Andrés Cabrera, JoAnn Kuchera-Morin, and Curtis Roads
Center for Research in Electronic Art
Technology (CREATE)
Media Arts and Technology (MAT) Program
University of California
3309 Phelps Hall, Santa Barbara,
California 93106-6065, USA
mantaraya36@gmail.com, {jkm,
clang}@create.ucsb.edu

The Evolution of Spatial Audio in the AlloSphere

Abstract: Spatial audio has been at the core of the multimodal experience at the AlloSphere, a unique instrument for data discovery and exploration through interactive immersive display, since its conception. The AlloSphere multichannel spatial audio design has direct roots in the history of electroacoustic spatial audio and is the result of previous activities in spatial audio at the University of California at Santa Barbara. A concise technical description of the AlloSphere, its architectural and acoustic features, its unique 3-D visual projection system, and the current 54.1 Meyer Sound audio infrastructure is presented, with details of the audio software architecture and the immersive sound capabilities it supports. As part of the process of realizing scientific and artistic projects for the AlloSphere, spatial audio research has been conducted, including the use of decorrelation of audio signals to supplement spatialization and tackling the thorny problem of interactive up-mixing through the Sound Element Spatializer and the Zirkonium Chords project. The latter uses the metaphor of geometric spatial chords as a high-level means of spatial up-mixing in performance. Other developments relating to spatial audio are presented, such as Ryan McGee's Spatial Modulation Synthesis, which simultaneously explores the synthesis of space and timbre.

Historical Background

The unique audio capabilities of the AlloSphere evolved out of a tradition of electroacoustic practice. The invention of the loudspeaker in the 1920s can be compared to the invention of the electric light bulb. Suddenly, it was possible to project sonic energy in spaces small and large, at any angle or intensity. But the use of loudspeakers in movie theaters, stadiums, railroad stations, phonographs, and home radios remained plain and functional. Only in the 1950s, with the dawn of the first theories of electronic music, did composers begin to exploit the aesthetic possibilities of sound projection via loudspeakers.

With its 400 loudspeakers and eleven-channel sound-routing system, the Philips Pavilion (1958), designed by Iannis Xenakis and Le Corbusier, pushed the concept of spatialized music to the forefront of aesthetic and technical interest (Trieb 1996). The GMEBaphone (Clozier 2001), developed in Bourges, and the Acousmonium (Bayle 1993), developed by the Groupe de Recherches Musicales (GRM), pioneered the current wave of interest in *pluriphonic* (many-loudspeaker) diffusion. Both were experiments with the concept of an orchestra of loudspeakers.

History of Spatial Audio at the University of California at Santa Barbara

The Center for Research in Electronic Art Technology (CREATE) at the University of California at Santa Barbara was formed in 1984 by JoAnn Kuchera-Morin. The research center focuses on research into digital audio and music, composition, and the development of music software. With the arrival of Curtis Roads in 1996, CREATE began to feature multichannel concerts with 8 to 20 loudspeakers onstage and around the 460-seat Lotte Lehmann Concert Hall. This variable-format system for sound projection was dubbed the Creatophone and was introduced in a concert in April 1998. The early setups were assembled around a foundation of Bowers and Wilkins B&W 801 loudspeakers combined with other types of speakers in the manner of the French loudspeaker orchestras. In 1999, Kuchera-Morin, Roads, and Stephen Pope contributed to the creation of the graduate program in Media Arts and Technology (MAT), which brought together faculty

Computer Music Journal, 40:4, pp. 47–61, Winter 2016
doi:10.1162/COMJ_a_00382
© 2017 Massachusetts Institute of Technology.

from the visual and spatial arts, music, electrical engineering, and computer science in an effort to create a transdisciplinary program around media arts.

In 2000, Kuchera-Morin submitted a proposal to the governor of California that eventually led to the construction of the California NanoSystems Institute housed in Elings Hall, which includes seven laboratories for MAT. One of these laboratories is the AlloSphere, conceived by Kuchera-Morin as a large-scale display instrument to serve as a multimodal data-discovery and data-exploration tool. Its associated Allosphere Research Group focuses on topics related to data visualization, scientific visualization, sonification, spatial audio, and interactive display and control, and is in charge of the development of the systems that drive the AlloSphere.

In parallel with the AlloSphere sound system, a permanent 8.1 Meyer Sound system was installed in the Lotte Lehmann Concert Hall in 2010, thanks to a generous contribution by the Corwin Chair of Composition, Clarence Barlow, and the labor of Matt Wright and MAT student Yutaka Makino. This supports eight UPJ-X1XP loudspeakers (300 W each) and one Meyer 600-HP subwoofer (2,250 W). This system acts as a performance platform in a live hall, and complements the AlloSphere spatial-audio instrument. Because it is installed in the Lotte Lehmann Concert Hall, the Creatophone is still used for most CREATE concerts. For a fuller portrait of CREATE activities, see the studio report by Roads et al. (2016). The AlloSphere is a more specialized space. Although suited for loudspeaker music concerts, is designed for a very different use, as described later in this article. Previous publications about the AlloSphere's development have mostly focused on the immersive visual display. This article presents the evolution, state, and goals of the sound system and architecture for the sphere.

