conductive to effective visualization"[11] or while displaying highly dimensional data. It may also be particularly effective when a time dimension is involved and when the information being displayed includes warnings, or calls for immediate action.[12]

Accounts from significant scientific events substantiate theoretical evidence that the auditory system is capable of discerning information that visual analysis is not. As Alice Eldridge has noted, "During the Voyager 2 space mission, the cause of the problems encountered as the craft approached Saturn could not be established,

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[9] Ibid.

[10] Stefania Serafin, Karmen Franinović, Thomas Hermann, Guillaume Lemaitre, Michal Rinott, Davide Rocchesso, "Sonic Interaction Design" in *The Sonification Handbook*, Ed. Thomas Herman, Andy Hunt and John G. Neuhoff (Berlin, Germany: Logos Verlag, 2011), 104.

[11] Oded Ben-Tal and Jonathan Berger, "Creative Aspects of Sonification" in *Leonardo*, Vol. 37, No. 3, (Cambridge, MA: The MIT Press, 2004), 231.

[12] Walker, Nees, 11.

graphical depictions of incoming data from onboard meters showing pure noise. But when a synthesizer was used to transform the data into sound, a "machine gun" effect was heard at the critical period, which led to the realization that the craft was being bombarded with electromagnetically charged micrometeoroids."[13]

1.1.2 Creative Listening

The capability to categorize and derive meaning from sound necessitates creative inference by the listener. Oded Ben-Tal and Jonathan Berger discuss this at length in their article *Creative Aspects of Sonification*, in which they conclude that, "sonification of data provides a similar but far more constrained case of creative engagement with auditory stimuli than that of musical listening."[14]

Ben-Tal and Berger argue "The act of listening to music involves tracking simultaneous changes in variables (such as frequency, amplitude or spectral distribution) and integrating them into a comprehensive mental image. When transferred to the realm of sonification this dynamic assembling of mental images can be utilized in many ways – to track dynamically changing trends in an immediate and intuitive way, or to draw abstract connections between patterns distinguishing relationships that may be otherwise difficult to perceive. As in music, multiple identities and similarities can be simultaneously represented. The resulting patterns emerging from the sonic continuum need not be static themselves. Salient features enable the listener to prioritize and attend to specific

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[13] Eldridge, 261.

[14] Ben-Tal, Berger, 229-230.

aspects of the data-intensive stream that reaches the ear, aspects that often result in a hierarchical organization. These can be used to extract structurally salient information from complex multidimensional data."

"To interpret sonified data, listeners draw upon their powers of auditory abstraction and categorization in order to identify patterns and detect trends. In this sense, sonification involves engaged creative listening similar to the active listening demanded by music. A critical aspect of such listening is that of categorical perception, in which a continuous variation in one or more parameters yields perceptually discrete categories."[15]

1.2 Factors for Sonification Design

Although auditory displays have been utilized to perceive and understand various phenomena long before concepts such as audification and sonification were formalized, they have recently become more frequently used in scientific, analytical, and artistic settings.[16] [17] [18] As Bruce N. Walker and Michael A. Nees point out in their *Theory of Sonification*, and Alice Eldridge expands on in her article *Issues in Auditory Display*, because of the field's relative recent formalization and its wide array of applications sonification still lacks a comprehensive theoretical foundation on which research and design can be based.

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[15] Ibid., 230.

[16] Gaël Dubus and Roberto Bresin, "Sonification of Physical Quantities Throughout History: A Meta-Study of Previous Mapping Strategies" in *Proceedings of the 17th International Conference on Auditory Display,* 2011, 1.

[17] Walker, Nees, 10.

[18] Andi Schoon and Florian Dombois "Sonification in Music" in *Proceedings of the 15th International Conference on Auditory Display,* 2009, 1.

Thus, the guiding principles of sonification can be best described as a combination of insights obtained from the convergence of many diverse fields, including music, audio engineering, computer science, informatics, and psychology.[19] [20]

1.2.1 Data, Task, and Function

The task of the listener, the attributes of the data to be sonified, and the overall function of the auditory display are key components in any system that employs sonification. In order to create a successful sonification the designer should consider:

- The task(s): Task refers to the functions that are performed by the human listener within a system or what the user needs to accomplish. For example, monitoring, data exploration, identification of trends, and multi-task performance.[21]
- The data: Data sets often need to be pre-processed before being displayed in a sonification. Processes may include a reduction in dimensionality, or a sampling to decrease volatility. What parts of the information source are relevant to the user's task and how much information the user needs to accomplish it should inform how the data is polled and processed.[22]
- The function: Function refers to the way in which the sonification will be used. In his *Introduction to this Special Issue on Nonspeech Audio* Bill

[19] Eldridge, 270.
[20] Walker, Nees, 9.
[21] Ibid., 19-22.
[22] Ibid., 18.

> Buxton describes the functionality of auditory displays in terms of three broad categories: 1) alarms and warning systems; 2) status and monitoring messages and 3) encoded messages or data exploration.[23]

The combination of task, data, and function presents major challenges in sonification design, constraining "the data-to-display mapping design space."[24]

1.2.2 Data Mapping

Ben-Tal and Berger propose "To be capable of offering insight, an auditory representation must be intuitive, relatively easy to learn, flexible and capable of encapsulating multiple dimensions into a single categorical perceptual event."[25] To achieve this, sonification design relies primarily on choices about how the information or data to be displayed is mapped onto sound. Since the mappings chosen by the designer seek to communicate information through the use of various acoustic dimensions, to be successful it is essential to consider how much of the displayed information is communicated to the listener, and how accurately the listener interprets it.[26] Eldridge argues "The key to accurate perceptions of the data is the development of intuitive and unambiguous mappings from data to display parameters."[27] As Walker and Nees point out "Mapping data to sound also requires a consideration of perceptual or "bottom up" processes, in that some

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[23] William Buxton, William Gaver, and Sara Bly, *Audio Interfaces: The Use of Non-Speech Audio at the Interface*, 1.5.
[24] Walker, Nees, 17-18.
[25] Ben-Tal, Berger, 230.
[26] Walker, Nees, 17-18.
[27] Eldridge, 267.

dimensions of sound are perceived as categorical (e.g., timbre), whereas other attributes of sound are perceived along a perceptual continuum (e.g., frequency, intensity)."[28]

Additionally, effective mappings will choose the most appropriate sound parameters to display specific sorts of data, will match "the data-to-display scaling function to the listener's internal conceptual scaling function," and consider the most suitable polarity.[29]

The purposeful addition of non-signal cues to a display is also recommended to provide context for the data being portrayed. In visual displays axes and tick marks increase readability by providing a context. A visual graph without these cues provides no way to estimate values. In sonifications contextual cues equivalent to axes, tick marks and labels, are recommended, so that the listener can perform the interpretation tasks.[30]

1.3 Approaches to Sonification

Sonification's wide array of intents carries diverse paradigms for design and application. Clearly sonification aims to use sound to signify data or other information, so a semiotic perspective in sound design might be advised.

Approaches to the signifying process have been classified along a continuum for sounds that ranges from analogic to symbolic (figure 1). Analogic representations

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[28] Walker, Nees, 17-18.
[29] Ibid., 24-25.
[30] Ibid., 26.

are characterized by a one-to-one mapping from data to display dimensions, creating a direct and intrinsic correspondence between structures in the data and the representation medium, as in the Geiger counter. In contrast, symbolic representations do not necessarily preserve the structural relationships of the data being represented; the referent may have an arbitrary or even random association with the sound employed by the display, but he or she must "categorically denote some aspect of it, exemplified by the auditory alarm."[31] [32]

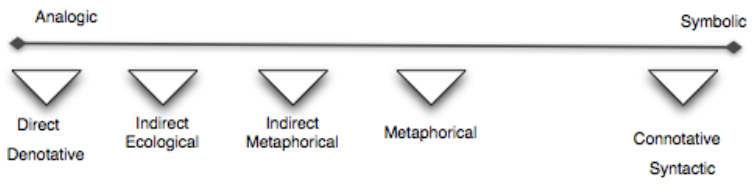

Figure 1: The analogic-symbolic representation continuum.[33]

The most common sonification techniques include:

Earcons: abstract sounds that function as symbolic representations of actions or processes. The sounds don't have an ecological relationship to the action they portray.[34] They can be used in combination to convey more complex messages. In the simplest form, these are used as alarm signals.[35]

Auditory icons: short sounds that have an analogic relationship with the process they represent.[36] Like earcons, auditory icons provide feedback from the graphical

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[31] Eldridge, 261.
[32] Walker, Nees, 22-23.
[33] Ibid., 23.
[34] Ibid.
[35] Eldridge, 262.
[36] Walker, Nees, 23.

user interface, but instead of using arbitrary motifs, selections are modeled on everyday sounds. This approach is seeks to aid learnability by evoking common metaphors.[37]

Audification: "the direct translation of data into the auditory domain. This guarantees an intrinsic correspondence between structures in the data and the representation medium, such as is found in the Geiger counter. This technique has proved particularly effective in the analysis of seismic data, in which the frequency of vibrations is accelerated to the range of human hearing."[38]

Auditory augmentation: "a sonification type where the real physical structure-born sound of real-world objects such as a keyboard or table is recorded and modified in real-time."[39]

Model-based sonification: "Taking an ecological stance… the approach aims to capitalize upon the auditory system's ability to extract information from the acoustic signal created by our interaction with the world."[40] "A model-based sonification therefore requires the reframing of the data as a virtual scenario and the definition of a virtual physics. Once defined, these laws can be used to measure

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[37] Eldridge, 262.
[38] Ibid.
[39] Serafin, Franinović, Hermann, Lemaitre, Rinott, Rocchesso, 104.
[40] Eldridge, 262.

how the elements react to external excitation by the user. Information about the data can then be derived from these measurements."[41]

Parameter mapping sonification: This method involves "the mapping of data dimensions onto display dimensions. Display dimensions may be parameters that determine the tone (timbre) of the sound (modulation depth or speed, spectral evolution, attack time, etc.), parameters such as frequency, volume, or tempo, or even high-level musical structures such as motifs."[42]

An alternate categorization of sonification approaches outlined by Alberto de Campo in his article *Towards a data sonification design map space* can be helpful to conceptualize the overall nature of the display: 1. event-based; 2. model-based; and 3. continuous.[43] The sonification designer should consider through which approaches the data is most effectively represented.

1.4 Issues

While sonification has proven to be a useful tool to display data in various fields, the varying effectiveness of different applications raises several issues. Broadly speaking, it must be remembered that the communication of data is mediated by creative decisions made by the sonification designer. Thus the communication of information will be conditioned by the quality of the design. In this way it is

[41] Ibid.
[42] Ibid.
[43] Walker, Nees, 15.

important to understand that what a listener hears in a sonification is the mapping or assignment of sound to data, and not the data itself. Therefore, the quality of the communication of data may be compromised by any shortcomings in the design. The following issues must be considered:

Arbitrary Mappings: In his article Rainwire: Environmental Sonifcation of Rainfall, Dave Burraston points out the problematic nature of mapping data to sound through arbitrary means: "Generally, methods of sonification of environmental data for scientific application to date have been based on digital sound generation from *data*, as opposed to analogue means. In such projects the phenomena under examination have been sampled to create data sets that are subsequently 'mapped' in an arbitrary way to sound synthesis engine parameters that produce audio output. However, the more the data is mediated, the less direct the relationships are between the stimuli and responses. The resultant audio in typical sonification bears a somewhat arbitrary relationship to the source phenomena, because the process is abstracted through the creation of a data set."[44] A contrasting possibility is that the mapping may not be arbitrary enough. The search for direct relationships between the stimuli and the response could lead to a less effective sonification model. Since sonification is often used as a tool to communicate specific information about a phenomenon it is possible that a system that is too literal will not filter out unneeded aspects of the stimuli like noise, or

[44] Dave Burraston, "Rainwire: Environmental Sonification of Rainfall" in *Leonardo*, Vol. 45, No. 3 (Cambridge, MA: The MIT Press, 2012), 288.

will fail to create a hierarchical sound structure that may in some cases impede effective communication.

Data propensity to sonification: The structure of the data under examination should be carefully considered. Conclusions should be drawn as to whether the sonification is an appropriate medium by which display the data. For example it's been suggested that "audification of seismic data is more successful than that of other data such as stock market figures, due to a shared physics."[45]

Data lost in translation: Since most sonifications are designed constructs and rely on *a priori* understanding of the behavior of the data being displayed. Consequently, if the data behaves in different way than expected there is a possibility that the auditory display will not communicate this effectively.

Perceptual non-linearities: The non-linear nature of the human auditory system poses important issues to sonification design. Perceptual asymmetries that affect the perception of pitch, timbre, and amplitude, present could make for potential distortions in the understanding of the data. Equal loudness curves or Fletchen-Munson curves, for example, show that the perception of loudness varies across the frequency range. Figure 2 shows the perceived loudness for nine different loudness levels. To curves are determined by asking listeners to match the intensity of a sound at different frequencies so that it matches a reference sound

[45] Eldridge, 267.

set at 1000 Hz. The curves demonstrate the non-linear perception of loudness, which has important ramifications for sonification design. For example if a sonification is mapping a stream of data to frequency and another to amplitude, the varying perception of loudness may affect the overall design.

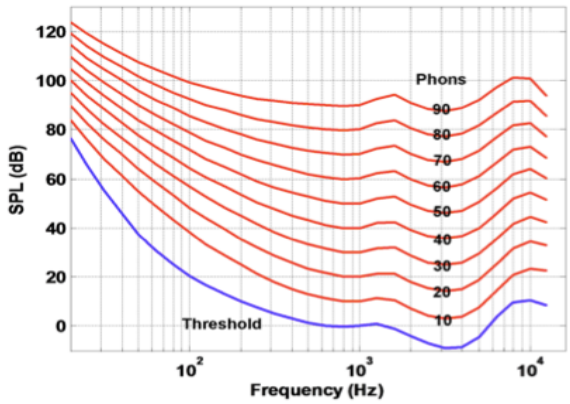

Figure 2 - Equal loudness curves showing the perception of loudness in relationship to frequency.[46]

"Even when intuitive mappings are developed, the limited number of orthogonal dimensions in sound space potentially creates perceptual interactions that can distort the way relations within the data are perceived. Numerous studies have demonstrated that the auditory dimensions of pitch, loudness, and timbre interact perceptually."[47] Other perceptual phenomonons such as masking may present problems in the communcation of data as well.

