Live Auralization of Cappella Romana at the Bing Concert Hall, Stanford University

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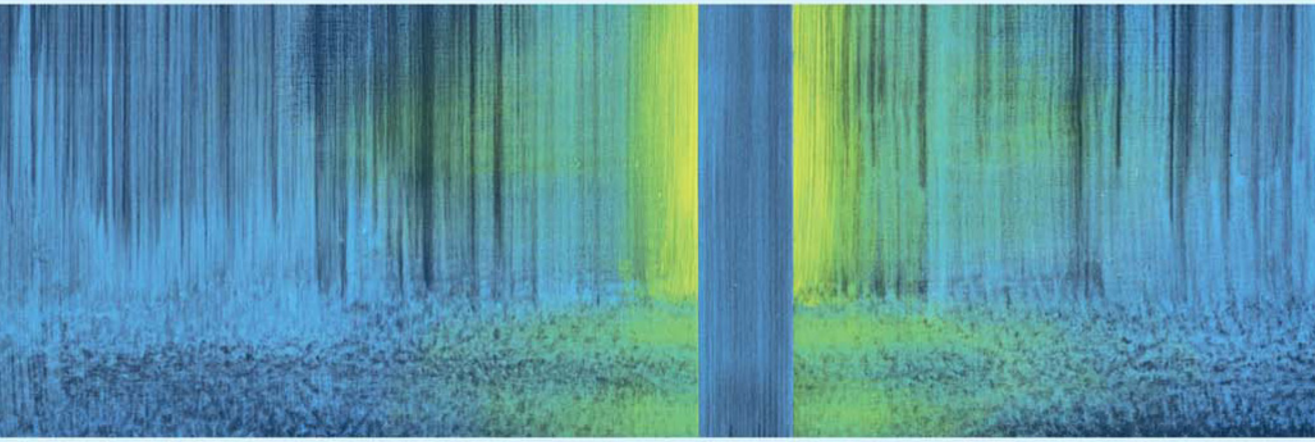

IN BYZANTIUM

Music, Acoustics, and Ritual

Edited by Bissera V. Pentcheva

An Ashgate Book

ROUTLEDGE

Aural Architecture in Byzantium

Emerging from the challenge to reconstruct sonic and spatial experiences of the deep past, this multidisciplinary collection of ten essays explores the intersection of liturgy, acoustics, and art in the churches of Constantinople, Jerusalem, Rome, and Armenia, and reflects on the role digital technology can play in re-creating aspects of the sensually rich performance of the divine word. Engaging the material fabric of the buildings in relationship to the liturgical ritual, the book studies the structure of the rite, revealing the important role chant plays in it, and confronts both the acoustics of the physical spaces and the hermeneutic system of reception of the religious services. By then drawing on audio software modelling tools in order to reproduce some of the visual and aural aspects of these multi-sensory public rituals, it inaugurates a synthetic approach to the study of the pre-modern sacred space, which bridges humanities with exact sciences. The result is a rich contribution to the growing discipline of sound studies and an innovative convergence of the medieval and the digital.

Bissera V. Pentcheva is professor of medieval art at Stanford University, USA. She has published three books to date: *Icons and Power: The Mother of God in Byzantium*, *The Sensual Icon: Space, Ritual, and the Senses in Byzantium*, and *Hagia Sophia: Sound, Space, and Spirit in Byzantium*. Her articles on phenomenology and aesthetics of medieval art have appeared in *The Art Bulletin*, *Gesta*, *Speculum*, *RES Journal of Anthropology and Aesthetics*, *Performance Research International*, and *Dumbarton Oaks Papers*.

Aural Architecture in Byzantium

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Edited by
Bissera V. Pentcheva

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10 Live auralization of Cappella Romana at the Bing Concert Hall, Stanford University

Jonathan S. Abel and Kurt James Werner

Introduction

The reverberant properties of a space have long been considered an acoustic signature of that space.[1] In his 2015 article "Space within Space: Artificial Reverb and the Detachable Echo," Jonathan Sterne traces out the legacy of this idea and its eventual relaxation. To describe this "separation of sounds from themselves" (their physical presence in space, that is, their reverberation), he coined the phrase "detachable echo."[2] Although the traditional association between sounds and their reverberation has been somewhat loosened in the thinking of, for example, modern architectural acoustics and artistic uses of artificial reverberation, the classical link between sound and space is an essential part of understanding the sonics of certain places, including Hagia Sophia.

Sound is intrinsically experiential; to fully understand the sound of a space, we must *hear* it. Even the most hardened signal-processing engineer would admit that studying an impulse response (the output of a dynamic system when presented with a brief input signal, or, in other words, the acoustic signature of the space) is only a supplement to, not a substitute for, listening to a piece of music in the interior characterized by that response. Space intimately relates musicians to their musical material; some music can be fully experienced only in its intended context. Consider what is lost when we try to reproduce the sound of a symphony orchestra through laptop speakers; consider how out of place a marching band might sound in a large concert hall.