Design of the AlloSphere

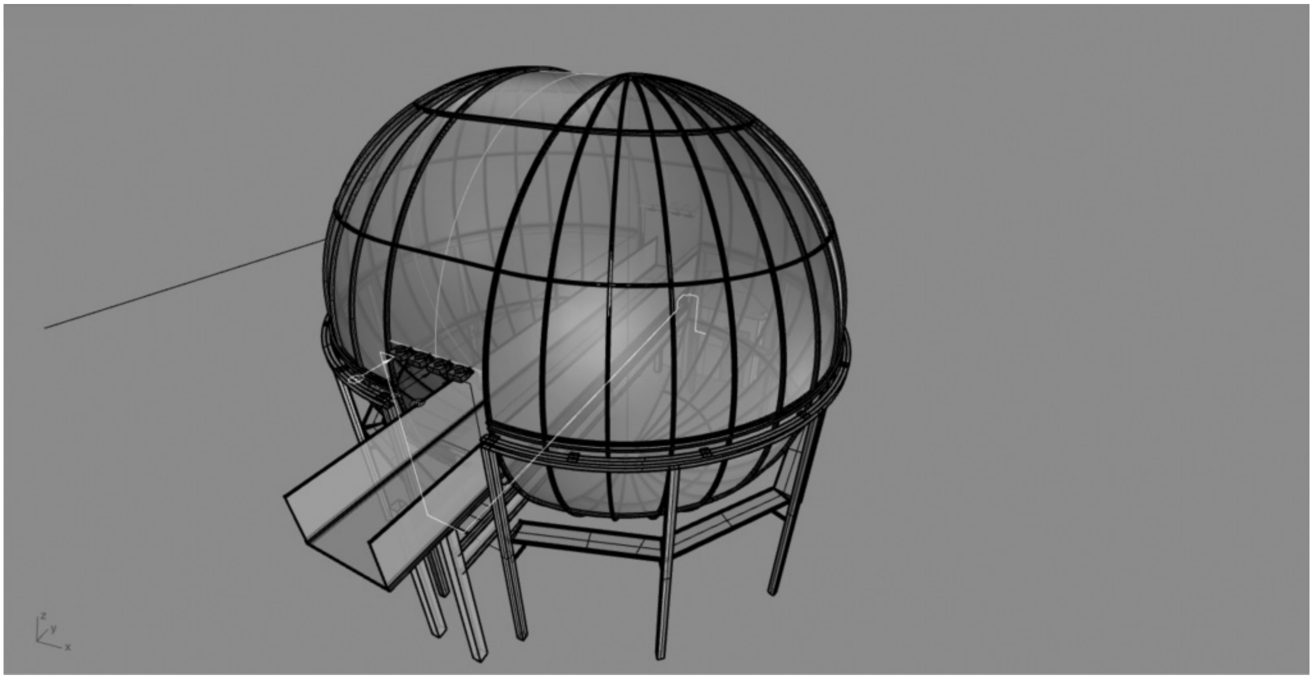
The AlloSphere instrument's hardware and software design is based on Kuchera-Morin's research in music composition, performance, and media systems. The AlloSphere was designed as an immersive multiuser, interactive platform for visual and aural composition and performance. In practice, it serves as a research instrument for composing and rendering large scale *n*-dimensional data sets, running simulations, and solving mathematical equations for data exploration and discovery.

The instrument consists of a metal sphere 10 meters in diameter, where immersive, full 360-degree, interactive sound and image are rendered in real time through a computer cluster. The sphere hangs within a three-story empty cube treated with extensive sound-absorption material, making it one of the largest near-to-anechoic chambers in the world. The sphere is composed of two hemispheres constructed of perforated aluminum designed to be optically opaque and acoustically transparent (less than 3-dB variation within the audible range), with a bridge running diametrically through it (as shown in Figure 1). Up to 24 people can assemble comfortably on the bridge.

The projection system comprises 26 high-definition, active, stereo video projectors driven by a 14-computer rendering cluster. The image covers the entire sphere and is calibrated to appear as a single high-pixel-density display. For a detailed discussion on the construction of the AlloSphere and the projection system and technologies, see the report by Amatriain et al. (2009).

The audio system of the AlloSphere instrument facilitates the integration of 3-D spatial audio within a multitude of important research areas. Used for interactive sonification of complex data sets, research has included the sonification of the cosmic microwave-radiation background with scientists working on the Planck Satellite mission (McGee et al. 2011) and the visualization and sonification of the time-dependent Schrödinger equation describing a hydrogen-like atom's wave-function combinations in superposition, with Luca Peliti of the Kavli Institute for Theoretical Physics (Putnam, Kuchera-Morin, and Peliti 2015). Designed as the data-discovery platform for new materials for media systems at the California NanoSystems Institute, the instrument's visual and aural display systems function as an interactive multiuser interface to experimental atomic data. Figure 2 shows a pair

Figure 1. The AlloSphere, with its bridge in the middle.



of researchers exploring microscope data in the sphere. Figure 3 presents a view of the AlloSphere showing projector and loudspeaker placement. Figure 4 shows a researcher exploring the projected solution to a complex mathematical equation. These diverse projects have shown the need for a flexible and general-purpose audio system. Knowledge of computer music, aesthetics and perception, and experience with loudspeaker orchestras and spatial audio have informed the design of each specific project's sonification, and have revealed the needs and requirements of the system going forward. The AlloSphere Research Group has endeavored to produce content and to support other teams working in the sphere to achieve results that are both scientifically valid and aesthetically pleasing.

The architectural specifications and the audio system of the AlloSphere work together to provide an immersive spatial-audio experience. Indeed, a primary design goal of the AlloSphere is to provide sense-limited resolution in both the audio and visual domains (Amatriain et al. 2007). In terms of audio, this requires covering the breadth of auditory perception in frequency, loudness, and dynamic range.

Table 1. Measured Noise Floor in the AlloSphere

Condition	*dB SPL (A-weighted)*
All equipment turned off	28.6
Inline duct fans off	33.2
Fans and projectors on	40.9
Entire system on	43.2

To provide an experience of the highest quality, other metrics, like effective signal-to-noise ratio (a useful dynamic range of more than 90 dB) and RT60 of less than 0.35 seconds from 100 Hz to 10 kHz are addressed. Equipment noise (HVAC, projectors, computers) is an important consideration. Table 1 shows measured noise levels for different configurations.

The AlloSphere was specifically designed to enable teams of interdisciplinary researchers to work together in conducting large-scale real-time

Figure 2. Immersed in nucleated steel the diameter of a hair, two researchers conduct interactive exploration of microscope data at the nanometer scale. (Photo by Kurt Kaminski.)

data mining. Researchers interact on the bridge of the AlloSphere in the manner of a performance ensemble using simultaneous interactive control of the display. This style of collaboration has taken diverse forms and has included simultaneous interaction with multiple control devices that mirror parameters or that provide different specific controls to each researcher.

Evolution of the Audio Hardware System

The AlloSphere audio system was developed in three phases. The audio research group that focused on the first implementation of a spatial audio system with the completion of the AlloSphere instrument in 2007 consisted of Xavier Amatriain and MAT graduate students along with Kuchera-Morin and Pope (Amatriain et al. 2007). This first prototype phase was completed in 2007, when 16 full-range active speakers were installed on three rings at different elevations, with the ring at the equator having eight loudspeakers, and a lower and upper ring with four loudspeakers each. Two subwoofers were installed at the edges of the bridge. The second phase was completed in 2009, when a total of 32 speakers were mounted, in addition to the two existing subwoofers.