Musical knowledge: There are contradictory opinions on whether previous musical experience affects user performance in auditory displays. While some

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[46] Simon Carlile, "Psychoacoustics" in *The Sonification Handbook*, Ed. Thomas Herman, Andy Hunt and John G. Neuhoff (Berlin, Germany: Logos Verlag, 2011), 47.
[47] Eldridge, 268.

research concludes that "the effectiveness of different displays was influenced by musical experience,"[48] others have found that "research has generally found weak to non-existent correlations between musical experience and performance with auditory displays. One plausible explanation for the lack of relationship between musicianship and auditory display performance is the crude nature of self-report metrics of musical experience, which are often the yardstick for describing the degree to which a person has musical training."[49]

Learning: Sonification offers an innovative approach to information display. Walker and Ness argue that the novelty of auditory displays "stands as a potential barrier to the success of the representation unless the user can be thoroughly and efficiently acclimated to the meaning of the sounds being presented."[50] As with any system that requires understanding of an internal set of rules and functions, the effect of practice and familiarity with sonifications, and the amount of learning required for the user to employ them effectively must be considered in the assessment and application of sonifications.[51]

1.5 Conclusion

Despite these issues sonification has proven to be a useful method to convey information when properly applying the design principles listed above. A few

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[48] Ibid., 269.
[49] Walker, Nees, 29.
[50] Ibid., 30.
[51] Eldridge, 270.

remarkable examples of both analytical and artistic applications are summarized in the next chapter. The diversity in approaches to sonification speaks to the interest that the field has aroused across disciplines. As discussed in the next chapter, the development of these methods is closely connected to the advancement of technology. Therefore, we can expect further progress in the field.

2. Sonification Applications and Practices

2.1 History of Sonification

The history of auditory portrayals of data could potentially include research by Pythagoras, Kepler, Mozart, and Dufay.[52] Auditory displays were employed for multiple purposes before concepts such as audification and sonification were formalized: Automatic alarm signals, and striking clocks were used in Greece and medieval China to provide information about elapsed time.[53] By the turn of the 20th century devices that converted information into sound to assist in tasks were invented. These included the Geiger counter, which measures ionizing radiation and turns the data into pulsing sound signals,[54] and the Optophone, "a device used by the blind, that scans text and generates time-varying chords of tones to identify letters, are examples of such devices."[55] More recently, with the invention and development of the computer, complex systems have been created that allow for the sonification of complicated data sets such as stock market data, weather patterns, seismographs, DNA sequences, and chaotic attractor functions.[56]

As demonstrated by this overview, the history of sonification is inextricably linked to the history of technology. The development of new tools and mediums led to advances in sonification applications and techniques. The increasing availability of

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52 http://spdf.gsfc.nasa.gov/research/sonification/documents/Chapter1.pdf, 3.

53 Dubus, Bresin, 1.

54 http://en.wikipedia.org/wiki/Geiger_counter

55 http://en.wikipedia.org/wiki/Optophone

56 Paul Vickers and Bennett Hogg, "Sonification Abstraite/Sonification Concrete: An Aesthetic Perspective Space For Classifying Auditory Displays In The Ars Musica Domain" in *Proceedings of the 12th International Conference on Auditory Display*, 2006, 21

technology and accessibility of data to the general public has also impacted the field, facilitating the participation of non-scientific population, including artists.

As with the history of auditory representation, throughout the history of music, "reproducing data by means of sound has played a role, without however being explicitly referred to as "sonification"."[57] In retrospect, works that have been classified in categories such as transformation, or analogy "can be identified as *data music*."[58]

In the early 20th century, recording technology allowed innovative creative methods, some of them facilitating sonification. In 1923, the Hungarian painter and Bauhaus artist László Moholy-Nagy suggested "to change the gramophone from a reproductive instrument to a productive one"[59] by etching graphic signs into blank gramophone discs. In the early 1930's he transferred this concept to the medium of film. "This time, he drew his abstract forms directly onto the optical sound track, which, when played back, generated electrical impulses by means of a photocell that were then in turn converted into sound."[60] Recording technology also permitted the speeding up and slowing down of pressure waves, allowing phenomena such as bat calls and earthquakes that were outside of the hearing range to be converted into perceivable sound events.

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[57] Schoon, Dombois, 1.
[58] Ibid.
[59] http://www.rosab.net/format-standard/pdf_download/uk-Medium_as_instrument.pdf
[60] Schoon, Dombois, 1.

The development of the electronic music field and of technology at large allowed works like Alvin Lucier's Music for Solo Performer, composed in 1965, which uses EEG sonification, and Charles Dodge's *Earth's magnetic field* which converts changes in measurements of the planet's magnetic field into sound through digital and analog sound synthesis.

As with scientific application of auditory display, the development of the computer, and more recently, the accessibility of large quantities of data through the Internet have facilitated an increase in the number of compositions and sound installations using sonification. In *Dreaming of a Major Third* (1997) Christina Kubisch converts sunlight into the sound of bells garnering data using reflective solar panels that function as sunlight sensors.[61] In 2001, Florian Dombois correlating audified seismograms with geophysically calculated visualizations to develop a virtual 3D environment of the Indonesian volcano Mt. Merapi.[62] In 2006, Ambrose Field created *The CIA factbook V1.0* a sonification with data from the ICAD world dataset and the CIA online Factbook.[63] In *Test Pattern*, from 2008, Japanese sound artist Ryoji Ikeda created a system that converted any kind of data into barcode and binary patterns to create an audiovisual installation.[64]

The increasing variety of approaches to sonification in both artistic and scientific veins "is characteristic of the field, and is due in part to the range of

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[61] Claudia Tittel, "Sound Art as Sonification, and the Artistic Treatment of Features in our Surroundings" in Organised Sound, Vol. 14, Issue 1, (Cambridge, UK: Cambridge University Press, 2009), 57.

[62] Schoon, Dombois, 2.

[63] Ambrose Field, "Global Music: The World by Ear, The CIA Factbook v1.0 – a 190 Channel Concert Sonification" in *Proceedings of the 12th International Conference on Auditory Display,* 2006, 1.

[64] http://www.ryojiikeda.com/project/testpattern/

applications."[65] Consequently, the resulting sounds and structures are as diverse as the methods applied.[66]

2.2 Repertoire

Artistic sonification is particularly prone to a wide diversity of approaches, since it is unrestrained from task-oriented design and can explore methods on their own terms without a relationship with the data or the user. This has resulted in many remarkable works. In this short summary of repertoire, projects with very different approaches and creative intentions are reviewed to give the reader an overview of the possibilities already explored in the field. These projects, in combination with the research overviewed in the first chapter, informed the concepts and methodology applied in *The Chromochord Installation*. Additionally, they represent a developing aesthetic current with which *The Chromochord Installation* seeks to be in dialogue.

Charles Dodge's *Earth's magnetic field* (1970)

In contrast to much electronic music of the 1960's and 1970's where sound structures all designed and organized by the composer, Charles Dodge's *Earth's magnetic field* from 1970 converts a physical phenomenon into sound. The piece uses the natural succession of *Kp* indices during 1961 to create successions of

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[65] Eldridge, 261.

[66] Schoon, Dombois, 2.

notes.[67] The *Kp* index measures the average changes in the Earth's magnetic field from a network of geomagnetic observatories.[68] "This musical interpretation consisted of setting up a correlation between the level of the *Kp* reading and the pitch of the note (in a diatonic collection of over four octaves), and compressing the 2,920 readings for the year into just over eight minutes of music time."[69] Sudden commencements, which are rapid changes of the Earth's magnetic field, influence attributes such as tempo, dynamics, and register in both the larger and smaller dimensions of the work.[70]

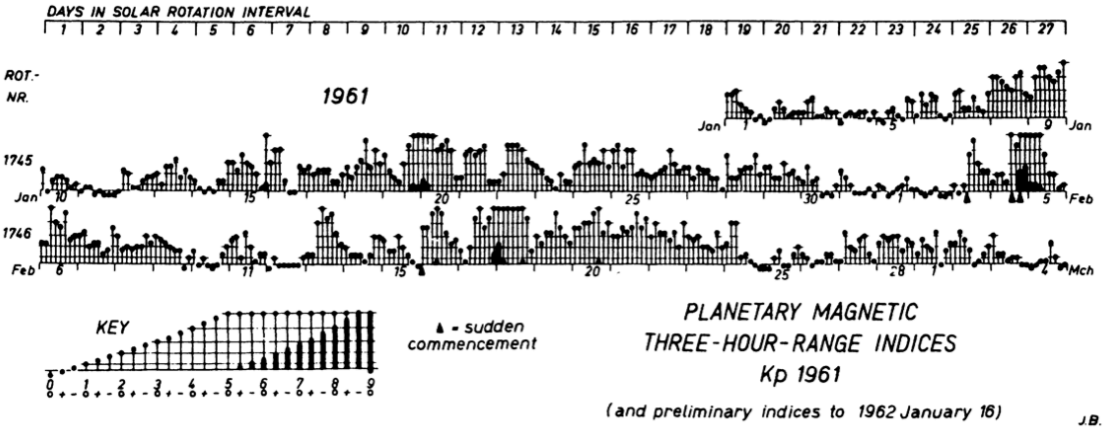

Chart with Kp readings used in Charles Dodge's Earth's magnetic field.

Dodge used the *Kp* data only for specific parts of the sonification design. Certain aspects, such as timbre and panning, were "chosen freely"[71] by the composer.

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67 Charles Dodge, Earth's Magnetic Field LP liner notes

68 http://en.wikipedia.org/wiki/K-index

69 Charles Dodge, Earth's Magnetic Field LP liner notes

70 Ibid.

71 Ed M. Thieberger and Charles Dodge, "An Interview with Charles Dodge" in *Computer Music Journal*, Vol. 19, No. 1 (Cambridge, MA: The MIT Press, 1995), 19-20.

Christina Kubisch's *Clocktower Project* (1997)

While *Earth's magnetic field* inhabits a fairly small and finite time scale, and thus arbitrarily distorts the data set by compressing data from a whole year into minutes, Christina Kubisch's ongoing installation, *Clocktower Project*, maintains a direct time relationship with the data. While Dodges' piece focuses on a global phenomenon, Kubisch's work exemplifies an audiovisual installation "concretely related to its spatial environment."[72]

Through the installation Kubisch restored the century-old clocktower at Mass MoCA, which had been out of service since 1986. The clock was equipped with a 750-pound and a 1,000-pound bells, which stopped ringing with the closure of the building. Kubisch saw the loss of these bell sounds from the clocktower as the "loss of an important local building."[73]

The Mass MoCA synopsis of the installation describes: "With this in mind, she undertook to restore the clock in a way that would also mark the arrival of contemporary art in the city. A classically trained musician and professor of experimental art, Kubisch began playing the bells like musical instruments, ringing them with their clappers as well as hammering, brushing, and striking them with various tools. She recorded the sounds with a digital recorder.

Kubisch then placed small solar sensors in a band encircling the tower just under the bell window. The sensors relay information about the intensity and location of

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[72] Tittel, 57.

[73] http://www.massmoca.org/event_details.php?id=152

the sun to a computer inside the tower. A unique software program, designed for this project by Berlin engineer Manfred Fox, interprets the solar information and combines Kubisch's pre-recorded bell sounds in response to light conditions. Thus, a sunny summer morning generates loud, distinct, metallic tones, while a gray afternoon in winter brings about softer, somewhat melancholy sounds."[74] At night, as the solar panels register less light, *The Clocktower Project* falls silent, connecting the presence of daylight with sound.

By reactivating the bells in a new way, Kubisch "reawakened the symbolic function of the tower in a new and different way, giving them both another identity."[75] And through the sonification of the tower's ever-changing surrounding environment Kubisch's mappings reflect an elastic artistic conception. Where Dodge and Stockhausen had data before creating the works, and could arrange and re-arrange it in ways that fixed their aesthetic goals, Kubisch designed an environment that could respond to predictable but variable circumstances.

Ryoji Ikeda's *Test pattern* (2008) and *Dataphonics* (2006)

"*Test pattern* is a system that converts any type of data (text, sounds, photos and movies) into barcode patterns of 0's and 1's."[76] *Dataphonics* is a music project that "focuses on the relationship between the sound of data and the data of sound."[77] In

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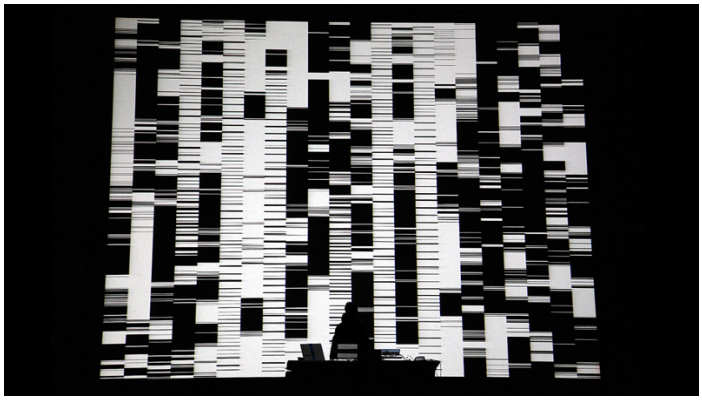
[74] Ibid.
[75] Tittel, 57.
[76] http://www.ryojiikeda.com/project/testpattern/
[77] http://www.ryojiikeda.com/project/datamatics/

it various non-audio data were forcefully converted to audio data and used as "the material for an hour-long composition."[78]

Both are examples of sonifications in which the way the data is processed is more significant than the data that it converts. What matters is not the information you input into the system but the system itself which forcefully transcodes any data into an aesthetically controlled environment of extreme sounds. This conclusion does not infer that the type of data input into the system isn't important. Inputting different data would probably alter the resulting sonification significantly. Nevertheless, the focus of the design remains on the transcoding mechanism and its highly controlled data conversion.