This is a concern not only for listeners, but also for performers. Musicians alter aspects of their performances, including tempo, articulation, and timbre, according to the space in which they are performing.[3] A recent study showed that reverberation time significantly affected tempo and timing precision.[4] Although it also observed that effects on intonation were not very strong, the study was limited to a choir singing Western classical music (Anton Bruckner's sacred motet "Locus Iste"). Anecdotally, we have evidence that in the context of modal music, which characterizes medieval chant, both intonation and the trajectory of pitch "glide" between notes are affected by the performance space.

Singers collaborate with space itself during a performance, and properties of the space can have pronounced effects on their chant; unsurprisingly, performers decidedly favor one space over another. These subjective preferences can sometimes be linked to measurable objective features.[5] As an example, I. Nakayama studied subjective preference judgments of an alto recorder soloist in a simulated reverberation environment, one with only a single reflection. Even in a simplified environment like this, the alto recorder soloist strongly preferred certain time delays.[6]

Unfortunately, logistics, geography, and even politics can keep us from performing and experiencing music in context in its most appropriate spaces. This is the case with Hagia Sophia and Byzantine cathedral chant. The building was transformed into a mosque in 1453 following the Ottoman conquest of the city. With the establishment of the modern Republic of Turkey, the structure was secularized and made into a museum. As a result, concerts and liturgical music are no longer permitted. At the same time, there is a resurgence of interest in the elaborate Byzantine cathedral chant.[7] To overcome these limitations and place together the music within the space for which it was composed and within which it was performed, we can turn to artificial reverberation to re-create the sonic experience of the Great Church using signal processing.

The process of re-creating the aural experience of a particular space is called *auralization*.[8] Successful auralization is a complex task that involves cultural and musical sensitivity to the target space and its aural context, technical skills in signal processing, artificial reverberation research, and access to potentially complex sound-reinforcement hardware (loudspeakers).[9] Auralization has a long history, stretching back to the 1930s, although the target spaces of auralization are often much more ancient.[10]

Researchers have begun to uncover how ancient spaces are characterized by distinctive sonic properties that carry ritual significance.[11] The El Castillo pyramid in Chichén Itzá, Mexico, built sometime between the ninth and the twelfth centuries as part of a Mayan religious site, produces a chirplike sound (a "repetition pitch glide") in response to a hand clap, a result of the geometry of the pyramid's stairs.[12] This chirplike clap response approximates remarkably the sound of the quetzal bird, which held an important place in Mayan culture and religious life.[13] Similarly, the ancient (dating to at least 1200 BC) underground galleries at Chavín de Huántar, Peru have distinct acoustics. Dense and energetic early reflections, a short reverberation time, and wide soundfields create an acoustic experience of envelopment and can heighten a sense of indeterminate sound source location.[14] Along with visual and other sensory manipulations, the acoustics of the underground galleries at Chavín contributed to the ritual experience at the site.[15] After completing rudimentary acoustic measurements inside six diverse ancient structures in the British Isles, Robert Jahn, Paul Devereux, and Michael Ibison found that each sustained a strong resonance at a frequency between 95 and 120 Hz (hertz). Jahn speculates that since these prominent resonance frequencies are within the adult male voice range, the interaction between chanting and cavity resonances were invoked for ritual purposes.[16]

Researchers employ auralization to mimic the sonic properties of archaeological sites,[17] either on its own or alongside other aids, such as visual re-creations, as part of "virtual time travel" or "experiential archaeology."[18] For example, digital waveguide networks (networks of bidirectional delay lines that explicitly simulate traveling waves) have been used to imitate the acoustics of galleries at Chavín.[19] "Convolution-based approaches (see the next section, wherein convolution and its application to artificial reverberation and auralization are described) are common and have been used in particular as part of a hybrid wave field synthesis (simulation of the soundfield using multiple loudspeakers related to Hyugen's principle) and Ambisonics (full sphere surround sound based on spherical harmonics) system to create an auralization of

Stonehenge."[20] Auralization technology is mature enough that it can effectively simulate even complex concert halls.[21]

However essential the sonic signatures of spaces such as archaeological sites, concert halls, and churches may be, they are not immutable. Since ancient times, an understanding of the importance of the acoustics of spaces has been accompanied by attempts to manipulate those sonic imprints. Early techniques for affecting the auditory properties of spaces involved passive modifications to the structure. In 30 BCE, the architect Vitruvius reported on a well-established tradition of using resonating vases, which can be understood as Helmholz resonators, set up in theaters and intended to modify the acoustic properties of the space.[22] In the twentieth century elaborate signal processing-based approaches have been worked out to control the acoustics of concert halls, a process called active acoustic enhancement.[23] The goals of active acoustic enhancement may include repairing poor acoustics[24] or tailoring a concert hall's response to the divergent acoustic needs of a variety of aural situations, including spoken word, chamber music, and full-scale symphonic works.[25] These systems can even help to control the acoustics of outdoor venues; the Lares system at Chicago's Frank Gehry-designed Pritzker Pavilion is exemplary.[26] Active acoustic enhancement systems tend to be permanent installations. By contrast, the system described in this chapter is mobile, non-site-specific, and employs off-the-shelf and even open-source technology.