The third phase was completed in 2012. This is the current configuration of the sphere, consisting of 54 Meyer Sound MM4XP self-powered speakers (220 W each) and one Meyer 600-HP subwoofer (2,250 W) on the ground. Figure 5 shows the mounting brackets and cabling for the loudspeakers immediately behind

Figure 3. View of the Allosphere showing projectors and loudspeakers in the middle ring.

the spherical screen. The MM4XPs are configured in three rings: a center ring at ear level made up of 30 speakers; and two additional rings, one below and one above, each with twelve speakers at an elevation of approximately 40 degrees. Two primary considerations drove this layout: (1) the need to supplement loudspeaker density both in the horizontal plane and in elevation, and (2) the practical constraints of adding loudspeakers. A higher density was selected for the horizontal plane, primarily because better localization acuity was desired here, but also because the sphere's construction made the mounting of loudspeakers simpler, more consistent, and more regular at this level.

The loudspeaker layout and numbering for the current setup can be seen in Figure 6. The loudspeakers are driven by six daisy-chained Echo Digital Audio AudioFire boxes, each providing twelve channels of input and output that present themselves as a single "aggregate" device on a Mac Pro desktop computer running Mac OSX. The somewhat unconventional numbering groups speaker rings together with groups of loudspeaker amplifiers and audio interfaces.

Future Loudspeaker Additions

The next phase will add 28 loudspeakers for a total of 82 loudspeakers and one subwoofer. This will increase the density in the upper hemisphere by adding two more rings above and below the existing elevated ring to increase localization accuracy for Ambisonics, vector base amplitude panning (VBAP), and point-source (i.e., single-loudspeaker) spatialization. This has been decided through careful listening and experience with the system to determine where perceived sound localization needs better precision and detail. It has become clear that a single elevated ring cannot provide clear and distinct variations in elevation required for our purposes. We

Figure 4. The bridge of the AlloSphere showing an immersion into the solution of a ray-cast interactive fractal equation. (Photo by Paul Wellman.)

require clear and unambiguous localization that can match visual elements, and this will require higher loudspeaker density in the upper hemisphere, where the salient action and attention is concentrated. Speakers at the zenith and the bottom of the sphere will also be added. We are currently in the planning stages for this installation. Although we already have the hardware, the current barrier to completing this installation is the logistical challenge of mounting and cabling the speakers in the small space between the sphere and the walls and of accessing the upper areas of the sphere.

Evolution of the Audio Software System

Although audio in the AlloSphere traces its roots to loudspeaker orchestras and electroacoustic multichannel practice, its peculiar requirements have resulted in a set of software libraries that facilitate generic rendering of data-driven sound scenes. The visual scene potentially presents elements in every direction, with any size and shape, from any distance, and moving at any speed. Sound must be able to directly reinforce the visual scene, so relying on loudspeakers as individual sources would not work adequately. Therefore, spatialization techniques are desired that perceptually approximate those source positions where no specific loudspeaker is present.

The audio system in the Allosphere has always supported heterogeneous software systems, and there is provision to support common third-party platforms like Csound, SuperCollider, Pure Data, and Max/MSP. The hardware and software infrastructure in the AlloSphere has directly followed the needs of projects and specific tools, and in

Figure 5. Loudspeaker mounts and cabling. (Photo by Dennis Adderton.)

Figure 6. The current loudspeaker layout in the AlloSphere.

Figure 5

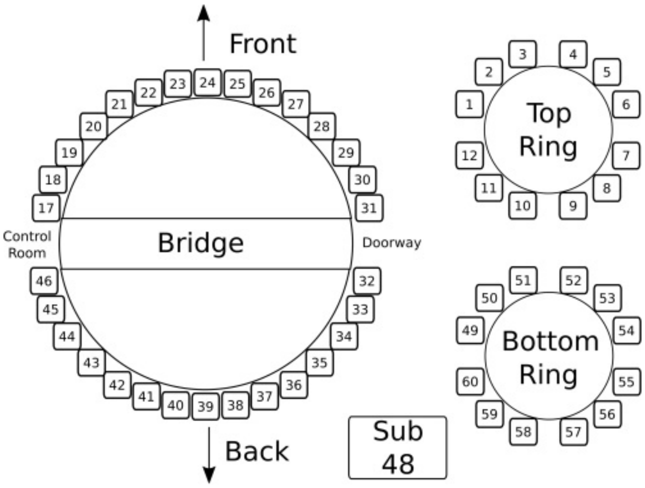


Figure 6

this way the needs of the content have pushed the technology forward. The first content developed for the AlloSphere used Max/MSP, and the Cosm libraries were developed to assist this task (Wakefield and Smith 2011). Max/MSP has since served as an adequate prototyping and development tool for the sphere. To create a more unified, seamless, and robust architecture for the cluster, however, it was decided that a set of C++ libraries needed to be developed to address in a unified manner the audio and graphics rendering servers. The CREATE Signal Library, originally developed by Stephen Travis Pope, was developed to support the development of audio content in the sphere through its synthesis and processing capabilities, and its set of spatialization algorithms, including VBAP and Ambisonics (Pope and Ramakrishnan 2003). Additionally, there were significant developments in VBAP reverberator design (McCoy 2005), Ambisonics decoding (up to eleventh order) (Hollerweger 2006; Wakefield 2006), and wave-field synthesis algorithms for dynamic scenes (Wolcott 2007) that were developed to expand the tools available when producing content for the Allosphere.

Although the system remains heterogeneous, and any software that runs on Mac OSX and can drive a large number of speakers can be used in the AlloSphere, the synchronization between audio and graphics rendering requires careful thought in the design and interactive capabilities of the software audio system. This synchronization inevitably involves coordinating an audio application running on one machine with 13 instances of the graphics rendering application running on each of the rendering servers. Systems like Omegalib address this issue, but its audio capabilities are limited.