Visuals during a performance of Test Pattern by Ryoji Ikeda[79]

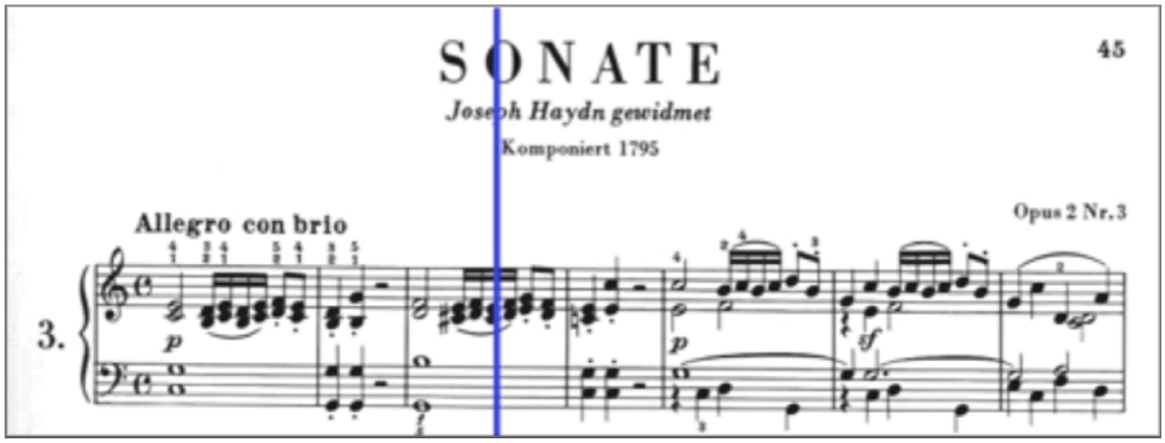
Johannes Kreidler's *Sheet Music* from *Five Conceptual Studies* (2012)

Similarly, in Johannes Kreidler's *Sheet Music* from *Five Conceptual Studies*, the sonification calls attention to its mapping method. In the piece a picture of a score

[78] Peter Krapp, *Noise Channels: Glitch and Error in Digital Culture*, (Minnesota: University of Minnesota Press, 2011), 61.

[79] http://www.ryojiikeda.com/project/testpattern/

by Joseph Haydn is converted into sound by interpreting the white space as silence and the black lines as events in a two dimensional space where the x-axis represents time and the y-axis represents frequency. *Sheet Music* is reinforced by a video that makes evident the technique being used, while creating the cognitive dissonance caused by seeing information that originally represents specific acoustic events in a musical tradition being interpreted through other means. Through this sonification, Kreidler is purposely subverting the meaning of data, by focusing on the "wrong" musical interpretation.



Screenshot from Johannes Kreidler's Sheet Music[80]

2.3 Aesthetics

Ryoji Ikeda's *Test Pattern* and *Dataphonics*, and Johannes Kreidler's *Sheet Music* turn the process of sonification into the artistic object; they find aesthetic potential in the action of transcoding itself and remove the constraining utilitarian primacy that the communication of data in scientific sonifications bears. Although they are different in intent than many scientific and artistic approaches, in that

[80] http://www.youtube.com/watch?v=vdbpJmsaNAw#t=48

they don't seek to communicate the data itself, both are still considered sonifications because they conform to the current definition, which requires that they are "systematic, objective, and reproducible."

These radical examples point to the different implications in the creation of scientific and artistic applications of sonification. While in scientific applications of sonification the issue of efficiency and objectivity is most important in artistic sonifications the aesthetic intent of the designer is at the top of the hierarchy. In contrast to science "the utility of art lies not in terms of work to which it can be put but to its intrinsic aesthetic qualities and value; art *is*, tools *do.*"[81]

Still, the different applications share many aspects. As shown in the two chronologies above there are many parallels and ambiguities between the scientific and artistic approaches.

In his article *An Introduction to Auditory Displays*, Gregory Kramer comment on the similarity in structure between sonification design and music composition.[82] Paul Vickers and Bennet Hogg expand on point in their article *Sonification Abstraite/Sonification Concrète: An 'Aesthetic Perspective Space' for Classifying Auditory Displays in the Ars Musica Domain*: "sonification renders data in sound to allow a human listener to detect and comprehend patterns and structures in that data, whilst a musician renders a musical score so as to make it audible and

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[81] Stephen Barrass and Paul Vickers, "Sonification Design and Aesthetics" in *The Sonification Handbook*, Ed. Thomas Herman, Andy Hunt and John G. Neuhoff (Berlin, Germany: Logos Verlag, 2011), 155.

[82] Gregory Kramer, "An Introduction to Auditory Display." *Auditory Display*, vol. XVIII of *Santa Fe Institute, Studies in the Sciences of Complexity Proceedings*, Ed. Gregory Kramer (Reading, MA: Addison-Wesley, 1994), 1–78.

thus make perceptible the music's structure and even give clues as to the composer's and the musician's emotional states."[83]

The definition on whether an application is scientific or artistic may have more basis on the intention of the sonification designer, rather than the design of the sonification itself. For example, we may find an artistic sonification that is extremely accurate with the way it represents data and could easily be utilized to assist with a task or we may find a scientific sonification that is aesthetically pleasing.

Interestingly, while the differences between the two kinds of applications are significant, so is the listener's role. Although, as discussed in the first chapter, the listener will listen to scientific sonifications in a way that is not so different to music (see **1.1.2**) the experience will be quite different, as most scientific applications require active listening, which may be connected to specific actions or analytical interpretation.

Furthermore, to ensure optimal communication analytical sonifications will have to take into consideration the user's own aesthetic preferences. The choice for appropriate sounds sources and techniques is the subject of much debate. The use of musical structures can be useful because many users will be familiar with them and possibly prone to understand them with less training. However musicality can

[83] Vickers, Hogg, 1.

be undesired as it has been posited that "musical grammars add another language level to the interface which would get in the way of the underlying data."[84]

"In their design of the WEBMELODY web server sonification system. Barra et al avoided the use of harmonic tonal sequences and rhythmic references because they believed that such structures might distract users by drawing upon their individual ". . . *mnemonic and musical (personal) capabilities*". Rather, they ". . . *let the sonification's timbre and duration represent the information and avoid recognizable musical patterns*". This, they said: . . . makes it possible to hear the music for a long time without inducing mental and musical fatigue that could result from repeated musical patterns that require a finite listening time and not, as in our case, a potentially infinite number of repetitions."[85]

Another example of a non-musical syntax in sonifications can be found in Gaver's SONICFINDER. "In looking for easily understood mappings… Gaver proposed a theory of 'everyday listening' which says that in everyday situations people are more aware of the attributes of the *source* of a sound than the attributes (parameters) of the sound itself: it is the size of the object making the sound, the type of the object, the material it is made of, etc. that interests the everyday listener… Everyday listening is in contrast to what Gaver calls 'musical listening' in which we are more interested in attributes of the sounds themselves: their pitch, their intensity, and so on."[86]

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[84] Ibid., 3.
[85] Ibid.
[86] Ibid., 2.

However, Vickers asks for caution when utilizing non-tonal music systems: "In the pursuit of aesthetic excellence we must be careful not to tip the balance too far in favour of artistic form. Much current art music would not be appropriate for an auralisation system. The vernacular is popular music, the aesthetics of which are often far removed from the ideals of the music theorists and experimentalists."[87] Vickers and Hogg continue, "just as poor aesthetics can get in the way of listening, 'good' aesthetics might become too seductively musical, distracting the listener from the information that is to be conveyed"[88]

Ultimately, several questions arise: If a sonification system is designed to correspond to the user's aesthetic preferences, how can those be measured? Should the system be personalized? Or should an average preference be measured in order to decide on the nature of the sounds used? How often must the chosen mappings be revised in order to adapt to society's changing taste? What makes a design so musical that it becomes distracting? Can these questions be resolved in an objective manner by further research on the field?

Paradoxically, by applying methods that are affected by subjective judgment the problem of aesthetics draws scientific sonification design into an old, ongoing debate in the arts; a debate which is unlikely to be solved in an objective manner.

Ultimately, while a good design for analytical purposes can be different from one designed for aesthetic reasons one must ask "whether scientific and musical

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[87] Ibid., 3.
[88] Ibid., 6.

objectives necessitate different approaches to sonification, or whether the same mapping can sometimes be useful for both."[89]

[89] Thierry Delatour, "Molecular Music: The Acoustic Conversion of Molecular Vibrational Spectra" in *Computer Music Journal*, 24:3, (Cambridge, MA: The MIT Press, 2000), 49.

Part Two:

An Introduction to and Technical Description of

The Chromochord Installation

3. *The Chromochord Installation* Project

The Chromochord Installation was created in collaboration with Josiah Zayner, a biochemist and bioengineer. The project was supported by the University of Chicago Arts|Science Initiative and sponsored by composer Prof. Howard Sandroff and biochemist Dr. Tobin Sosnick. Although Josiah dealt with the construction of the hardware, the distillation of the data, and the engineering of the proteins while I took care of the sonification engine and the composition, we both had input over decisions being made in every aspect of the project.

The project consisted of building a bioelectronic device that could measure nanometer level absorbance spectrum of the protein and transmit this information to a computer where the data would be converted to sound through a sonification engine. The resulting sonification was presented on May 8th, 2013 at the Logan Center for the Arts at the University of Chicago as an audiovisual installation.

3.1 *The Chromochord Installation* Principles

The Chromochord Installation was motivated by bioengineer Josiah Zayner's desire to allow "ordinary people" (non-scientists) to experience and interact with the AsLOV2 protein outside of a laboratory. This motivation set up some fundamental principles for the project. For example, the installation would have to reflect aspects of the protein both literally, through data-to-sound mapping, and metaphorically, through conceptual analogies. Aspects of the protein's characteristics that were used in the sonification include the protein's photocycle

length, degradation, its cyclic nature, and composite behavior. While the main intention behind the sonification was primarily artistic, it was of paramount importance that the sonification also transmitted basic data to the listener in a systematic manner.

The sonification is complimented by an abstract video, generated in Jitter, which is affected by the behavior of the proteins in a very rudimentary way. The video's role is to focus the audience attention without distracting from the sonification process.

3.2 The Protein

The LOV2 domain of Avena sativa phototropin 1 (AsLOV2) is a member of the Per-Arnt-Sim (PAS) family.[90] It is found in Oat plants where it normally functions in phototropism, moving towards light, and chloroplast rearrangements. Upon illumination the protein undergoes a conformational change (figure 3). This process is called a photocycle.

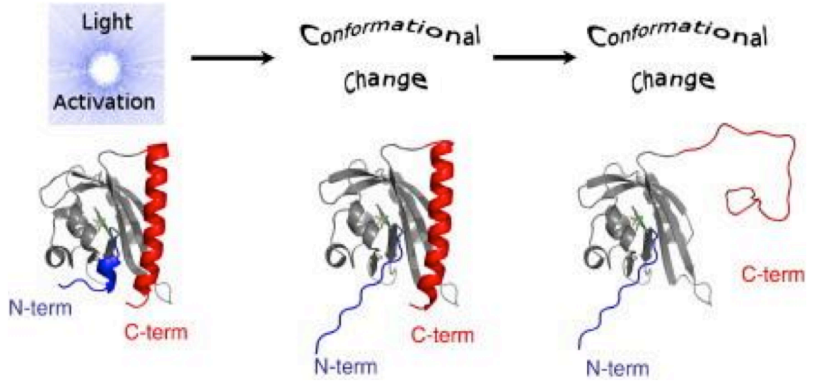


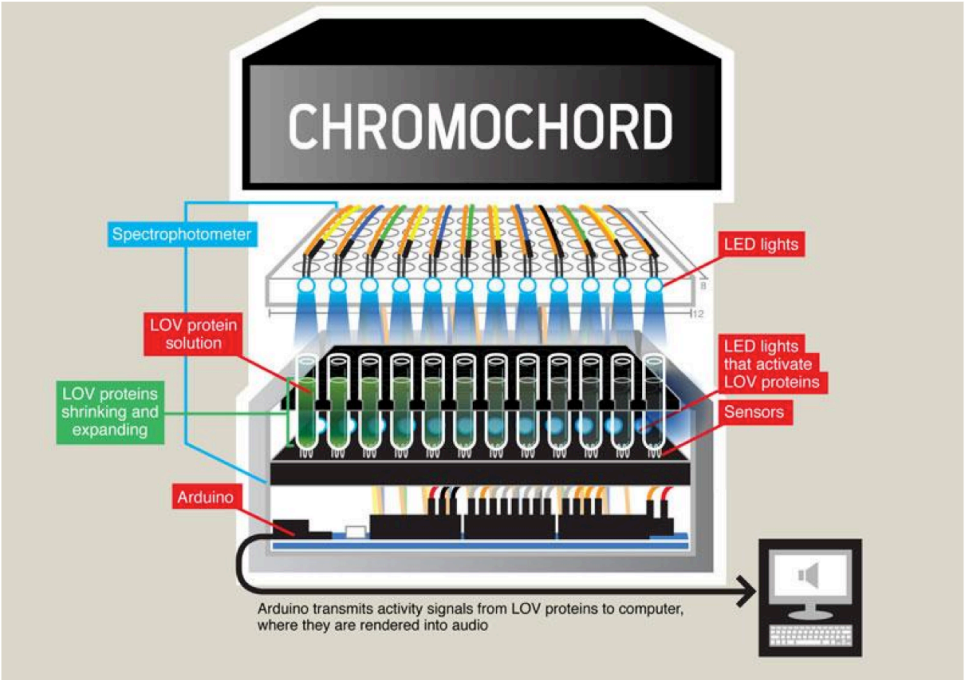
Figure 3: Comformational change in AsLOV2 during photocycle.

[90] Josiah P. Zayner, Chloe Antoniou and Tobin R. Sosnick, "The Amino-Terminal Helix Modulates Light-Activated Conformational Changes in AsLOV2" in *Journal of Molecular Biology*, 419, 1-2, (Elsevier, 2012), 61.

During the photocycle of the protein, its distinct optical spectra between 400 and 500 nm changes instantaneously as a flavin chromophore absorbs photons of blue light. This process is reversible and in the dark the optical spectra will return to its ground state over the course of ~80 seconds. The protein's reversible photocycle time and absorbance characteristics can be modified through engineering.[91]

For *the Chromochord Installation* AsLOV2 proteins with three different recoveries were engineered by Josiah Zayner.

3.3 The Chromochord



The operation of the Chromochord can be reduced to the following process:

12 wells containing solution of the light-responsive protein (AsLOV2), each with a LED light that set off the protein's chemical reaction, and with a

[91] Zayner, 61

spectrophotometer that measures changes in the protein. An ADC programmed in Arduino scales and filters the measurements and subsequently outputs them in two streams of data. One outputs the absorbance data of each well every 350 milliseconds; the other outputs the degradation data for each well every 6 minutes. These two streams are inputted to a Max/MSP patch through the serial port (USB) where it goes through the sonification process. The structure of the Max/MSP patch is described below.