In the twentieth century, audio engineers in broadcast and popular music recording developed a complex set of tools for manipulating spatial impressions in audio recordings.[27] Early approaches involved merely making recordings in locations with particular sonic effects or in specially designed echo chambers; later on, researchers devised electromechanical devices, including "plate reverb" (reverberation produced using a large steel plate) and "tape echo" (a type of delay or echo processor that uses analog recording tape to achieve the effect), to add to the palette of spatial manipulations. Beginning in the 1960s, researchers began working on digital signal-processing techniques that could accomplish these manipulations entirely in the digital realm. Today, a vast literature on digital artificial reverberation techniques continues to inform new research, including approaches to auralization.[28]

Concert halls are also characterized largely by their acoustics; the sound of a concert hall is a major element in experiencing live music. Alongside investigations into and re-creations of the sonic environment of ancient archaeological sites, researchers have employed auralization to preserve the acoustics of important concert halls for posterity.[29] Among many other studies, Lamberto Tronchin and Angelo Farina explored the acoustics of the former La Fenice opera house in Venice, whose unusual elliptical shape gave it a unique sound. When the building burned down on January 29, 1996, its restoration relied in part on Tronchin and Farina's acoustic measurements.[30]

Before specific architectures for concert halls were common, churches provided such spaces. Jaime Navarro, Juan J. Sendra, and Salvador Muñoz make a case for acoustic assessment of the Western Latin church.[31] Rafael Suárez, Alicia Alonso, and Juan J. Sendra considered the Romanesque cathedral of Santiago de Compostela in Spain as a case study on the relations between architecture, music, and liturgy.[32] Deborah Howard and Laura Moretti studied the relation between sacred music and architectural design in sixteenth-century Venice.[33] Related work aimed to quantify the acoustic heritage of mosques and Byzantine churches.[34]

In this context, the acoustics of Hagia Sophia present an opportunity for fascinating case studies that range from humanistic to scientific. Building on her previous work on the phenomenology of the icon in Byzantium, Bissera Pentcheva studied the multisensory aesthetics of Hagia Sophia, focusing in part on the link between the optical shimmer of marble and gold and the acoustic reflection properties of marble.[35] Earlier studies considered the acoustics of Hagia Sophia from a computational perspective.[36] Most recently, Wieslaw Woszczyk has conducted new acoustic measurements and offered an analysis of the acoustics of the space.[37]

This essay turns to the algorithmic process, known as auralization, by means of which the acoustic signature of Hagia Sophia can be imprinted on a recorded or live performance of Byzantine chant. Using digital technology allows us to re-create in present-day performance spaces aspects of the acoustic experience of Constantinople's Great Church. After introducing some basic reverberation concepts and terminology in the next section, we focus on the idea of the room response as it relates to auralization and architectural acoustics, and then describe a study conducted to validate our method of measuring and reproducing the acoustics of a space. Preliminary experiments on auralizing Hagia Sophia are then presented and build up to a discussion of three live performances involving acoustic re-creations of Hagia Sophia.

Architectural acoustics, auralization, and the room impulse response

Particularly in reverberant spaces, listening is as much about the space as it is about the sound source. In such interiors, the vast majority of the acoustic energy arriving at a listener from a sound source has interacted with objects and surfaces on its way to the listener. In doing so, the space imprints itself on sound, modifying sound according to the geometry and materials composing the space. As a result, different interiors, having different architectures, materials, and furnishings, will "feel" different sonically: imagine the contrast between hearing singing in a large church with marble floors and walls and the same singing in a small club with hardwood floors and upholstered furniture.

In this section, we describe the mechanism by which a room manipulates sound, infusing it with the room's acoustic character. We start by considering a very simple sound, that of a popping balloon. We then introduce the "impulse response" as embodying the acoustic signature of the room, and "convolution" as the computational process of applying an impulse response to a sound. Next, we argue that an acoustic space may be simulated for any sound by the application of a room impulse response via convolution. The remainder of this section is devoted to exploring concepts of impulse response, convolution, and auralization using the example of recordings made in Stanford University's Memorial Church (Figure 10.1).

To understand how a space processes sound, let's consider a particularly simple sound source, a balloon pop. The pressure waveform generated by a balloon pop is a short-duration pulse, lasting about a millisecond (ms) for a one-foot-diameter balloon, and is roughly shaped like the letter *N*. Over time, this so-called N-wave will propagate away from the position where the balloon was popped and eventually interact with surfaces and objects in the room to create reflections, which in turn will interact with the room and other surfaces and objects, and so on, creating more and more reflections.

This process is seen in a balloon-pop recording made in Memorial Church (Figure 10.2): a listener will hear the balloon pop and its interaction with the space in three parts, first on a "direct path" from the balloon (Figure 10.2, "direct path"), then via a

Figure 10.1 Memorial Church, Stanford University, interior.
Photograph provided by the Department of Special Collections and University Archives, Stanford University.

number of "early reflections" (Figure 10.2, "floor, chancel, dome, nave reflections"), which become increasingly dense and indistinguishable from noise, forming the "late-field reverberation" (Figure 10.2, "late-field reverberation").