Gain Control

A common problem when using a large number of loudspeakers is the need for global gain control, which is often solved with a dedicated and underutilized mixing console. Working together with the manufacturer, Echo Digital Audio, we were able to address this problem by developing a custom application that can centrally configure the AudioFire's entire internal signal processing. This allows us to adjust the gain and mute all 55 channels from a single application, without taxing the computer's CPU in the process or requiring additional routing software and operational procedures.

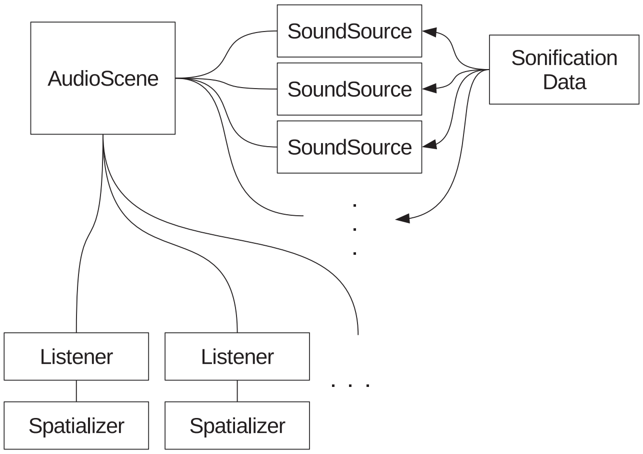
The AlloSystem Software Stack for Audio

The current AlloSystem libraries provide a toolkit for writing cross-platform audio/visual applications in C++, with tools to assist the synchronization of sound with graphics rendering required for distributed performance, interactive control, as well as a rich set of audio spatializers. Graduate student Ryan McGee ported the spatializers from the CREATE Signal Library to the AlloSystem AudioScene infrastructure (discussed subsequently) allowing the use of VBAP, distance-based amplitude panning (DBAP), or higher order ambisonics as the backend diffusion techniques. In practice, this means that the panning algorithm can be easily swapped out for comparison, exploration, and combination.

Graduate student Lance Putnam, who also wrote a large portion of the graphics system, developed the Gamma audio library. Gamma provides a set of C++ unit-generator classes with a focus on the design of audiovisual systems (Putnam 2014). The Gamma library allows synchronization of generators and processors to different "domains," permitting them to be used at frame or audio rate in different contexts, i.e., there is no need to downsample signals for the visuals as the signals and processes can be running at video rate within the graphics functions. The Gamma application programming interfaces (APIs) are also consistent with the rest of the graphics software, which makes learning and integrating the systems simpler. Putnam also developed a set of C++ classes in AlloSystem for spatial audio, including the infrastructure for generic spatializers and panners designed around the concept of scenes with sources and listeners. Similarly to the way a 3-D graphics scene is described to the graphics-rendering pipeline, which can then render through different "cameras" with different perspectives, an audio scene can be listened to by multiple "listeners" using different spatialization techniques and perspectives to render the sound. The scene consists sound-generating agents that are positioned and that can move freely in space. Multiple "Listeners" allow different renderings of the scene for different people. The technique can also be used to overlay multiple panning algorithms, as each "Listener" can use a different algorithm to render a scene. This architecture is suited to spatialized interactive data sonification as data objects can be directly mapped to these sound source agents.

Figure 7 shows an overview of this architecture using the C++ class names in the API. SoundSource objects represent a sound with a spatial location. They derive their state and sound from the data, and belong to an AudioScene object. AudioScenes themselves can have any number of Listener objects attached that perform the actual rendering of

Figure 7. Overview of the AudioScene architecture in the AlloSystem. SoundSource objects in an AudioScene describe the sound and its location. Listener objects render AudioScenes using different Spatializers that determine the panning algorithm (Ambisonics, VBAP, etc.).



sound, depending on the Spatializer they have been configured to use. Current spatializers include VBAP, DBAP, and up to third-order Ambisonics. This mechanism allows multiple participants wearing headphones to receive individualized audio with different perspectives of the scene, for example, through individualized head tracking or specific source masking. It also allows mixing different spatialization paradigms easily, so some elements can be panned using VBAP and others using Ambisonics, or Ambisonics of different orders can be combined. AudioScenes can also be made to render distance cues (high-frequency and level attenuation) and Doppler effect automatically from the spatial scene data when desired.

The AlloSystem library, which is designed to support distributed graphics rendering, can also be readily used for distributed audio rendering, taking advantage of the rendering cluster's computing power for computationally intensive audio processing. This is potentially useful for sonification of extremely large data sets, where the synthesis of each sound agent can be performed in parallel on separate machines, allowing for rendering that is both more complex and more nuanced.

Wave-Field Synthesis in the AlloSphere

Wave-field synthesis (WFS) was pursued initially as a spatialization technique, but it is not available in our current libraries. We now believe that WFS is impractical in the AlloSphere, as it is physically impossible (owing to practical mounting constraints) to achieve the high loudspeaker density theoretically required for adequate effect and quality of dynamic scenes with a sufficiently high spatial-aliasing frequency. Because elevation of sound images is such an important part of immersion in the sphere, something wildly impractical like spherical 3-D WFS would be required. Additionally, geometry plays against us, as the visual parallax effect behaves differently than the spatial reconstruction in WFS. Because the audio sources maintain their position no matter where the listener is located, whereas the stereo images actually appear to vary slightly with the viewer's position, there is a potential mismatch between visual and aural localization for listeners on different parts of the bridge. We have also been dissatisfied with the performance of WFS in our own tests of linear wave-field arrays, which seem not to justify the effort and expense of realization it in the AlloSphere.

AlloSphere Concert Series

The AlloSphere Concert Series was inaugurated on 18 February 2016 in a gala concert featuring invited composer John Chowning, the CREATE Ensemble, and graduate student works. The works used the heterogenous facilities to present various configurations including third-order Ambisonics decoding. This is the first of a series of AlloSphere spatial audio concerts that are planned for the future.

Recent Research in Multichannel Spatial Audio

The low-level previously discussed libraries have served as a foundation for spatial audio research and development. The libraries have also been used in multiple audiovisual works in the sphere. These works have ranged from artistic installations to tools for exploring scientific data, hence the spatial-audio research has covered a wide area. The various developments described here showcase the work related to spatial audio that has arisen from specific project needs. It highlights how content has driven technology and pushed forward research. This work ranges from technical developments geared towards control of sound-image width to better match the aural image with the visual sizes of elements in the scene, through developments to aid in the construction of multichannel aural spaces, to a novel audiovisual synthesis technique that exploits the uniqueness of the instrument. Video content and more detail can be found at the AlloSphere Web site (http://allosphere.ucsb.edu).