Figure 4: Sonification process flow

To trigger the protein's photocycle the LED light is activated causing the protein to absorb light, morph into unstable state, and gradually recover. A score (figure 5, full score in appendix B) containing the sequence that switches the 12 LEDs on and off is programmed within the Arduino and is repeated perpetually.

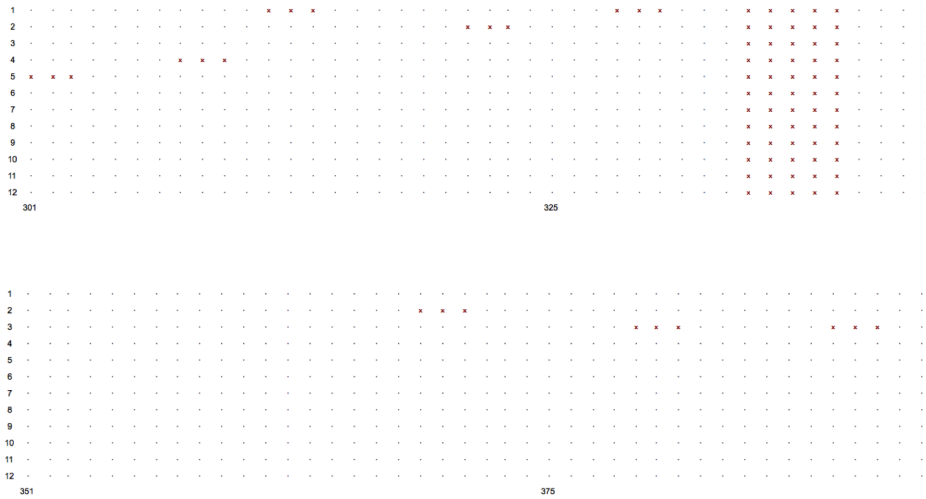


Figure 5: Chromochord Installation Cycle Score Excerpt
(x indicates when light is activated, x-axis = time, y-axis = well number)

Data related processing such as polling, denoising, and filtering, all occurs within the Chromochord's Arduino Due ADC. The fine-tuning that allows optimal data quality occurs during the Chromochord's start-up sequence.

3.4 Protein Specifications

For *the Chromochord Installation* all 12 wells of the Chromochord are utilized, each with one of three kinds of proteins.

- Protein wells 1-4: Short photocycle – between ~6 and ~8 seconds.
- Protein wells 5-8: Medium photocycle– between ~20 and ~30 seconds.
- Protein wells 9-12: Long photocycle – between ~50 and ~60 seconds.

All proteins should be in a non-degraded state at the onset of the installation.

3.5 The Chromochord Patch

The sonification process in *the Chromochord Installation* occurs in a patch programmed in Max/MSP 6 (Figure 6).

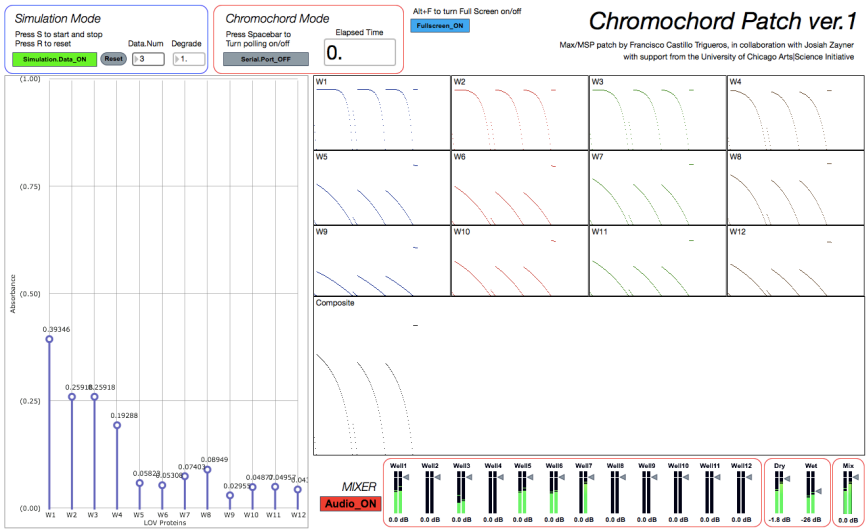


Figure 6: Screen shot of visual interface of the Chromochord Patch in Max/MSP

The Chromochord Patch structure can be divided into 4 modules, each with its own, specific function. The first deals with gathering and organizing the data from the Chromochord, the second contains 12 sound synthesis engines (1 per protein well) and the data mapping tasks, the third consists of a mixer that allows to balance the amplitude of the sounds from each synthesis engine. The last consists of the digital-to-analog converter (DAC) that allows the sonification's signal into audio. As shown in figure 7, the flow of information in these modules is always unidirectional.

Figure 7: Modules in The Chromochord Patch

3.5.1 Mixer and Digital-to-Analogue Converter

Since the unidirectional has been clearly illustrated in the flowchart in figure above the description of each component won't follow that order. The last to elements of the patch will be explained first because of their simplicity and their lack of relationship to the data coming from The Chromochord. The mixer receives the outcoming signal from all 12 synthesis engines and allows the amplitude for each of the engines to be adjusted. The levels should be adjusted depending on the acoustic properties of the room in which *The Chromochord Installation* is placed, balanced in a way that most effectively allows all 12 synthesis engines to be heard. The digital-to-analogue converter in Max/MSP can be adjusted to different sampling rates and bit depths. These should be set to the highest possible setting that doesn't interfere with the computer's optimal performance.

3.5.2 Data Management

The Chromochord Max/MSP Patch receives two streams of data from The Chromochord through the serial port (USB). One stream contains the absorbance data for each well and the other contains the degradation data for each well. As shown in figure 8, the data is immediately parsed and routed to the synthesis engines, as well as aggregated in order to measure composite absorbance and degradation.

The patch also includes a simulation data-producing mechanism that facilitates testing without The Chromochord.

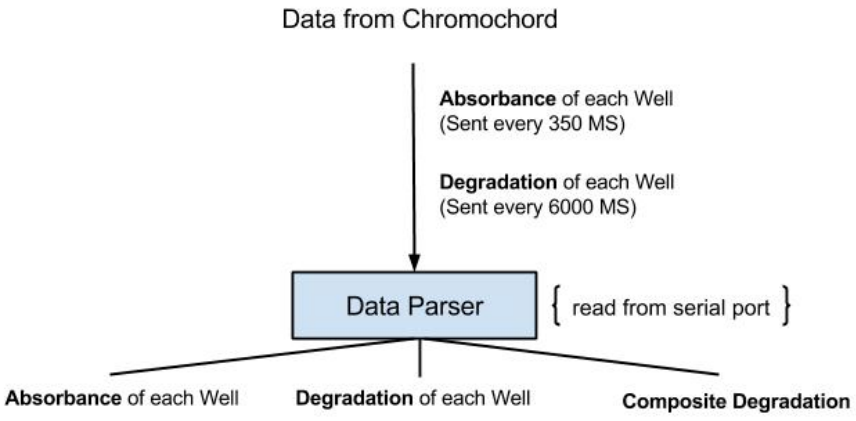


Figure 8: Data management in The Chromochord Patch

3.5.3 The Synthesis Engine

All sounds in The Chromochord's sonification environment are synthesized. Each of the 12 wells sending data from The Chromochord into the Max/MSP patch is mapped to a synthesis engine that relies on two components:

1) Noise
2) Filters based on spectral models

There are two kinds of noise used in the patch: white noise and pink noise. The noise is synthesized using native Max/MSP objects [noise~] and [pink~]. Immediately, the noise is funneled into one of two paths. One goes through a spectral filtering system, built using the CNMAT external [resonators~]. The other bypasses the spectral filtering system, goes through a low-pass filter that lightly modifies the noise, and out into the mixer.

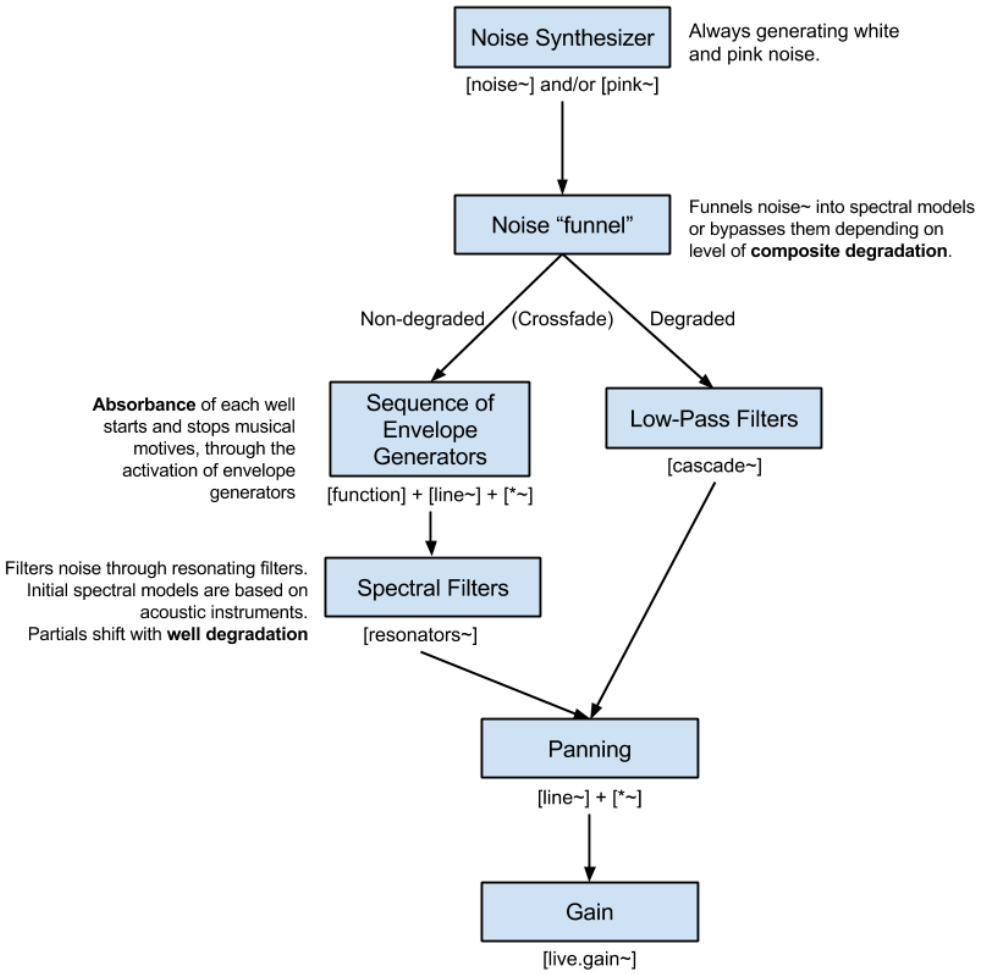


Figure 9: Synthesis engine with respective mappings in The Chromochord Patch

A mechanism, which is determined by the composite degradation of the proteins, cross-fades the amount of noise going into each of the two paths. When the

protein is in its initial, non-degraded state, the system funnels all of the noise into the spectral filters. As the protein degrades the system gradually cross-fades until the protein reaches its completely degraded state, at which the system bypasses the spectral filters completely. The result is the transition between a designed harmonic sound at one end and noise on the other.

3.5.3.1 Timbre Design

Each synthetic timbre created through the spectral filtering of noise with the [resonators~] objects is affected by the degradation of the protein in its corresponding well. The non-degraded protein data is mapped onto harmonic spectral models, each constructed with different snapshots of the spectra of different acoustic instruments. As the protein degrades the filters central frequencies shift creating non-harmonic timbres.

For example, a protein well that initially sounds similar to a viola is gradually transformed into a sound that is similar to a bowed suspended cymbal, due to its extremely inharmonic timbre. Each well goes through the same transformation, albeit each with its own transformation design. Thus, in the beginning of the installation we have several distinct timbres, as the different protein wells degrade their mapped timbres increasingly meld into each other and then dissipate into non-distinct noise.

The spectral models for all 12 wells and the operations by which they are transformed are included in Appendix A.

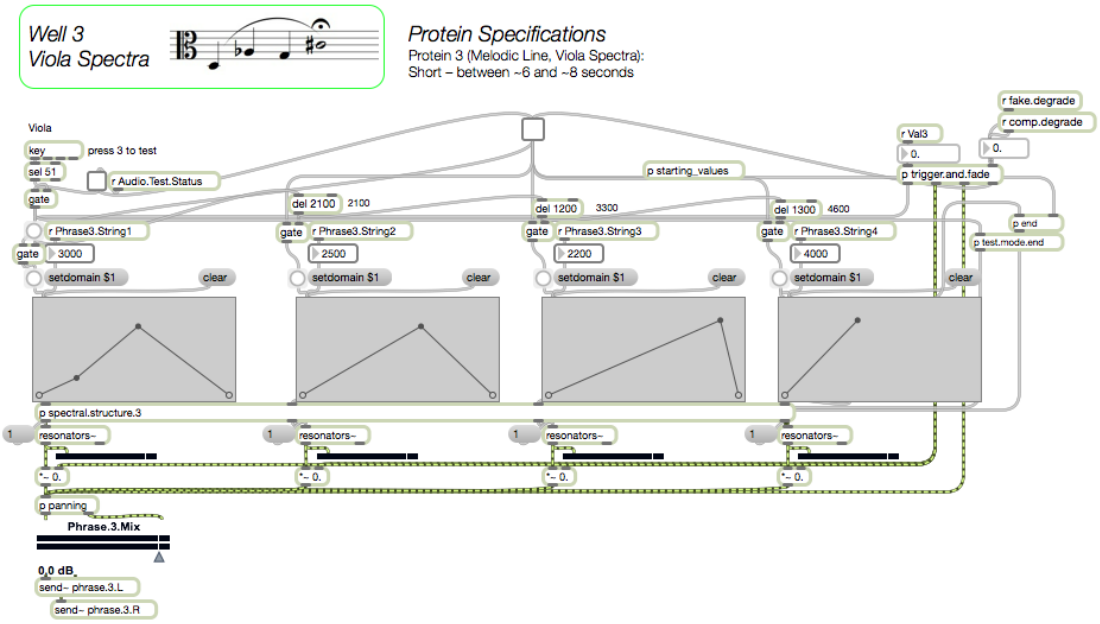


Figure 10: Screenshot of synthesis engine for protein well 3 in The Chromochord Patch

It is important to mention that a couple of the spectral models are applied to multiple protein models. Therefore, on its own, timbre is not sufficient to distinguish the different wells from each other.