The room response to the balloon pop is also illustrated by numerical simulation. Figure 10.3 presents a sequence of frames demonstrating how the balloon-pop sound (represented by a gray line) radiates from a point on the left side of a room (marked by an asterisk) and eventually fills the space with sound energy. A time stamp appears in the upper-right corner of each frame. The balloon pop is first a circle, then it becomes a folded circle after reflecting from the floor. The third frame (Frame 85) shows the wavefront passing through the listener position (marked by a circle) and has a black line between the source and listener; this is the direct path, which presents the route traversed by sound to first reach the listener from the source. The next frames (Frames 105 and 256) detail the arrival of the reflection from the floor and a reflection from the back wall and floor. Subsequent frames display the propagating wavefront being broken up into smaller and smaller segments, and tracing more and more complicated propagation paths between source and listener. In addition to the path's complexity increasing over time, the density of arrivals at the listener increases over time.

In the case of the balloon pop, as the N-wave and its reflections propagate, sound energy is absorbed through interactions with the materials and objects that compose the space (Figure 10.2). Each interaction will absorb a small fraction of the sound energy, and over time the sound energy will decay. In large spaces, absorbing surfaces

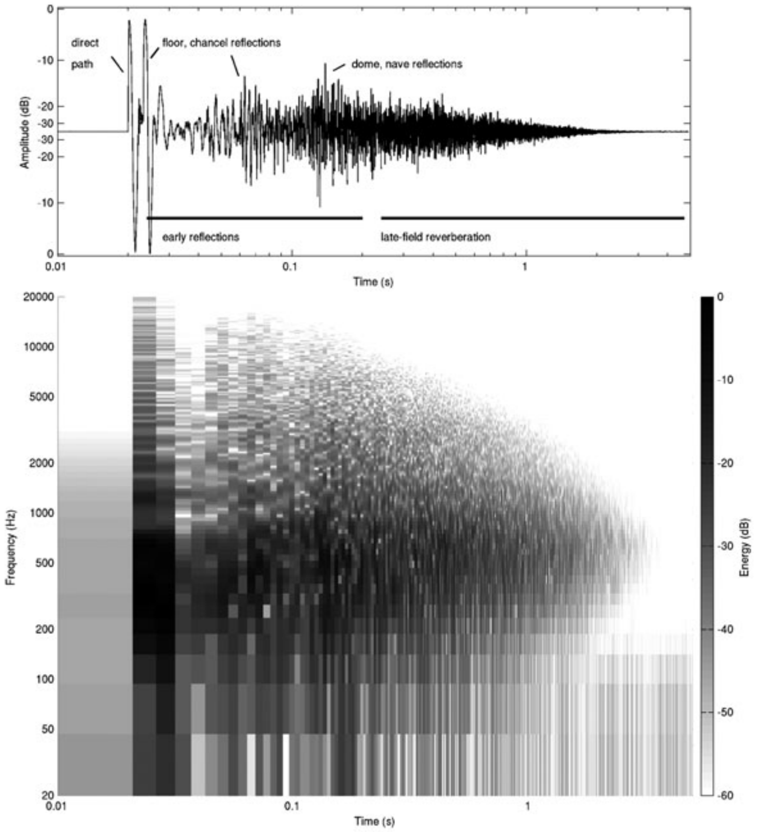

Figure 10.2 Memorial Church, Stanford University, balloon-pop response (above) and associated spectrogram (below).

Diagram by Jonathan S. Abel, 2015.

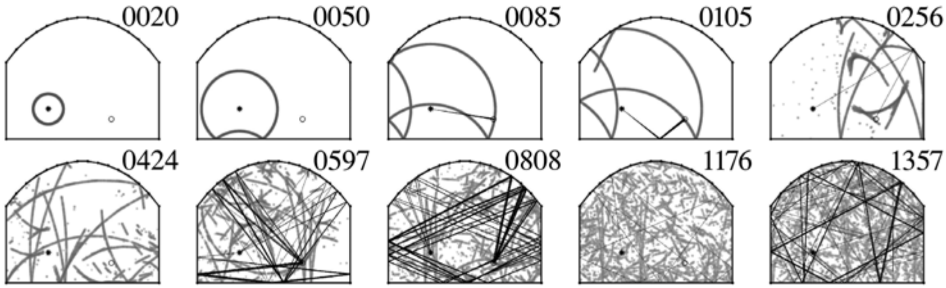

Figure 10.3 Numerical simulation of acoustic wave propagation in a domed structure, featuring wave fronts of a pressure pulse (gray) radiated from the source (asterisk) and propagation paths (black) from the source to the listener (circle), rendered at various time indices (upper right).

Diagram by Jonathan S. Abel, 2015.

are far apart and sound interacts with them relatively less frequently, leading to long decay times. By contrast, absorbing interactions occur more frequently in small spaces, and the decay times are shorter. In addition, sound energy is lost by propagating through the air, which absorbs a small fraction of the sound energy over every unit of distance traveled. Air absorption is stronger at high frequencies than low frequencies. This explains why thunder sounds more muffled the more distant the lightning strike. It also accounts for the relatively "dark" quality of large reverberant spaces, for which air takes up a greater portion of sound energy absorption, relative to reflecting surfaces.[38]