Surface Panner

As part of his research on spatial audio, Andrés Cabrera has extended and modified equal-power panning for multichannel loudspeaker systems through the addition of decorrelation for adequate perceived "width" control. This has required the addition and design of additional focus, width, and height parameters that allow detailed and expressive control of the perceived spatial extent and the shape of a virtual source. When a user specifies a position and extent, instead of finding triangles—as in VBAP—the loudspeakers contained in the active area are found and the gain is spread among them according to the focus parameter. Previous efforts for source spread in VBAP have attempted a similar algorithm but have typically provided only simple control of width and have not provided decorrelation, which is a significant issue when working in very dry spaces like the AlloSphere, where the room provides little reverberation. The focus can concentrate sound on the center or on the outer edge of the area. The decorrelation filters then ensure that the perceived sound image is not collapsed to a single position by the precedence effect. This technique is most effective in dense loudspeaker setups. High-performance, real-time, low-latency convolution filters have been implemented using the zita-convolver library. Decorrelation impulse responses for convolution can be generated using the Kendall method (Kendall 1995) or the deterministic method proposed by Zotter et al. (2011), with adjustments for use in multichannel settings. Decorrelation has also proven useful for Ambisonics decoding, which can be problematic when decoding lower orders (e.g., first-order soundfield microphone recordings) to the high number of speakers in the sphere.

Sound Element Spatializer

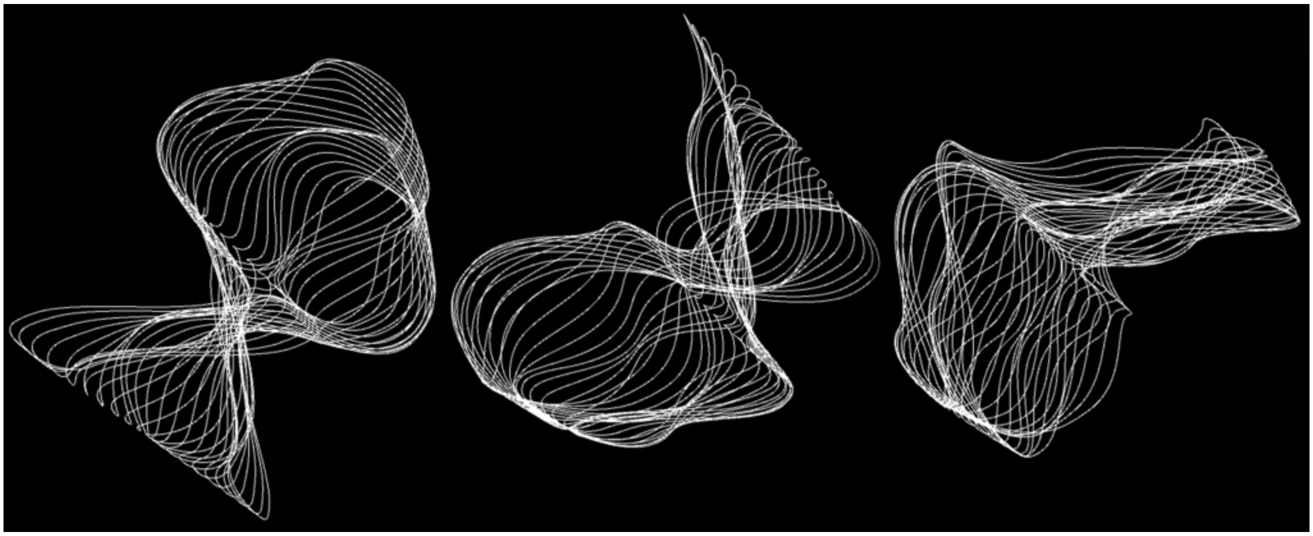
One of the obstacles to exploiting the capabilities of the AlloSphere's spatial audio system is the necessity of software programming for each individual piece. Unless one has a fully rendered 54.1 sound file and a suitable playback program, it will be necessary to program an up-mixing process from m to n channels, where $n = 55$.

As part of his doctoral research, McGee developed the Sound Element Spatializer for spatialization of an arbitrary number of simultaneous live or recorded sound sources over an arbitrary loudspeaker arrangement (McGee and Wright 2011). The standalone application features dynamic selection between multiple panning algorithms with distance cues including Doppler shift, air absorption, and gain attenuation. It also simulates high-speed movement of sound sources without artifacts, and precise control of sound trajectories using the OSC protocol. Through this, it allows real-time diffusion of works onto the AlloSphere's sound system.

Spatial Modulation Synthesis

McGee developed a novel synthesis technique combining space and timbre as part of his work in the AlloSphere (McGee 2015). By merging Chowning's and Stockhausen's connections between speed (or rate) and timbre with spatial movement, he devised a synthesis mechanism that simultaneously produces timbre and space. Moving oscillators back and forth at high speeds (sometimes close to the speed of sound), the Doppler effect produces frequency modulation, and the varying gain with distance produces amplitude modulation. The actual position of the virtual source can be used to position it in space. To realize this, a physically correct implementation of the Doppler effect needed to be developed as the common Doppler implementations assume relatively slow speeds and are physically

Figure 8. Paths of sound from Kinetic*, a piece by Ryan McGee utilizing his Spatial Modulation Synthesis technique.*



inaccurate at high speeds (see McGee 2015 for details). The DBAP technique was selected for panning, as most other techniques would result in too much granulation of the sound that would affect the timbre significantly. The speeds of virtual movement can be so fast that the result is not perceived as a source moving in space but as a "spatial source" (i.e., a source with inherent spatial properties). Figure 8 shows paths from McGee's interactive performance work for the sphere, *Kinetic*, which is based on a technique he developed called Spatial Modulation Synthesis.