3.5.3.2 Musical Motives (Quasi-Earcons)

The synthesis engine for each well is activated when its respective protein is going through its photocycle. When a protein well is in a stable state no sound events are triggered.

To make all wells distinguishable from each other, 12 distinct (though related) musical motives were created. The pitch content of each motive does not reflect any mapping and was designed in an intuitive way. However, each motive, by its

combination of timbre and motivic content should be easily recognizable by any listener. Furthermore, the musical motives which's construction is detailed below, allow the listener to identify the length of any given photocycle.

As explained above, when the AsLOV2 protein is struck by light a chemical process called "photocycle" is initiated. Although the length of a photocycle can be estimated with some accuracy there's always some variance, each cycle is slightly different, each chemical process unique.

As described in detail in chapter 3.4 *the Chromochord Installation* calls for three different approximate photocycle lengths so that four wells are filled with proteins with a short-length photocycle, four wells with a medium-length photocycle, and four with a long-length photocycle.

The musical motives can be grouped under three categories:

- Melodic Sequence
- Pulsating Chord
- Rhythmic Sequence/Gesture
- Polyrhythmic Texture

Melodic Sequence: 7 of the 12 protein wells (Wells 1, 3, 5, 7, 9, 11, and 12) are mapped to melodic musical motives. So that the wells can be identifiable from one another, each melodic sequence is unique in its pitch content, range, and rhythmic profile. However all of them are derived from a set of patterns, the most extreme similarity occurring between Well 1 and Well 3 where one is the inversion of the other. The length of the photocycle determines the length of the sequence. This

means that the phrase is sometimes unfinished, and sometimes its last note held. The absorbance of the protein is subtly mapped to the amplitude of the musical sequence, allowing the listener to track where each well is in its photocycle.

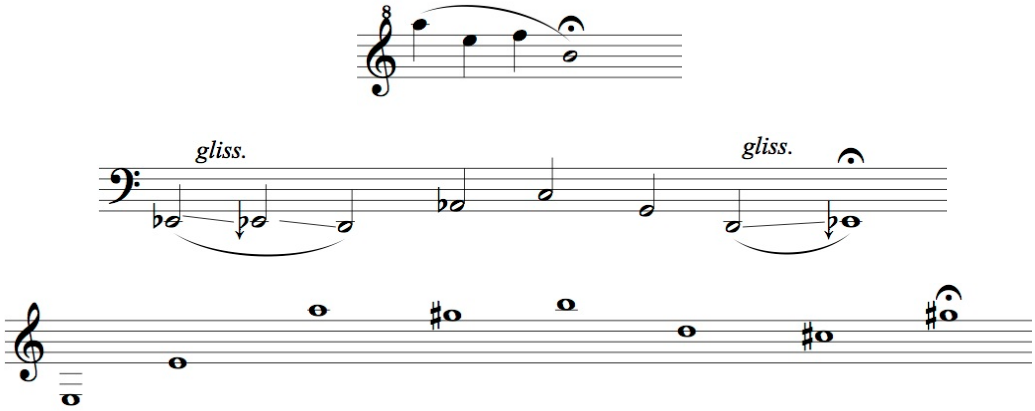


Figure 11: Three melodic sequences of different lengths (short, medium, long) that help the listener identify which protein well is active and how long its photocycle lasts.

Pulsating Chord: 3 of the 12 protein wells (Wells 4, 8, and 10) trigger a chord that is repeated while the protein is active. Although each well is mapped to a different timbre, and each chord is constructed of different intervals these three wells represent the most similarly sonified elements, carrying a greater risk of confusion. The ambiguity is explored in the composition. The length of the photocycle is mapped to the number of repetitions of the chord. The absorbance of the protein well is mapped to the rate of repetition of the chord (rate slows down as protein recovers), a mapping that is reinforced by subtle change in amplitude.

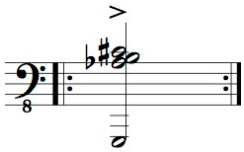


Figure 12: Pulsating chord that indicates an active Protein Well 10

Rhythmic Sequence/Gesture: One of the proteins wells (Well 2) is represented by a rhythmic sequence. The length of the photocycle can be identified by the duration of the sequence. It's absorbance by a subtle change in amplitude.

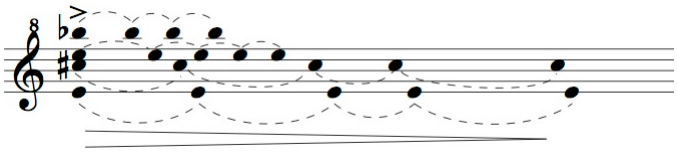


Figure 13: Rhytmic sequence played when Well 2 is active

Polyrhythmic texture: The remaining protein well (Well 6) is represented by a 12-part polyrhythmic texture. The length of the photocycle is represented by the duration of the texture. The absorbance rate is mapped onto the speed of the underlying pulse of the polyrhythm thus a higher textural density represents a lower absorbance and a lower textural density represents a higher absorbance. As with every other well, the absorbance is mapped onto subtle changes in amplitude.

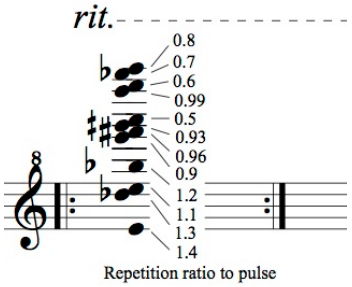


Figure 14: Well 6 Motive's harmony and ratios of repetition per pitch

3.6 Synopsis of Sonification Mappings

In summary, here's a list of the data-to-sound mappings:

- Active Photocycle (per protein well): Musical motives
    - Well recognition: Distinct musical motive, and timbre

    - Photocycle length/recovery time = Length of motive
    - Absorbance rate = Amplitude
- Degradation (per protein well): Spectral transformation
    - Pre-degraded state = Harmonic timbre
    - Degraded state = Inharmonic timbre
- Composite Degradation: Noise funnel
    - Pre-degraded state = Funnels noise into spectral filters (only perceivable when wells are active)
    - Degraded state = Bypasses spectral filters (always present)

3.7 Metaphorical Representations

While the activity and degradation of each protein well, as well as the composite degradation are systematically sonified other properties of the protein were used as metaphorical foundations for the composition of the installation. These include:

- The Cyclical nature of the photocycle
- Metaphorical degradation
- Composite nature of AsLOV2 protein

Cyclical nature of the photocycle: While this property is made evident by the repetition of the musical motives (since it is only logical that musical motives are repeated if the protein can recover and be re-triggered), the structure of the piece uses this principle as a structural element in the composition. The score, which contains instructions that tell the Chromochord when to switch on and off the

lights that trigger the different protein wells' photocycles, is repeated perpetually. Each cycle lasts for approximately 6 minutes. Besides the structural coherence that the cycle gives the piece, the repetition helps the listener understand how the proteins are changing over long stretches of time, how they are degrading in relation to one another. Since the light patterns are always exactly the same but the degradation of the proteins creates a different sonic result as the piece progresses, the changing nature of the proteins is highlighted in contrast to the unchanging mechanical impulses that trigger them.

Metaphorical Degradation: Although the degradation of the proteins is systematically sonified, the sonification itself is inspired by the idea of degradation. The opening environment, constructed of a musical syntax (melodies, counterpoint, orchestration, intensity) gradually transitions to a static sound environment (held colored noise.) So, while the pre-degradation sonification may be better understood by using listening strategies commonly applied to pieces of music, the post-degradation sonification could be better appreciated if one listens in the same way as listening to an atmospheric or natural environment.

Composite nature of proteins: Since the AsLOV2 protein works in groups in order to make plants move towards maximum light their composite nature is reflected in some aspects of the installation. While originally the composite absorbance triggered a flanging effect in the moments of maximum activity, this

was removed for aesthetic reasons. The video component from the installation still responds to the composite absorbance (see 3.10). Still, the composite degradation plays an extremely important part in the system by funneling the noise into or out of the spectral filters, therefore functioning as the primary mechanism by which the piece morphs from a musical syntax, constructed with melodic, contrapuntal, and harmonic materials, to a sound environment syntax, consisting of sustained layers of noise.

3.8 Independent/Arbitrary Elements:

While many decisions in the sonification of the AsLOV2 protein were made in response to the desire to communicate aspects of the protein both literally, through data-to-sound mapping, and metaphorically, through conceptual analogies, some decisions were made for other reasons. These include the following:

Choice of timbres: Although informed by the necessity to differentiate the wells, the choice of the timbre assigned to each well was decided with the goal of creating an enigmatic and aesthetically appealing sound environment.

Musical motives design: As with the choice of timbres the musical motives were designed to aid the differentiation of all 12 wells. The actual composition of each motive was motivated by musical factors.

Score, light triggering and cycle length: The score, which instructs the Chromochord when to turn lights on and off was composed to create musical interest through varying densities, contrapuntal techniques, suggestive silences, and a climatic build-up. The cycle's length was also motivated by aesthetics.

Panning: To create a sense of viscosity all 12 synthesis engine sounds slowly move throughout the stereo field at different rates.

3.9 Considerations

While *the Chromochord Installation* successfully communicates certain properties of the proteins behavior through sonification, it is apparent that, because of its musically oriented design, it isn't useful for analysis or scientific tasks. On the other hand, the decision to make sure that those properties protein behavior are communicated created specific conditions that constrained creative decisions. In light of this paradox, two considerations must be made:

1) In a scientific application where the transmission of information is paramount several mappings would be different:

- Each well would start with its own timbre to facilitate effective identification by the listener.

- Musical motives would be more consistent in treatment, yet more distinguishable in profile. For example, all wells would be mapped to melodic sequences, but each sequence would have a well-defined pattern.
- The state of the absorption rate, currently mapped very subtly to the amplitude of musical phrases and occasionally to repetition rates would be mapped in a more straightforward manner.
- A systematic use of range would be employed to emphasize certain mappings.
- A marker, such as a click at a regular pulse, to delineate time and provide context to the sonified events.
- Masking of sound events would be avoided.

2) A more musical application that would inhibit the understanding of the properties of the protein could include:

- A score where the lights switch for irregular periods of time. Allowing musical motives to last longer.
- A less systematic application of amplitude to allow for motives that increase in volume and don't follow the absorption pattern of the protein.

4. Conclusion

The application of sonification allowed visitors to *the Chromochord Installation* to experience aspects of the AsLOV2 light responsive protein in an informative and aesthetically satisfying way. *The Chromochord Installation* contributed to the practice of artistic sonification with its innovative use of bioelectronics. The construction of an instrument that allowed the manipulation of the protein and the collection of its behavior's data sets it apart from data collection pieces like Christina Kubisch's *Clocktower Project* and Charles Dodge's *Earth's Magnetic Field* where the data sonified is caused by an unprovoked phenomenon, denying the composer agency over the data. *The Chromochord Installation's* success in communicating the protein's behavior clearly while setting it to appealing musical structures is also unique. While the sonification, because of its musically oriented design, doesn't communicate all aspects of the protein behavior, it still conveys the main components of the protein's chemical reaction and does so through poetic means. This success can be attributed to the effective application of the sonification concepts discussed in Chapter 1. Additionally, the successful use of contemporary computer music techniques, such as spectral synthesis, to communicate data could be useful for scientific oriented sonifications.

Finally, because sonification tends to require the composer or designer to take into account both the data and the listener's communication with the data, and because many fascinating phenomena are suitable to be converted into sound, the possibilities for innovation are enormous, if not endless. Each phenomenon

contains different data structures forcing the composer to invent new methods that successfully transmit the data, potentially leading to new musical structures and concepts. Thus, we can state that not only is sonification a powerful tool for analytical and artistic purposes, it could also be a transforming force behind the always evolving tradition of music composition.

Bibliography

Barrass, Tim. "Description of Sonification for ICAD 2006 Concert: Life Expectancy." *Proceedings of the 12th International Conference on Auditory Display,* 2006.
http://cogsci.eecs.qmul.ac.uk/oldpages/icad2006/proceedings/concert/life.pdf

Ben-Tal, Oded and Jonathan Berger. "Creative Aspects of Sonification" *Leonardo*, Vol. 37, No. 3 (2004): 229-232. Cambridge, MA: The MIT Press, 2004.

Burraston, Dave. "Rainwire: Environmental Sonification of Rainfall." Leonardo, Vol. 45, No. 3 (2012): 288-289. Cambridge, MA: The MIT Press, 2012.

Buxton, William, William Gaver, and Sara Bly. *Audio Interfaces: The Use of Non-Speech Audio at the Interface*. http://www.billbuxton.com/Audio.TOC.html

de Campo, Alberto. "Toward a Data Sonification Design Space Map." *Proceedings of the 13th International Conference on Auditory Display,* 2007.
http://iem.kug.ac.at/fileadmin/media/iem/altdaten/projekte/publications/paper/toward/toward.pdf

Delatour, Thierry. "Molecular Music: The Acoustic Conversion of Molecular Vibrational Spectra." Computer Music Journal, 24:3, (Fall 2000): 48–68. Cambridge, MA: The MIT Press, 2000.

Dubus, Gaël and Roberto Bresin. "Sonification of Physical Quantities Throughout History: A Meta-Study of Previous Mapping Strategies." *Proceedings of the 17th International Conference on Auditory Display,* 2011.
http://www.speech.kth.se/prod/publications/files/3612.pdf

Dunn, John and Mary Anne Clark. "Life Music: The Sonification of Proteins." Leonardo, Vol. 32, No. 1 (1999): 25-32. Cambridge, MA: The MIT Press, 1999.

Eldridge, Alicia. "Issues in Auditory Display." *Artificial Life*, Vol. 12, Issue 2 (2006): 259-274. Cambridge, MA: The MIT Press, 2006.

Field, Ambrose. "Global Music: The World by Ear, The CIA Factbook v1.0 – a 190 Channel Concert Sonification." *Proceedings of the 12th International Conference on Auditory Display,* 2006.
http://cogsci.eecs.qmul.ac.uk/oldpages/icad2006/proceedings/concert/cia.pdf

Hermann, Thomas, Andy Hunt and John G. Neuhoff (Eds.) *The Sonification Handbook*. Berlin, Germany: Logos Verlag, 2011.