In the Memorial Church balloon-pop recording plotted in Figure10.2, the time axis is presented on a logarithmic scale to magnify details of the perceptually important balloon-pop response onset. The direct path arrival and reflection from the floor exist as clear N-waves at the beginning of the balloon-pop response. A number of early reflections, possibly from the apse and dome, appear near the 0.04 and 0.07 second marks, and another set, likely from the rear of the nave, arrive near 0.15 seconds. After these reflections, the response gives way to a noiselike late field, with frequencies in the 500 Hz range lasting nearly 4 seconds. High frequencies decay more quickly due to air absorption and a small amount of carpet, both of which preferentially absorb high rather than low frequencies. The church has a considerable number of stained-glass windows, which absorb low-frequency energy and reduce the reverberation time for frequencies below about 200 Hz. Comparing the portion of the energy arriving directly from the source (the first N-wave) with that which has been reflected (the rest of the balloon-pop response) shows that the reflected energy accounts for a sizable part of the sonic signature. This corresponds to reflected energy playing a significant role in the perception of sound in this space.

To understand how the space impacts a more complicated sound, a singer, Konstantine Buhler, was recorded in Memorial Church by two microphones simultaneously: a small headset microphone positioned next to his mouth and a room microphone on a stand in the nave (Figure 10.4, C), roughly 25 feet from the singer in the chancel (Figure 10.4, B). Because the headset microphone was so close to the singer's mouth compared to the dimensions of the church, the sound it recorded contained the singing mixed with a nearly imperceptible amount of reverberation. Such "close-miked" recordings, which capture the source essentially without room acoustics, are referred to as "dry" or anechoic; the recorded sound will feel close and clear. By contrast, most of the sound energy recorded at the room microphone was reflected many times from surfaces and objects in the church. These recordings, described as "wet," will sound distant and reverberant.

To visualize their sonic features, the dry and wet recordings were processed into spectrograms (Figure 10.5, above, dry; Figure 10.5, center, wet), which show how sound energy across the frequency range of human hearing evolves over time. Different sound frequencies will stimulate different locations along the cochlea (part of the inner ear); analogously, different sound frequencies will stimulate different "spectrogram 'bins'" along the spectrogram's frequency axis. Because of this similarity, spectrograms are widely used to analyze sound and its human perception. In fact, when the spectrogram is applied to music, aspects of the musical score are apparent. In the dry recording spectrogram (Figure 10.5, above), sung pitches generate horizontal lines at multiples of the fundamental frequency. The change in singing pitch over time is clear, as are many note onset and release times. Sibilant and other unvoiced sounds, by contrast, occupy

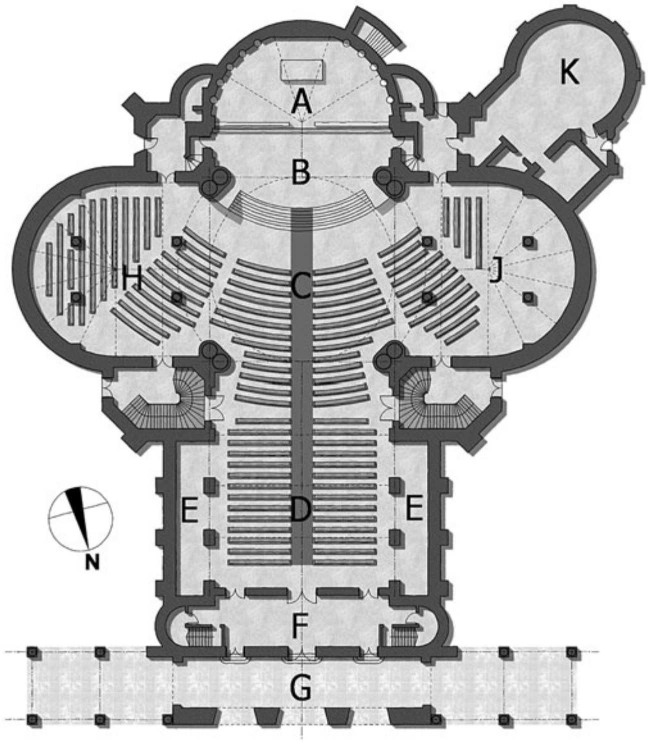

Figure 10.4 Memorial Church, Stanford University, floor plan.

Plan by Mcginnly, licensed under CC BY-SA 3.0 via Commons, https://commons.wikimedia.org/wiki/File:Stanford_Memorial_Church_Plan.jpg#/media/File:Stanford_Memorial_Church_Plan.jpg.

broad ranges of frequency and appear in the spectrogram as noiselike patches (Figure 10.5, above, just after the 1.0-second mark).

The dry (Figure 10.5, above) and wet (Figure 10.5, center) spectrograms display a number of changes that reveal the acoustic signature of the building on the singing. First, all of the wet spectrogram features have been smeared (that is, the sound is imprinted with the reverberant acoustics of the space) over time compared with those of the dry performance. This is particularly noticeable during silences and when the singer is gliding into a note, such as at 1.5 and 6.0 seconds; it is also consistent with one's experience of reverberation in the church. Second, what were solid horizontal lines tracing out a steady pitch energy in the dry recording have become scalloped and variable in intensity in the wet recording. The spectrogram illustrates that reflections in the church are combining sung notes at slightly different times in a type of chorus effect to create a complex pattern of constructive and destructive interference. This scalloping can also be observed in the dry recordings of a chorus of singers.