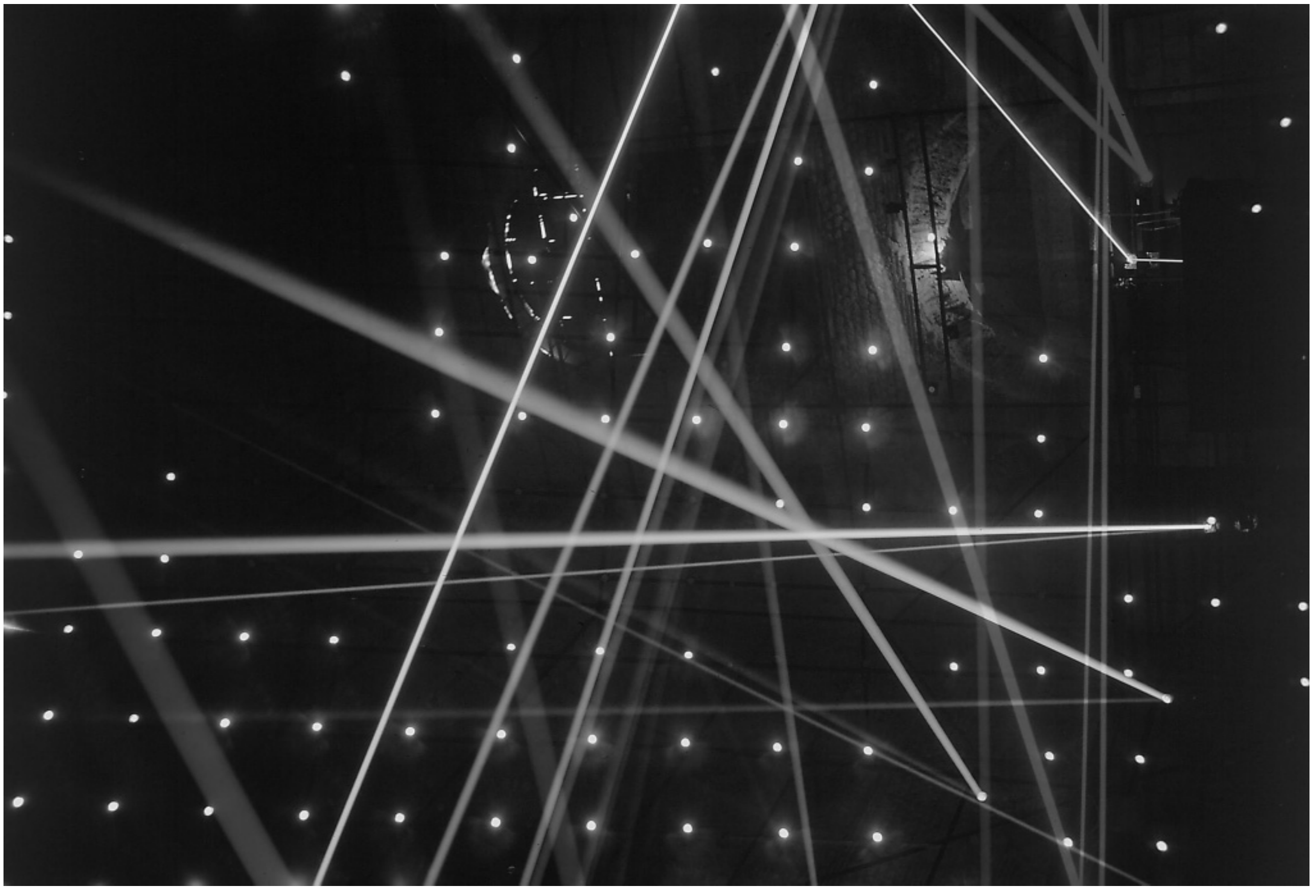
Zirkonium Chords, Theory of Geometric Spatial Chords

Zirkonium is a program for sound spatialization developed by former MAT student Chandrasekhar Ramakrishnan (2007). Originally developed for the Klangdom at the Zentrum für Kunst und Medientechnologie (ZKM), a 47-speaker environment installed in the ZKM's Kubus auditorium, Zirkonium can easily be adapted to other loudspeaker environments as well. The aim of the software is to simplify the use of space as a compositional parameter. Zirkonium can be used as a standalone application for creating a multitrack, spatialized composition or simply as a tool for spatialization within another program. The capability to read and play sound files in a variety of formats with arbitrary numbers of channels is built in, as is the ability to incorporate live input from an audio device. Zirkonium also provides the means to compose, store, and play a spatial choreography.

Zirkonium Chords is a SuperCollider extension to Zirkonium that provides a graphical user interface for generative up-mixing. It is designed by Roads and coded by Ramakrishnan. The design derives from a practice that Roads used manually in pluriphonic projection of his stereo compositions. A *spatial chord* is mapping from *m* channels of input to *n* loudspeakers (Roads 2015). Roads cued these chords to change at critical structural junctures in the unfolding of a work. Thus, the spatial architecture coincides with the musical mesostructure. The inspiration for the notion of spatial chords came from Roads's 1972 experience of Xenakis's impressive *Polytope de Cluny*, in which geometrical polyhedra were formed by multiple lasers and mirrors under digital control (see Figure 9).

By analogy to the laser projections in Xenakis's work, a spatial chord deploys a combination of sources to present a unique spatial geometry. To give a simple example, instead of projecting a stereo sound to left-front and right-front speakers, we