Hermann, Thomas. "Taxonomy and Definitions for Sonification and Auditory Display." *Proceedings of the 14th International Conference on Auditory Display, 2008.* http://sonification.de/publications/media/Hermann2008-TAD.pdf

Hermann, Thomas and Andy Hunt. "An Introduction to Interactive Sonification." IEEE Multimedia, Vol. 12, No. 2, (April-June 2005): 20-24. http://www.computer.org/csdl/mags/mu/2005/02/u2020.html

Ikeda, Ryoji. http://www.ryojiikeda.com/

Kramer, Gregory. "An Introduction to Auditory Display." *Auditory Display*, vol. XVIII of *Santa Fe Institute, Studies in the Sciences of Complexity Proceedings*, 1–78. Edited by Gregory Kramer Reading, MA: Addison-Wesley, 1994.

Krapp, Peter. *Noise Channels: Glitch and Error in Digital Culture*. (Minnesota: University of Minnesota Press, 2011)

Kreidler, Johannes. http://www.kreidler-net.de/

Nesbitt, Keith V. and Stephen Barrass. "Evaluation of a Multimodal Sonification and Visualisation of Depth of Market Data." Proceedings of the 2002 International Conference on Auditory Display, Kyoto, 2002. http://www.icad.org/websiteV2.0/Conferences/ICAD2002/proceedings/51_KeithNesbitt.pdf

Polli, Andrea. "Atmospherics/Weather Works: A Spatialized Meteorological Data Sonification Project." *Leonardo*, Vol. 38, No. 1 (2005): 31-36. Cambridge, MA: The MIT Press, 2005.

Schoon, Andi and Florian Dombois. "Sonification in Music." *Proceedings of the 15th International Conference on Auditory Display,* 2009. http://www.icad.org/Proceedings/2009/SchoonDombois2009.pdf

Sturm Bob L. "Composing for an Ensemble of Atoms: the Metamorphosis of Scientific Experiment into Music." *Organised Sound*, 6, (2001): 131-145. Cambridge, UK: Cambridge University Press, 2001.

Swain, Joseph P. "The Concept of Musical Syntax." *The Musical Quarterly*, Vol. 79, No. 2 (Summer, 1995): 281-308. Oxford, UK: Oxford University Press, 1995.

Tittel, Claudia. "Sound Art as Sonification, and the Artistic Treatment of Features in our Surroundings." Organised Sound, Vol. 14, Issue 1, (April 2009): 57-64. Cambridge, UK: Cambridge University Press, 2009.

Thieberger, Ed M. and Charles Dodge. "An Interview with Charles Dodge." *Computer Music Journal*, Vol. 19, No. 1 (Spring, 1995): 11-24. Cambridge, MA: The MIT Press, 1995.

Weinberg, Gil and Travis Thatcher. "Interactive Sonification: Aesthetics, Functionality and Performance." *Leonardo Music Journal*, Vol. 16, *Noises Off: Sound Beyond Music* (2006): 9-12. Cambridge, MA: The MIT Press, 2006.

Vickers, Paul and Bennett Hogg. "Sonification Abstraite/Sonification Concrete: An Aesthetic Perspective Space For Classifying Auditory Displays In The Ars Musica Domain." *Proceedings of the 12th International Conference on Auditory Display*, 2006.

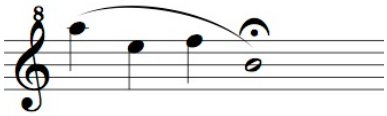
Zayner, Josiah P., Chloe Antoniou and Tobin R. Sosnick, "The Amino-Terminal Helix Modulates Light-Activated Conformational Changes in AsLOV2" in *Journal of Molecular Biology*, 419, 1-2, (Elsevier, 2012), 61-74.

http://www.massmoca.org/

Appendix A: Absorbance and Degradation Mappings per Well

Well 1 (*Melodic Line, Bell Spectra*): Short – between ~6 and ~8 seconds.

Phrase:



Spectral Structure for [resonators~]:

Frequency	Gain	Decay Rate
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

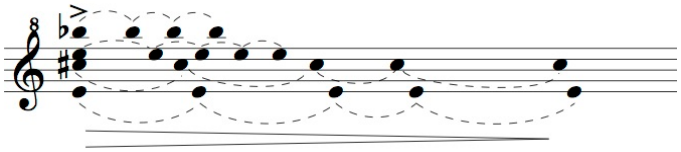
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
8436.972656	0.000182	2.087234
548.98	0.004109	2.093862
89.147461	0.000329	3.483103
246.435303	0.018966	4.177723
10268.275391	0.000135	5.0
2126.662109	0.000056	6.003992
90.937744	0.000052	9.526221
226.832031	0.009717	10.0003
1201.37915	0.000045	12.047483

Model exciter: Pink noise [pink~]

Well 2 (*Percussive gesture, Bell Spectra*): Short – between ~6 and ~8 seconds.

Gesture:



Spectral Structure for [Reson~]:
(See Well 1)

Frequency	Gain	Decay Rate
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

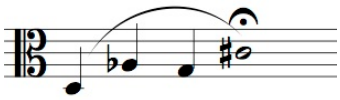
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
15436.972656	0.000182	2.087234
3548.98	0.004109	2.093862
6089.147461	0.000329	3.483103
1246.435303	0.018966	4.177723
16268.275391	0.000135	5.0
9126.662109	0.000056	6.003992
20.937744	0.000052	9.526221
8226.832031	0.009717	10.0003
1201.37915	0.000045	12.047483

Model exciter: Impulse

Well 3 (*Melodic Line, Viola Spectra*): Short – between ~6 and ~8 seconds.

Phrase:



Spectral Structure for [Reson~]:

Frequency	Gain	Decay Rate
2235.328613	0.00008	1.
2157.875977	0.002564	1.034247
1569.160156	0.001285	1.068495
1373.212402	0.009633	1.102742
981.115601	0.003516	1.136989
784.644775	0.006034	1.171236
588.837219	0.001186	1.205484
392.459534	0.008638	1.239731
3138.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956
4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777

Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
(-)2764.671387	0.00008	1.
(-)1842.124023	0.002564	1.034247
(-)1930.84	0.001285	1.068495
2173.212402	0.009633	1.102742
(-)18.884399	0.003516	1.136989
(-)1215.355225	0.006034	1.171236
3588.837219	0.001186	1.205484
(-)2307.540527	0.008638	1.239731
1738.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956
4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777

(Well 3 Spectra continued…)

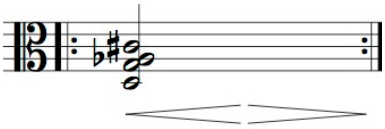
2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

Model exciter: White noise [noise~] and Pink noise [pink~]

Well 4 (*Repeating Chord, Viola Spectra*): Short – between ~6 and ~8 seconds.

Chord:



Spectral Structure for [Reson~]:
(See Well 3)

Frequency	Gain	Decay Rate
2235.328613	0.00008	1.
2157.875977	0.002564	1.034247
1569.160156	0.001285	1.068495
1373.212402	0.009633	1.102742
981.115601	0.003516	1.136989
784.644775	0.006034	1.171236
588.837219	0.001186	1.205484
392.459534	0.008638	1.239731
3138.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956

Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
235.328613	0.00008	1.
237.875977	0.002564	1.034247
669.160156	0.001285	1.068495
2173.212402	0.009633	1.102742
657.115601	0.003516	1.136989
84.644775	0.006034	1.171236
3588.837158	0.001186	1.205484
3092.459473	0.008638	1.239731
1738.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956

(Well 4 Spectra continued…)

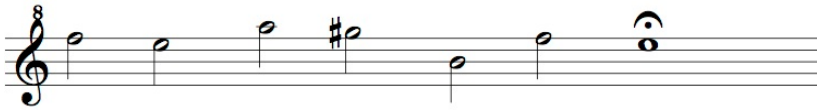
4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777
2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777
2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

Model Exciter: White noise [noise~] and Pink noise [pink~]

Well 5 (*Melodic Line, Bell Spectra*): Medium – between ~20 and ~30 seconds.

Phrase:



Spectral Structure for [Reson~]:
(See Well 1)

Frequency	Gain	Decay Rate
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

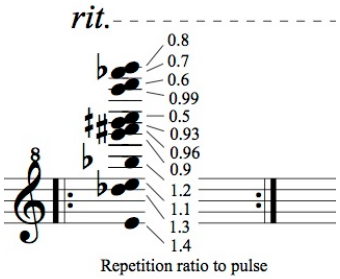
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
8436.972656	0.000182	2.087234
548.98	0.004109	2.093862
89.147461	0.000329	3.483103
246.435303	0.018966	4.177723
10268.275391	0.000135	5.0
2126.662109	0.000056	6.003992
90.937744	0.000052	9.526221
226.832031	0.009717	10.0003
1201.37915	0.000045	12.047483

Model exciter: White noise [noise~] and Pink noise [pink~]

Well 6 (*Percussive polyrhythm, Bell Spectra*): Medium – between ~20 and ~30 secs.

Polyrhythm:



Spectral Structure for [Reson~]:
(See Well 1)

Frequency	Gain	Decay Rate
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

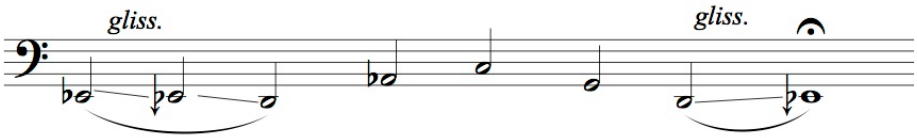
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
8436.972656	0.000182	2.087234
548.98	0.004109	2.093862
89.147461	0.000329	3.483103
246.435303	0.018966	4.177723
10268.275391	0.000135	5.0
2126.662109	0.000056	6.003992
90.937744	0.000052	9.526221
226.832031	0.009717	10.0003
1201.37915	0.000045	12.047483

Model exciter: Impulse

Well 7 (*Melodic Line, Cello Spectra*): Medium – between ~20 and ~30 seconds.

Phrase:



Spectral Structure for [Reson~]:

Frequency	Gain	Decay Rate
196.28064	0.02288	1.
98.106201	0.123875	1.062971
392.532501	0.010404	1.125942
249.31	0.00007	1.188912
133.262207	0.00013	1.251883
588.953247	0.003139	1.314854
294.455475	0.009737	1.377825
784.989136	0.004066	1.440795
686.915283	0.009678	1.503766
1079.061523	0.003335	1.566737
490.601715	0.0098	1.629708
2452.507812	0.000351	1.692679
1667.327393	0.000801	1.755649
882.950989	0.001274	1.81862
656.310608	0.000234	1.881591
2256.249756	0.000264	1.944562
1569.655029	0.000791	2.007532
1373.415649	0.000968	2.070503
980.941406	0.001416	2.133474
2549.187012	0.000381	2.257221
2157.920654	0.000273	2.485786
2059.37793	0.000143	2.714351
1316.574829	0.000049	2.942916
1176.398193	0.000483	3.171481
1471.792358	0.00027	3.4
563.409546	0.000276	3.62861
2648.248535	0.000113	3.857175
2486.353271	0.000183	4.08574
2354.210693	0.00017	4.314305
1277.4552	0.000296	4.54287
344.002319	0.000116	4.771435
50.039303	0.000817	5.

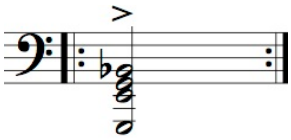
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
316.28064	0.02288	1.
298.106201	0.123875	1.062971
1192.532471	0.010404	1.125942
1049.31	0.00007	1.188912
203.262207	0.00013	1.251883
88.953247	0.003139	1.314854
3294.455566	0.009737	1.377825
84.989136	0.004066	1.440795
686.915283	0.009678	1.503766
1079.061523	0.003335	1.566737
490.601715	0.0098	1.629708
2452.507812	0.000351	1.692679
1667.327393	0.000801	1.755649
882.950989	0.001274	1.81862
656.310608	0.000234	1.881591
2256.249756	0.000264	1.944562
1569.655029	0.000791	2.007532
1373.415649	0.000968	2.070503
980.941406	0.001416	2.133474
2549.187012	0.000381	2.257221
2157.920654	0.000273	2.485786
2059.37793	0.000143	2.714351
1316.574829	0.000049	2.942916
1176.398193	0.000483	3.171481
1471.792358	0.00027	3.4
563.409546	0.000276	3.62861
2648.248535	0.000113	3.857175
2486.353271	0.000183	4.08574
2354.210693	0.00017	4.314305
1277.4552	0.000296	4.54287
344.002319	0.000116	4.771435
50.039303	0.000817	5.

Model exciter: Pink noise [pink~]

Well 8 (*Repeating Chord, Viola Spectra*): Medium – between ~20 and ~30 secs.

Chord:



Spectral Structure for [Reson~]:
(See Well 3)

Frequency	Gain	Decay Rate
2235.328613	0.00008	1.
2157.875977	0.002564	1.034247
1569.160156	0.001285	1.068495
1373.212402	0.009633	1.102742
981.115601	0.003516	1.136989
784.644775	0.006034	1.171236
588.837219	0.001186	1.205484
392.459534	0.008638	1.239731
3138.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956
4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777

Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
235.328613	0.00008	1.
237.875977	0.002564	1.034247
669.160156	0.001285	1.068495
2173.212402	0.009633	1.102742
257.115601	0.003516	1.136989
84.644775	0.006034	1.171236
13588.836914	0.001186	1.205484
13092.46	0.008638	1.239731
1738.03	0.000737	1.273978
2943.639648	0.001402	1.308225
2549.816406	0.001287	1.342473
2353.818848	0.001063	1.37672
3335.86792	0.000171	1.410967
2745.666748	0.000597	1.445214
1961.765747	0.008175	1.479462
196.24411	0.003083	1.513709
1765.481445	0.001529	1.547956
4119.84082	0.000119	1.582204
1177.162842	0.002635	1.616451
4706.737305	0.000056	1.650698
3725.803223	0.000116	1.684945
3923.371094	0.000231	1.719193
3531.317383	0.000116	1.75344
4317.620117	0.000049	1.787687
1702.111206	0.000067	1.821934
5490.777344	0.000052	1.856182
2016.451416	0.000073	1.890429
5687.316406	0.00004	1.924676
2854.288086	0.000077	1.958923
2826.404785	0.000045	1.993171
2496.986084	0.000043	2.027418
2976.129395	0.000094	2.095912
748.756836	0.000053	2.13016
3276.490967	0.000043	2.164407
1447.598022	0.000073	2.265241
2436.338135	0.000065	2.389548
6868.796387	0.000058	2.513855
2456.93042	0.000089	2.638163
2663.008057	0.000046	2.76247
6084.226074	0.000051	2.886777

(Well 8 Spectra continued…)

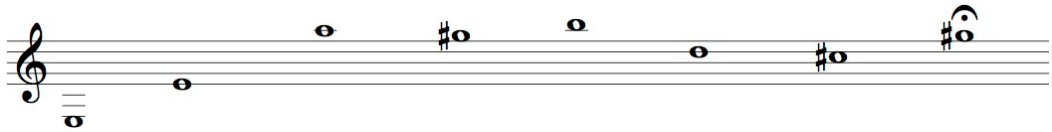
2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

2185.458496	0.00005	3.011084
6278.35791	0.000039	3.135391
3091.102783	0.00011	3.259699
3042.021729	0.000037	3.384006
1930.164062	0.000047	3.508313
7064.882812	0.000042	3.63262
1539.160522	0.00004	3.756927
5098.438477	0.000036	3.881235
2908.371338	0.000145	4.005542
1329.217407	0.000034	4.13
362.624786	0.000065	4.254156
2630.354248	0.00005	4.378463
2048.811768	0.000126	4.50277
1513.122681	0.000137	4.627078
1885.236328	0.000054	4.751385
1401.662964	0.000089	4.875692
4513.285645	0.000033	5.