We now turn our attention to the process by which sound is transformed by an acoustic space. Note that irrespective of the nature of the sound—whether, for example, a balloon pop or a singing voice—the mechanism by which a space generates a set of reflections and reverberation will be the same. In other words, a space processes

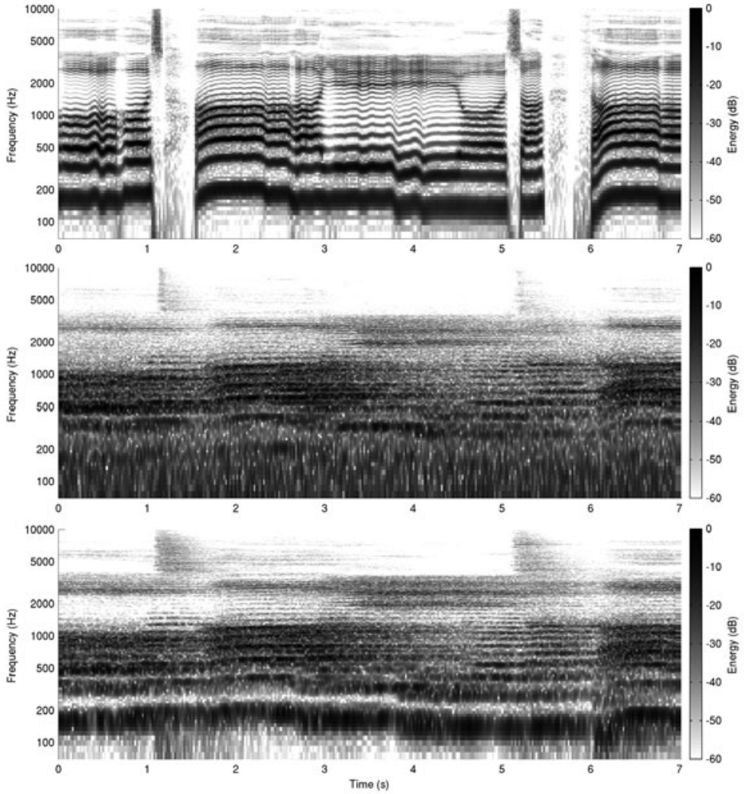

Figure 10.5 Spectrograms of chant recorded in Memorial Church, Stanford University, headset microphone (above), nave microphone (center), and simulated nave microphone (below).

Diagram by Jonathan S. Abel, 2015.

sound in a fixed way, without regard to the particulars of the sound. Consider that any sound can be thought of as being composed of a sequence of overlapping pulses, or sound "atoms," each scaled in amplitude according to the sound pressure at that point in time. Assume that the response of the space to a single, isolated atom—say, the response to a balloon pop—is measured or otherwise known. Now, the response of the space to a given sound is simply the sum of the known responses of each of the pulses or atoms forming the sound. Put differently, each atom of sound will drag behind it an entire atom response's worth (think balloon-pop recording's worth) of reflections and reverberation.

This mechanism can be seen in a comparison of the dry and wet recording spectrograms in view of the balloon-pop response. What are distinct time-frequency regions in the dry spectrogram (Figure 10.5, above) have been smeared over time in the wet spectrogram (Figure 10.5, center) in exactly the same manner that the initial N-wave of the balloon-pop spectrogram (Figure 10.2, below) is smeared over time. The dry singing pitch trajectories become smeared and noiselike in the wet spectrogram. Additionally, high-frequency sibilant sounds (Figure 10.5, just after 1.0 and 5.0 seconds) reverberate for relatively shorter times, as anticipated by the balloon-pop response (Figure 10.2, below).

The sequence of pulses imprinted with the acoustic signature of the space can be expressed computationally: if the atoms are one-sample-wide unit pulses or "impulses," then the response of the space to such an atom is referred to as an impulse response. The computational process of summing such impulse responses scaled according to the signal samples is called convolution, and the sound signal is said to be "convolved with the impulse response."

The impulse response encapsulates everything relevant about the acoustics of the space for the source and listener positions used to record it. As a result, the qualities of an acoustic space are typically studied by analyzing features of impulse responses measured in the space. Moreover, convolution with the impulse response can be applied to generate the room response to any given sound. This fact means that to simulate a space, only the impulse response needs to be known. This is remarkably convenient, as the alternative of measuring the response of the space to even a small number of anticipated sounds would be prohibitively costly. For this reason, convolution with room impulse responses lies at the heart of most room acoustics simulation systems, including our live auralization system, described below.

Auralization using balloon-pop recordings

What is needed to simulate the acoustics of Hagia Sophia is a set of impulse response measurements. There are many methods available to measure room impulse responses, most commonly involving playing test signals such as swept sinusoids or Golay codes into the space from a loudspeaker and recording the room's response at a set of microphones.[39] The drawback of this approach is that it requires a significant amount of time to set up and tear down the equipment and to make the measurements. Since access to Hagia Sophia is very limited, these approaches were not available to us. In our work, which is part of the "Icons of Sound" project, we circumvented the logistical difficulties associated with loudspeaker-based measurement by relying on balloon-pop responses, recorded by Bissera Pentcheva in May and December of 2010 in Hagia Sophia. This approach calls for only a handheld recorder, a balloon, and a few minutes of time. Yet this illusory "ease" conceals the unavoidable long overseas flight and extended negotiations with the local museum authorities.