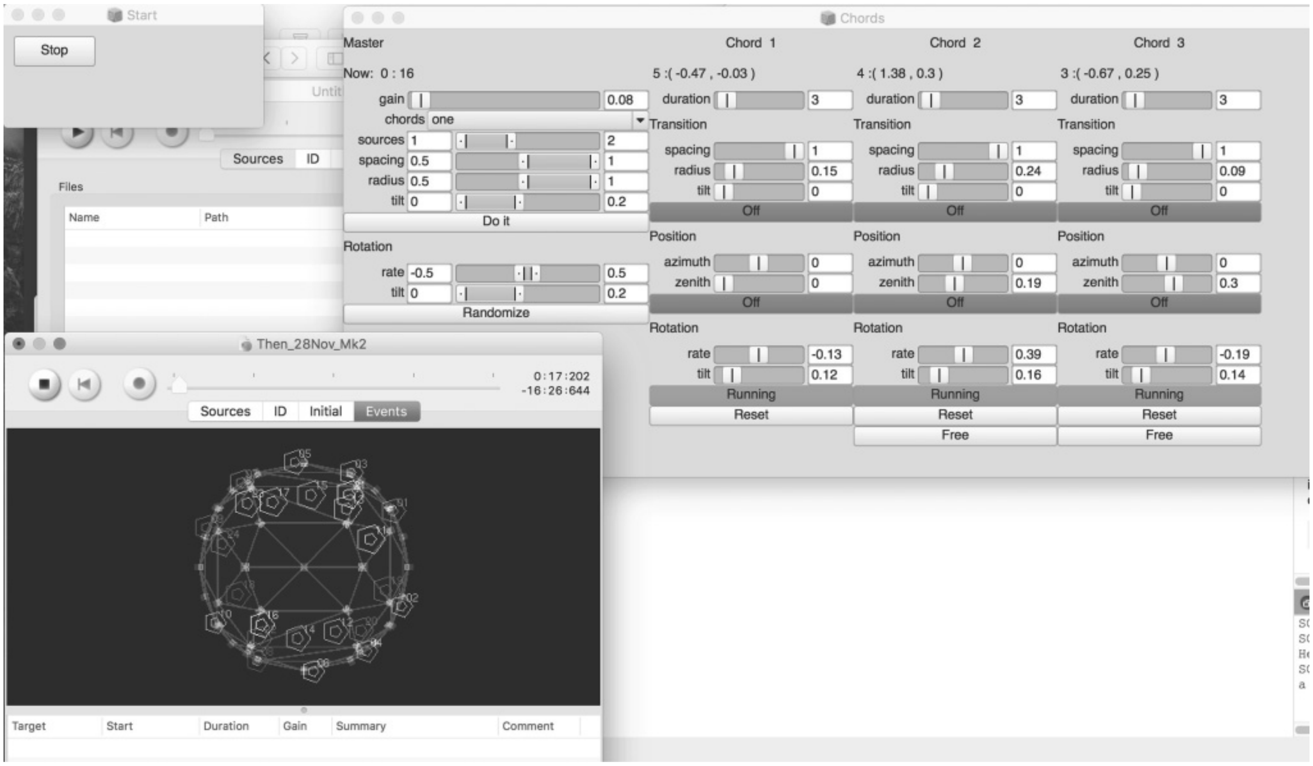
Figure 9. Laser projections and flash light scaffolding of Xenakis's Polytope de Cluny, *Paris (1972). By courtesy of Les Amis de Iannis Xenakis (www.iannis-xenakis.org).*



project it to the left front and the right rear. In this case, a sound that normally pans from left to right now pans diagonally through the audience. A slightly more complicated situation might involve a third or fourth source loudspeaker to create a two-dimensional geometrical configuration in a ring of loudspeakers around an audience. With a small number of loudspeakers, the task of spatial chord projection can be managed manually using a standard analog mixing console.

In the AlloSphere and other spaces with dozens of loudspeakers, the idea of spatial chords extends to three dimensions. Semiautomated up-mixing is necessary, because several dozen loudspeakers might be deployed to articulate a three-dimensional geometry. Software assistance also permits the use of transformations on chords, including rotation and tilting. All operations can be deployed in real time, or the results can be stored for fixed playback later. In effect, m channels of input are mapped via n loudspeakers to o virtual points in space ($m < n < o$). Zirkonium Chords has been tested both in the AlloSphere and in concert with the ZKM Klangdom.

Figure 10 shows a screenshot of the Zirkonium application. The window at the bottom left is a real-time display of the point sources of a chord. In this case, they are projected onto the grid of the ZKM Klangdom. The Master column in the main window (top right of Figure 10) has faders for the number of sources in the initial chord and for their spacing, radius, and initial tilt. Rotation faders determine the rate of rotation and the dynamic tilt. Three simultaneous chords can be projected at a time. For each chord, a duration control determines



Master

Now: 0 : 16

gain 0.08
chords one
sources 1 2
spacing 0.5 1
radius 0.5 1
tilt 0 0.2

Rotation
rate -0.5 0.5
tilt 0 0.2

	Chord 1	Chord 2	Chord 3
	5 :(-0.47 , -0.03)	4 :(1.38 , 0.3)	3 :(-0.67 , 0.25)
duration	3	3	3
Transition			
spacing	1	1	1
radius	0.15	0.24	0.09
tilt	0	0	0
Position			
azimuth	0	0	0
zenith	0	0.19	0.3
Rotation			
rate	-0.13	0.39	-0.19
tilt	0.12	0.16	0.14

0:17:202
-16:26:644

Figure 10. Prototype of the spatial chords interface in Zirkonium.

how long it takes to go from the current chord to the next one. The spacing, radius, and tilt of each new chord are controlled with faders, as is the chords' azimuth and zenith in 3-D space. Faders are provided for the rotation and tilt for each new chord. The button labeled Running starts the formation of a new spatial chord.

The concept of spatial chords emerged from a personal compositional need Roads had. Only later did we become aware of related systems, such as SpaceMap, which has been used by Meyer Sound (Elison 2013). Enda Bates (2015) extended SpaceMap to nonsymmetrical speaker layouts. The interactive interface of Zirkonium Chords remains, however, uniquely powerful musically, with its simple controls of number of sources, and their spatial proximity, rotation speed, and tilt. The key insight of spatial chords is that they work by algorithmically generating groups of sound sources with particular positional relationships between them. It then allows control of the group as a unit, making it possible to choreograph complex spatialization by controlling a manageable number of parameters. In this work, Bates has proposed a manifold-based panning approach. Zirkonium Chords implements a manifold-based panner. Zirkonium Chords takes an arrangement of source positions in a 3-D space, projects these positions onto a screen-based 2-D surface, and uses 2-D coordinates to specify sound-source positions, simplifying control.

Education in Spatial Audio

The art and science of spatial audio is interwoven into the fabric of the MAT curriculum. The Audio Programming Series, a two-year introduction into audio programming, has one course devoted exclusively to spatial audio. Additionally, Cabrera has taught an annual course devoted to spatial audio, where the AlloSphere has played a role in helping students experience spatial audio and the different techniques associated with it. The first course focuses on technical programming aspects related to spatial audio, the second course seeks to explore the practice and techniques of spatial audio. Although these courses are an optional part of the curriculum, attendance has not been limited to students with an audio background, and interesting results have emerged outside the AlloSphere in installation and sculpture work that integrates spatial audio. Students have also delved deep into technical issues, fixing problems and expanding the AlloSphere spatial audio libraries.