Model exciter: Impulse

Well 9 (*Melodic Line, Bell Spectra*): Long – between ~50 and ~60 seconds.

Phrase:



Spectral Structure for [Reson~]:
(See Well 1)

Frequency	**Gain**	**Decay Rate**
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

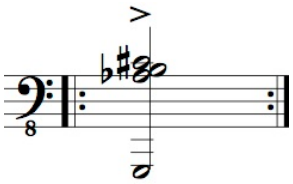
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	**Gain**	**Decay Rate**
26436.972656	0.000182	2.087234
6948.98	0.004109	2.093862
5239.147461	0.000329	3.483103
5046.435547	0.018966	4.177723
16268.275391	0.000135	5.0
12426.662109	0.000056	6.003992
2590.937744	0.000052	9.526221
13726.832031	0.009717	10.0003
4001.37915	0.000045	12.047483

Model exciter: Pink noise [pink~]

Well 10 (*Repeating Chord, Bell Spectra*): Long – between ~50 and ~60 seconds.

Phrase:



Spectral Structure for [Reson~]:
(See Well 1)

Frequency	Gain	Decay Rate
17436.972656	0.000182	2.087234
7048.98	0.004109	2.093862
5289.147461	0.000329	3.483103
2646.435303	0.018966	4.177723
13268.275391	0.000135	5.0
13126.662109	0.000056	6.003992
2690.937744	0.000052	9.526221
13226.832031	0.009717	10.0003
2601.37915	0.000045	12.047483

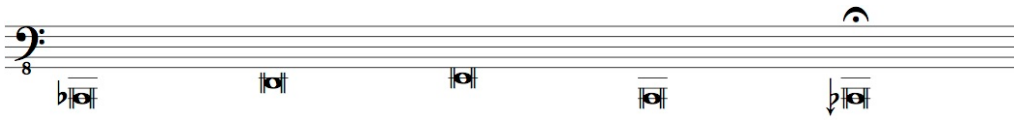
Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
26436.972656	0.000182	2.087234
6948.98	0.004109	2.093862
5239.147461	0.000329	3.483103
5046.435547	0.018966	4.177723
16268.275391	0.000135	5.0
12426.662109	0.000056	6.003992
2590.937744	0.000052	9.526221
13726.832031	0.009717	10.0003
4001.37915	0.000045	12.047483

Model exciter: Impulse

Well 11 (*Melodic Line, Bass Spectra*): Long – between ~50 and ~60 seconds.

Phrase:



Spectral Structure for [Reson~]:

Frequency	Gain	Decay Rate
73.058273	0.011448	0.2
182.061584	0.005593	0.3
109.292664	0.00697	0.323363
291.443085	0.000803	0.480045
436.714203	0.000352	0.636726
363.793518	0.001534	0.793408
546.57312	0.000619	0.950089
509.142914	0.000183	1.106771
691.026794	0.000269	1.263452
617.96759	0.000081	1.420134
473.351257	0.000155	1.576815
654.806885	0.000257	1.733497
582.27	0.000327	1.890179

Spectral Structure after complete "degradation" for [resonators~]:

Frequency	Gain	Decay Rate
53.058273	0.011448	0.2
82.061584	0.005593	0.3
429.292664	0.00697	0.323363
3291.443115	0.000803	0.480045
527.714233	0.000352	0.636726
163.793518	0.001534	0.793408
1615.57312	0.000619	0.950089
1209.142944	0.000183	1.106771
1691.026855	0.000269	1.263452
617.96759	0.000081	1.420134
473.351257	0.000155	1.576815
654.806885	0.000257	1.733497
582.27	0.000327	1.890179

(Well 11 Spectra continued…)

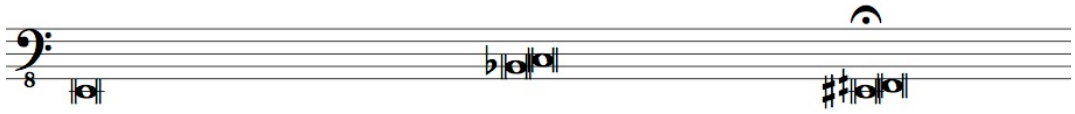
145.831253	0.002401	2.04686
909.471558	0.00023	2.203542
764.172546	0.000269	2.360223
254.6315	0.000812	2.516905
1416.002686	0.000038	2.673586
1273.601074	0.000159	2.830268
1238.779541	0.000064	2.986949
1201.484009	0.000106	3.143631
1129.676392	0.00011	3.3
1092.537598	0.000126	3.456994
983.54895	0.000118	3.679425
400.042206	0.000924	4.248131
327.442322	0.000491	4.816838
1021.050293	0.00006	5.385544
1528.79	0.00012	5.954251
837.586975	0.000128	6.522957
1709.937256	0.000059	7.091664
1165.015381	0.00011	7.66037
1055.633911	0.000122	8.229077
219.794556	0.000209	8.797784
1345.707764	0.000117	9.36649
800.470154	0.000087	9.935197
947.286438	0.000058	10.503903
874.482361	0.000149	11.07261
1382.396484	0.000052	11.641316
1311.051392	0.000067	12.21

145.831253	0.002401	2.04686
909.471558	0.00023	2.203542
764.172546	0.000269	2.360223
254.6315	0.000812	2.516905
1416.002686	0.000038	2.673586
1273.601074	0.000159	2.830268
1238.779541	0.000064	2.986949
1201.484009	0.000106	3.143631
1129.676392	0.00011	3.3
1092.537598	0.000126	3.456994
983.54895	0.000118	3.679425
400.042206	0.000924	4.248131
327.442322	0.000491	4.816838
1021.050293	0.00006	5.385544
1528.79	0.00012	5.954251
837.586975	0.000128	6.522957
1709.937256	0.000059	7.091664
1165.015381	0.00011	7.66037
1055.633911	0.000122	8.229077
219.794556	0.000209	8.797784
1345.707764	0.000117	9.36649
800.470154	0.000087	9.935197
947.286438	0.000058	10.503903
874.482361	0.000149	11.07261
1382.396484	0.000052	11.641316
1311.051392	0.000067	12.21

Model exciter: White noise [noise~] and Pink noise [pink~]

Well 12 (*Melodic Line, Piano Spectra*): Long – between ~50 and ~60 seconds.

Phrase:



Spectral Structure for [Reson~]:

Frequency	**Gain**	**Decay Rate**
57.003849	0.000517	1.
116.069115	0.001121	1.045398
1701.21228	0.000125	1.090795
1644.012329	0.000669	1.136193
1575.025513	0.000246	1.18159
1508.563477	0.000585	1.226988
1443.72644	0.000936	1.272385
174.168259	0.008259	1.317783
2462.894043	0.000137	1.36318

Spectral Structure after complete "degradation" for [resonators~]:

Frequency	**Gain**	**Decay Rate**
5057.003906	0.000517	1.
1006.069092	0.001121	1.045398
401.21228	0.000125	1.090795
4644.012207	0.000669	1.136193
672.025513	0.000246	1.18159
1348.563477	0.000585	1.226988
2512.726562	0.000936	1.272385
84.168259	0.008259	1.317783
9462.894531	0.000137	1.36318

(Well 12 Spectra continued…)

2248.226807	0.000115	1.408578
2039.745605	0.000315	1.453975
1971.55	0.000237	1.499373
1841.128296	0.000336	1.54477
1253.506836	0.006118	1.590168
1067.26	0.000991	1.635566
823.16748	0.003344	1.680963
703.320801	0.001115	1.726361
584.366211	0.003868	1.771758
525.384216	0.000872	1.817156
466.830841	0.000953	1.862553
407.868225	0.007937	1.907951
349.02124	0.003474	1.953348
290.677032	0.01948	1.998746
2317.471191	0.000128	2.044143
2178.362305	0.000151	2.089541
2108.970215	0.00015	2.134938
1379.559326	0.001798	2.198751
1129.032593	0.001631	2.363531
944.486694	0.002792	2.52831
763.158936	0.003663	2.693089
2389.153564	0.000084	2.857868
1905.32251	0.00022	3.022648
1769.432373	0.000844	3.187427
1316.691406	0.001198	3.352206
1191.735229	0.002571	3.516986
1005.150635	0.00042	3.681765
883.663574	0.003335	3.846544
643.293152	0.00102	4.011323
232.642822	0.005296	4.176103
2533.703125	0.000056	4.340882
1408.950195	0.000064	4.505661
1288.117554	0.000138	4.670441
1468.69165	0.000152	4.83522
1525.096069	0.000514	5.

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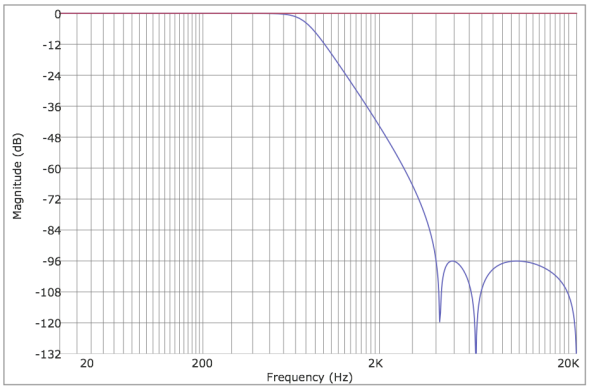
1408.950195	0.000064	4.505661
1288.117554	0.000138	4.670441
1468.69165	0.000152	4.83522
1525.096069	0.000514	5.

Model exciter: White noise [noise~] and Pink noise [pink~]

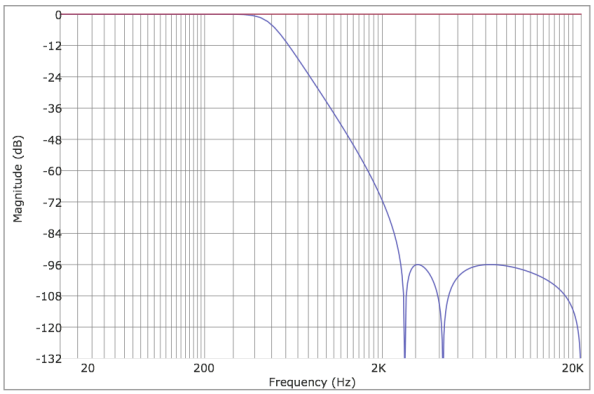
Composite degradation filters

Well 1



Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 4000, Order: 5, Response: Lowpass

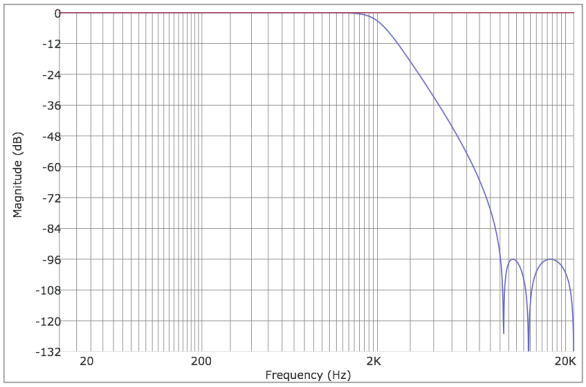
Well 3



Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 2500, Order: 5, Response: Lowpass

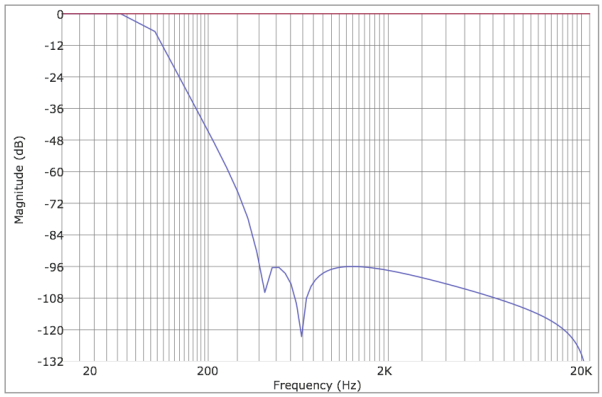
Well 4 *(Unfiltered)*

Well 5



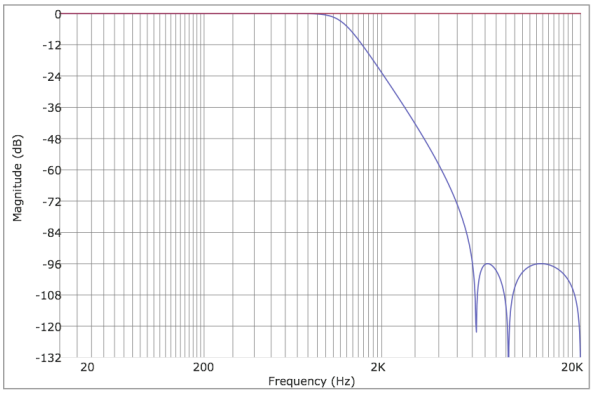
Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 9100, Order: 5, Response: Lowpass