Balloon-pop responses are not impulse responses, however, and we developed a method to convert our balloon-pop recordings into impulse responses.[40] This method was unproven, and to test its effectiveness we conducted an experiment using the dry and wet recordings of a student, Konstantine Buhler, singing in Memorial Church, as described above. Leaving a microphone at position C shown in Figure 10.4, we popped several balloons from where Buhler had been singing (Figure 10.4, position B) and recorded the responses. We converted the balloon-pop recordings into room impulse responses using our method and then convolved the estimated impulse responses with the dry recording to obtain a simulated Memorial Church response at position C to Buhler's singing.

The spectrogram of the simulated position C signal is plotted (Figure 10.5, below) on the same time axis as the spectrogram of the signal actually recorded at position C (Figure 10.5, center). The spectrograms and sound of the recorded and simulated signals are very similar in the mid-frequencies and above, verifying the effectiveness of the room simulation via impulse response measurement. Where they differ is in the low frequencies, where the church heating system (which could not be turned off) added noise to the recording. It was an unexpected benefit of the simulation that, compared to the actual recording, stray environmental noises were eliminated.

Postproduction auralizations in a virtual Hagia Sophia

The convolution of the acoustic signature of Stanford University's Memorial Church, using an impulse response derived from a balloon pop, serves as a proof of concept.[41] Convolution done as a postproduction process, that is, using prerecorded sound to convolve with a room signature, does not allow musicians to interact with the space in real time.[42] To overcome this limitation, we developed a real-time method for imprinting Hagia Sophia's sonic signature onto a live performance. This system makes it possible for musicians to hear the effect of the space on their singing in real time and make adjustments accordingly. They thereby have substantially the same aural experience as performing in the real space.

As before, we started with a balloon-pop response. A balloon pop recorded by Pentcheva in Hagia Sophia, December 2010 (Figure 10.6), was converted into an impulse response suitable for live auralization (Figure 10.7).[43] This recovered impulse response has a few interesting features, not least of all its length—it takes roughly 11 seconds for the impulse response to decay from a comfortable listening level to the

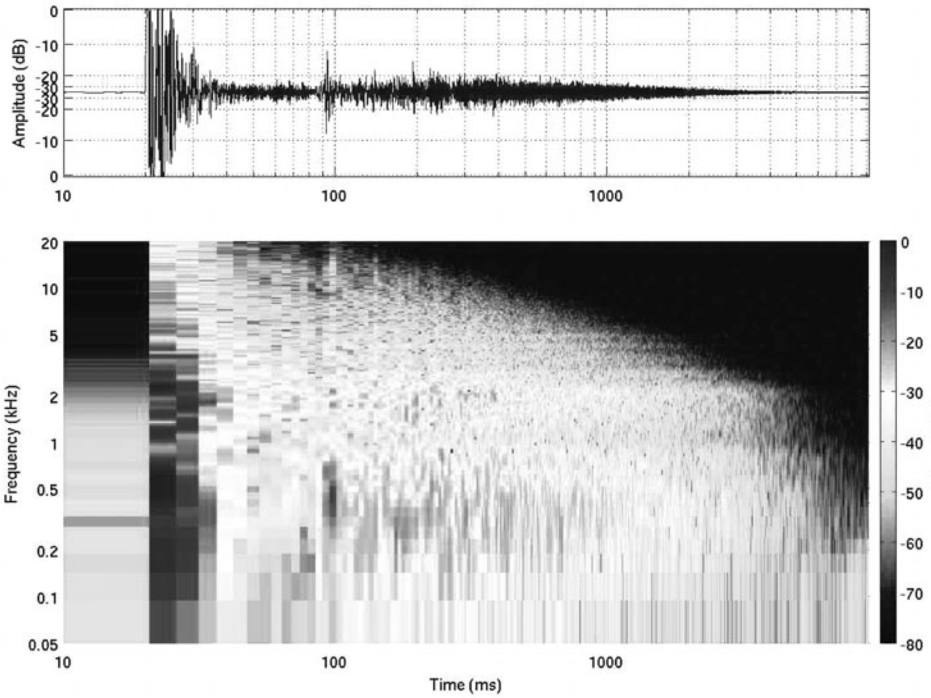

Figure 10.6 Hagia Sophia, Istanbul, balloon-pop response (above) and associated spectrogram (below), December 2010.

Diagram by Jonathan S. Abel, 2015.