Conclusions

Fusing 3-D graphics and 3-D sound, the goal of Kuchera-Morin's AlloSphere has been to erase boundaries between science and art through transdisciplinary research. The AlloSphere Research Group pursues this goal by designing experiments in interactive real-time scientific visualization and sonification of information that are programmed by artist-technologists. The question, "Is it science or is it art?," can be answered simply: It is both. Scientific data can be projected in a boring, dull, and ordinary fashion, or in an exciting, beautiful, and extraordinary fashion. Making the data beautiful means making it visually and sonically interesting, even impressive (a "Wow!" effect), which encourages detailed exploration. Spatial audio in 360 degrees supports and enhances 360-degree 3-D imagery. This full multimodal immersion produces a compelling experience. As we navigate the visualized scientific data, sound cues emanating from those features act as sonic signatures. Recognition of sonic signatures becomes a second clue to the morphology of the observed structure. Sound has been realized as direct mapping of visual structures as sound generating agents, and it has also been used to display visually complex structures that cannot be displayed in a practical way in three-dimensional space.

Acknowledgments

The capabilities of the AlloSphere audio system have been a team effort over a period of a decade. We would like to thank our former colleague, Matt Wright, for his many essential contributions. The current design of the AlloSphere audio hardware system was largely the result of his efforts. Other members of the spatial audio team over the years have included Xavier Amatriain, Lance Putnam, Graham Wakefield, Ryan McGee, Dennis Adderton, and Stephen Pope. Thanks also to Chandrasekhar Ramakrishnan for his kind assistance with Zirkonium Chords.

This research was only possible thanks to the generous support of the Robert W. Deutsch Foundation, the National Science Foundation under grants 0821858, 0855279, and 1047678, and the U.S. Army Research Laboratory under MURI grant W911NF-09-1-0553.

References

Amatriain, X., et al. 2007. "Immersive Audio and Music in the AlloSphere." In *Proceedings of the International Computer Music Conference*, pp. 276–283.

Amatriain, X., et al. 2009. "The AlloSphere: An Immersive Multimedia Instrument for Scientific Data Discovery and Artistic Exploration." *IEEE Multimedia* 16(2):64–75.

Bates, E. 2015. "SpaceMaps, Manifolds and a New Interface Paradigm for Spatial Music Performance." Paper presented at the BEAST FeaST, 30 April–2 May 2015, University of Birmingham, UK. Available online at www.researchgate.net/publication/276920098. Accessed October 2016.

Bayle, F. 1993. *Musique acousmatique: Propositions, positions.* Paris: Buchet/Chastel.

Clozier, C. 2001. "The Gmebaphone Concept and the Cybérnaphone Instrument." *Computer Music Journal* 25(4):81–90.

Elison, S. 2013. "SpaceMap: 20 Years of Audio Origami." *Lighting and Sound America* April:80–88.

Hollerweger, F. 2006. "Periphonic Sound Spatialization in Multi-User Virtual Environments." Master's thesis, Institute of Electronic Music and Acoustics, Graz, Austria.

Kendall, G. S. 1995. "The Decorrelation of Audio Signals and Its Impact on Spatial Imagery." *Computer Music Journal* 19(4):71–87.

McCoy, D. 2005. "Ventriloquist: A Performance Interface for Real-Time Gesture-Controlled Music Spatialization." Master's thesis, University of California, Santa Barbara, Media Arts and Technology Program.

McGee, R. 2015. "Spatial Modulation Synthesis." In *Proceedings of the International Computer Music Conference*, pp. 246–249.

McGee, R., and M. Wright. 2011. "Sound Element Spatializer." In *Proceedings of the International Computer Music Conference*, pp. 1–4.

McGee, R., et al. 2011. "Sonifying the Cosmic Microwave Background." *Proceedings of the International Conference on Auditory Display*. Available online at hdl.handle.net/1853/51765. Accessed October 2016.

Pope, S., and C. Ramakrishnan. 2003. "The Create Signal Library ("Sizzle"): Design, Issues and Applications." In *Proceedings of the International Computer Music Conference*, pp. 415–422.

Putnam, L. 2014. "Gamma: A C++ Sound Synthesis Library Further Abstracting the Unit Generator" In *Proceedings of the International Computer Music Conference and the Sound and Music Computing Conference*, pp. 1382–1388.

Putnam, L., J. Kuchera-Morin, and L. Peliti. 2015. "Studies in Composing Hydrogen Atom Wave Functions." *Leonardo Journal* 48(2):158–166.

Ramakrishnan, C. 2007. *Zirkonium.* Karlsruhe: ZKM Institut für Musik und Akustik. Available online at ima.zkm.de/zirkonium/ZirkoniumManual.pdf. Accessed October 2016.

Roads, C. 2015. *Composing Electronic Music: A New Aesthetic.* Oxford, UK: Oxford University Press.

Roads, C., et al. 2016. "CREATE Studio Report 2016." In *Proceedings of the International Computer Music Conference*, pp. 255–257.

Trieb, M. 1996. *Space Calculated in Seconds: The Philips Pavilion, Le Corbusier, Edgard Varèse.* Princeton, New Jersey: Princeton University Press.

Wakefield, G. 2006. "Third-Order Ambisonic Extensions for Max/MSP with Musical Applications." In *Proceedings of the International Computer Music Conference*, pp. 123–126.

Wakefield, G., and W. Smith. 2011. "Cosm: A Toolkit for Composing Immersive Audio-Visual Worlds of Agency and Autonomy." In *Proceedings of the International Computer Music Conference*, pp. 13–20.

Wolcott, W. 2007. "Wave-Field Synthesis with Real-Time Control." M.Sc. thesis, University of California Santa Barbara, Media Arts and Technology.

Zotter, F., et al. 2011. "Phantom Source Widening with Deterministic Frequency Dependent Time Delays." In *Proceedings of the International Conference on Digital Audio Effects*, pp. 307–312.

Copyright of Computer Music Journal is the property of MIT Press and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.