Well 7



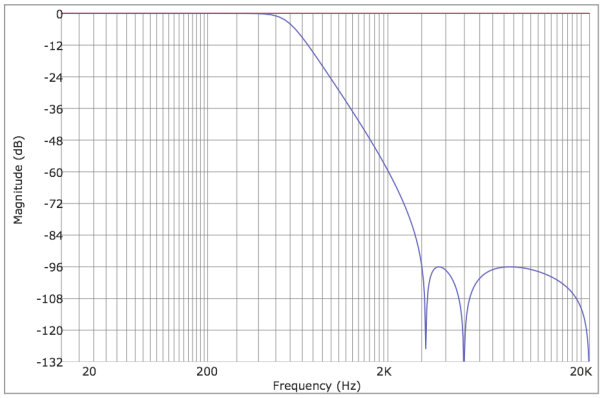
Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 400, Order: 5, Response: Lowpass

Well 9



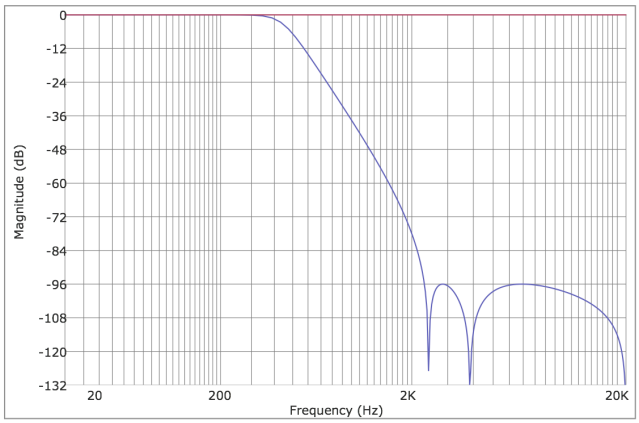
Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 6000, Order: 5, Response: Lowpass

Well 11



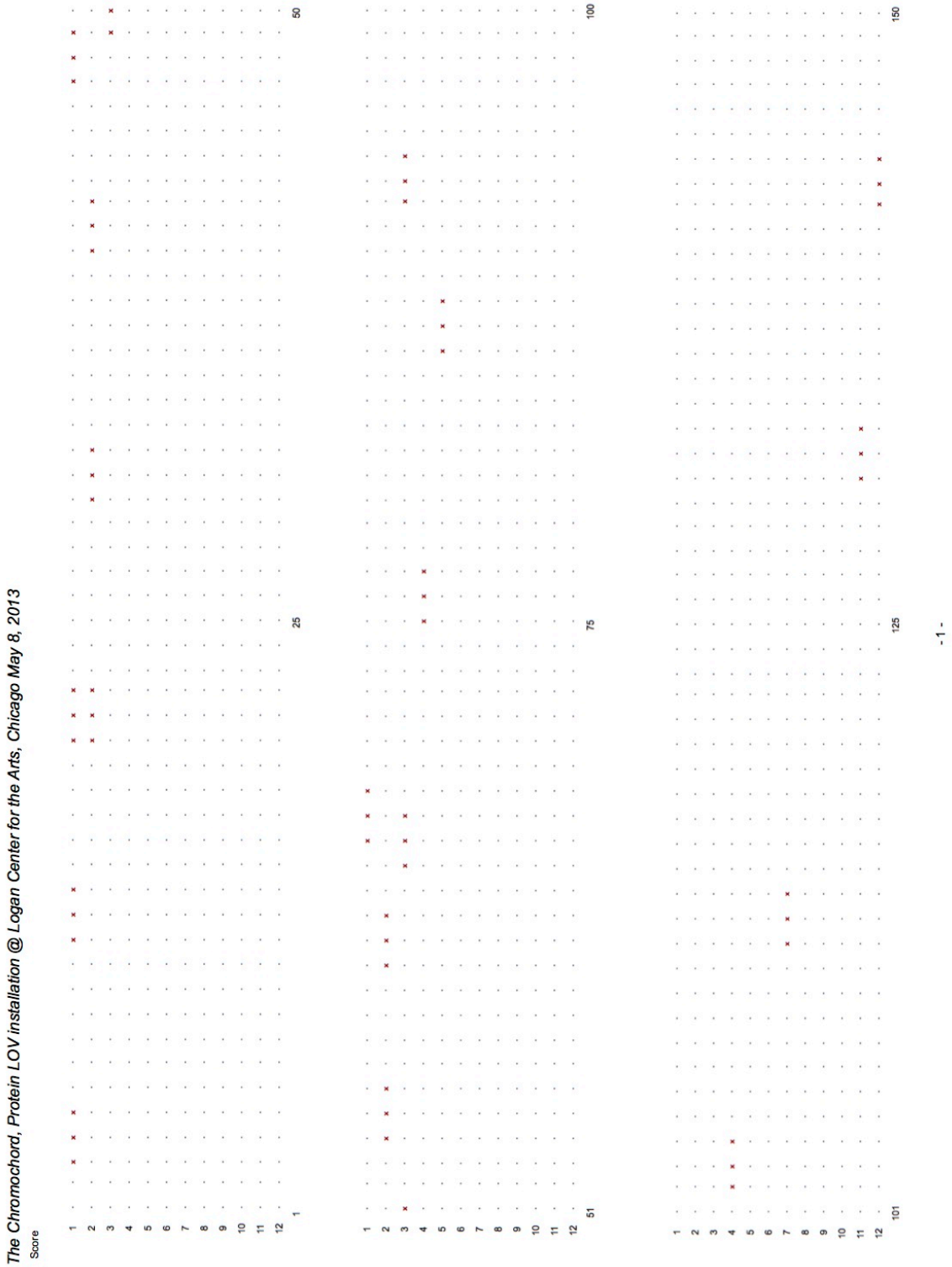
Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 3000, Order: 5, Response: Lowpass

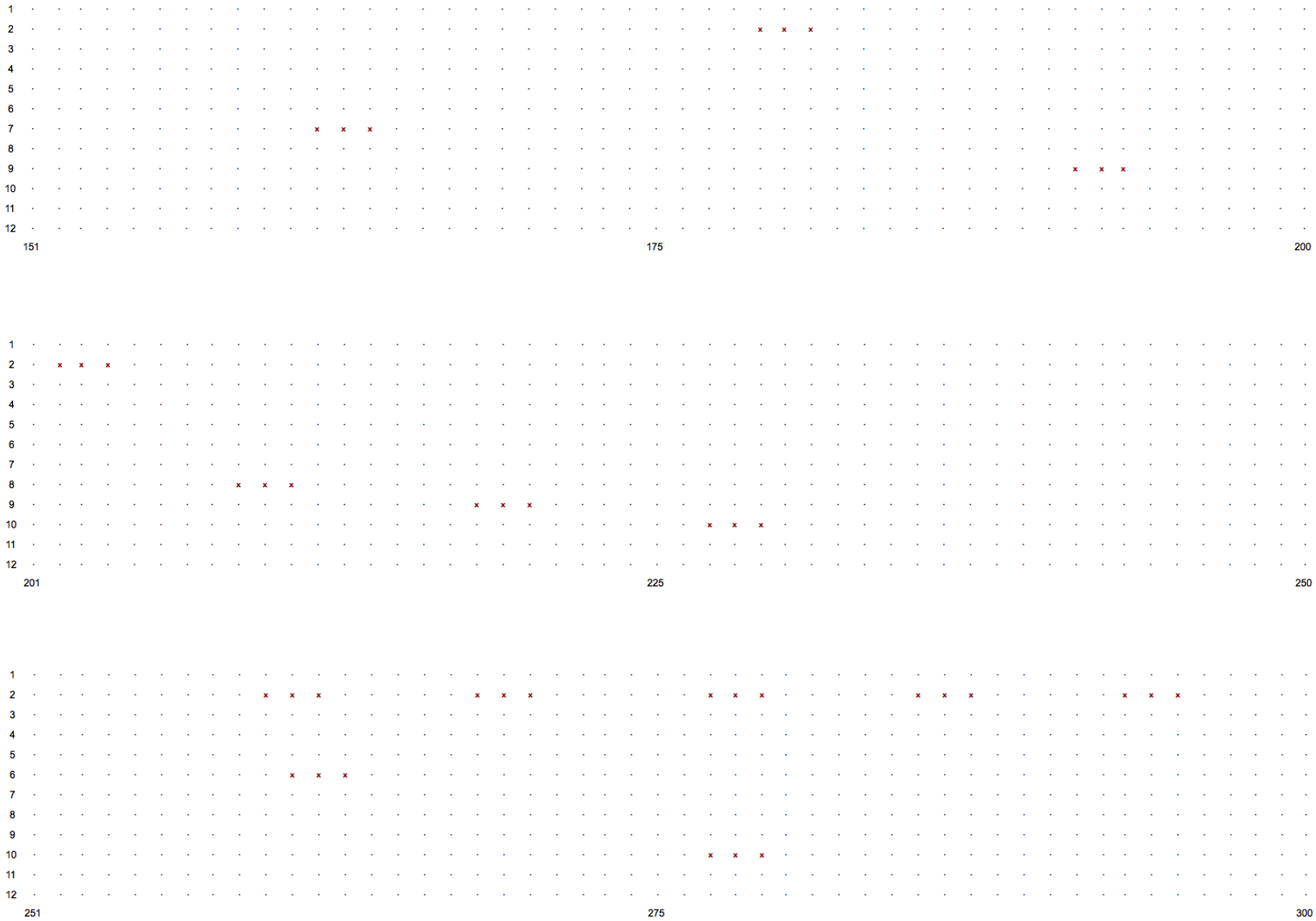
Well 12

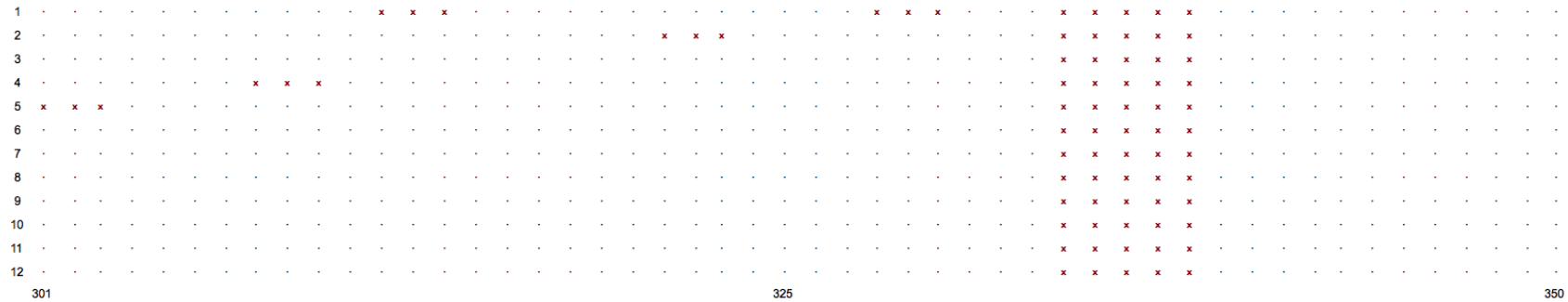


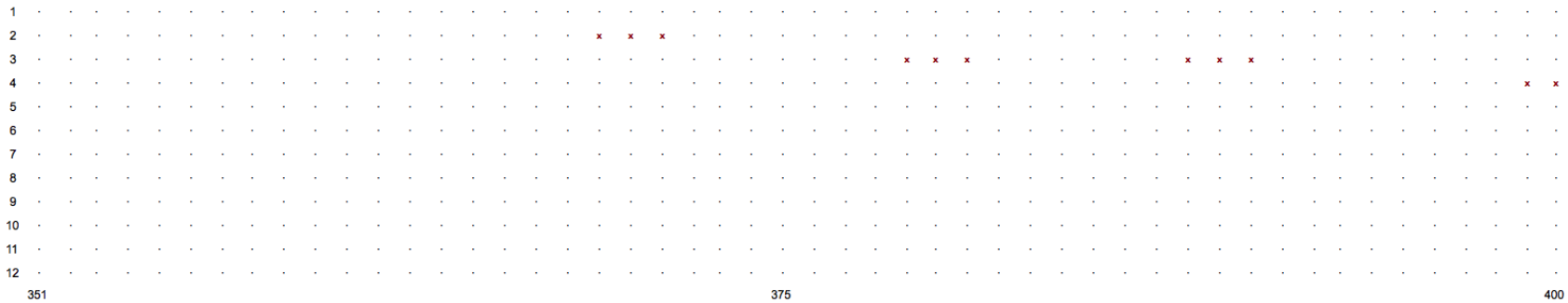
Topology: Crebyshev-2, Stopband Attenuation: 96, Frequency: 2300, Order: 5, Response: Lowpass

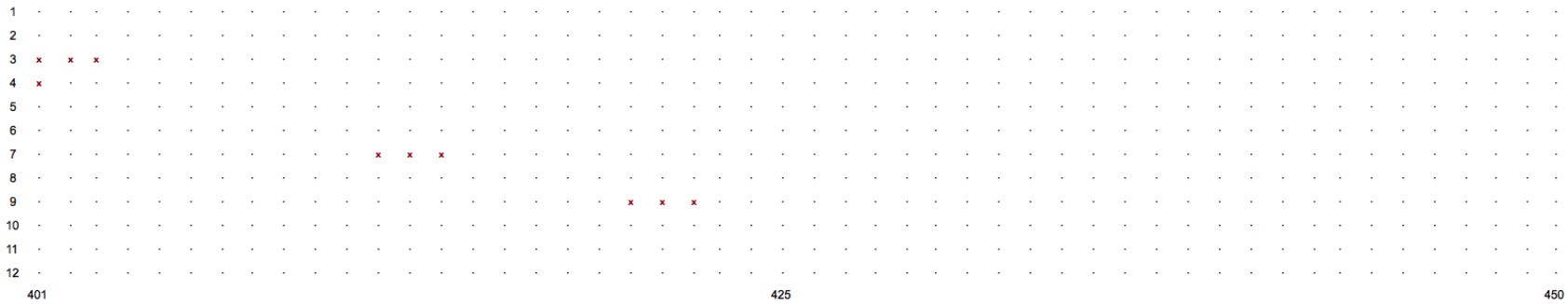
Appendix B: Score




1
2
3
4
5
6
7
8
9
10
11
12
151
175
200
201
225
250
251
275
300


1
2
3
4
5
6
7
8
9
10
11
12
301
325
350


1
2
3
4
5
6
7
8
9
10
11
12
351
375
400


1
2
3
4
5
6
7
8
9
10
11
12
401
425
450