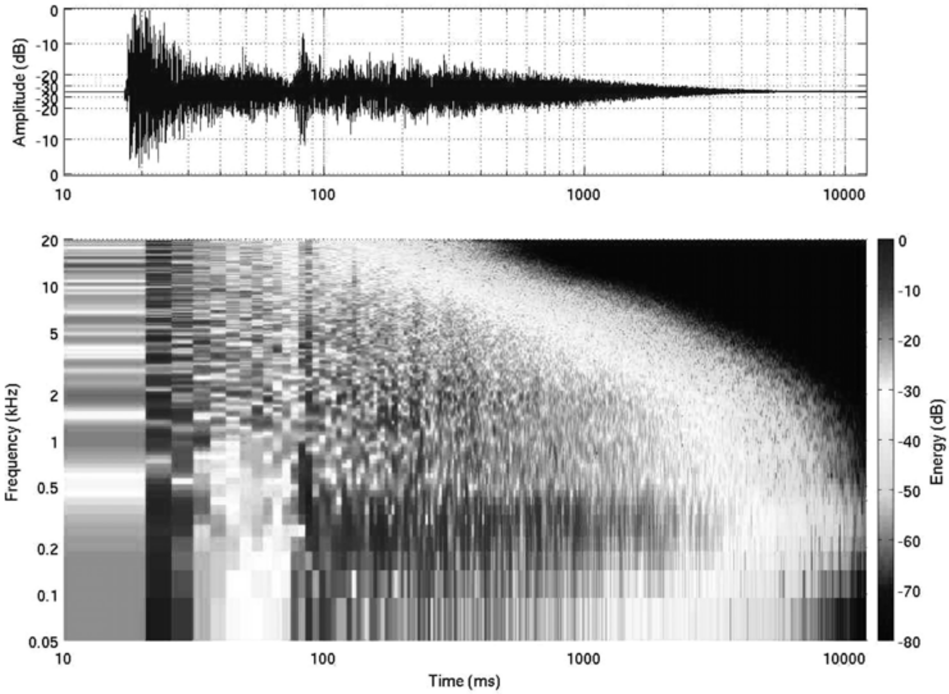

Figure 10.7 Hagia Sophia impulse response (above) and associated spectrogram (below), recovered from the December 2010 balloon-pop response recording (Figure 10.6).
Diagram by Jonathan S. Abel, 2015.

threshold of human audibility (approximately 60 dB (decibels) below conversation level). In addition, the listening position for this impulse response, about 10 meters from the balloon, is dominated by reflected energy, the “wet” portion of the impulse response. We can associate certain features of the impulse response with the geometric features of Hagia Sophia. For instance, the large spike around 100 ms (milliseconds) and the “wash” that builds to a wide peak around 300 ms issue from complex reflections produced by the dome and colonnades.

In advance of the public concert, an experimental recording session was conducted in 2011 in a small recital hall (“the Stage”) at Stanford University’s Center for Computer Research in Music and Acoustics (CCRMA) (Figure 10.8). It featured thirteen members of Cappella Romana, a renowned group specializing in performances of Byzantine chant. To enable these professional singers to adjust aspects of their performance, such as vocal balance and articulations, in response to the reconstructed Hagia Sophia acoustics, the auralization system needed to operate in real time and to allow the chanters to hear each other and themselves in the simulated space.

In this recording, we used Countryman B2D headset microphones (Figure 10.9), in order to capture each singer’s voice on a separate track. A digital audio workstation (MOTU Digital Performer) was used to record the singers’ voices, and we processed them to form a dry stereo mix. The mix was convolved in real time with stereo left

Figure 10.8 Cappella Romana at a recording session, Center for Computer Research in Music and Acoustics (CCRMA), Stage, Stanford University, March 2011.

Photograph © Dave Kerr, 2011.

Figure 10.9 Mark Powell, a singer with Cappella Romana, outfitted with a headset microphone (Countryman B2D) and earbud headphones at the Cappella Romana March 2011 recording session (Figure 10.8).

Photograph © Dave Kerr, 2011.

and right statistically independent impulse responses derived from the December 2010 Hagia Sophia balloon-pop recordings, forming a wet stereo mix.[44]

The chanters were positioned in a circle so that they could see each other and the conductor (Figure 10.8). Earbud headphones made available to them the dry and wet mixes, and each performer could control the balance between wet and dry mixes and the overall level in the individual's earbud signal. In this way, the performers could hear their own singing and each other in the simulated Hagia Sophia and interact accordingly. Providing feedback over headphones made it possible to keep the microphone signals dry, absent of any of Hagia Sophia acoustics.

The group began warming up without simulated acoustics; during this time microphone levels and equalizations were set. The simulated acoustics were then enabled, placing the performers in a virtual Hagia Sophia. Next, the performers were given a chance to acclimate to the environment. Their initial reaction, expressed simultaneously by several of the chanters, was, "Oh, let's play!" The chanters reported interacting reasonably naturally with the space, slowing their tempo to accommodate Hagia Sophia's long reverberation time. The ison (the drones) particularly enjoyed singing in the virtual acoustics, because they found it easy to "ride" the resonances.

The group performed a number of chants, including: 1) a *prokeimenon* (psalmic verses prefacing the readings from the Epistle in the Divine Liturgy (Eucharistic rite), or introducing the Old Testament readings at *hesperinos* (vespers) or the New Testament at *orthros* (laudes) or morning service finishing at dawn); 2) a *kontakion* (sung sermon); and 3) a congregational setting for Psalm 140 [141] sung at vespers, all of which we processed in postproduction into stereo and surround recordings. Recording the individual tracks anechoically made a number of editing options available that would be precluded when recording such a group in the actual space using room mics, as is conventional. This is because, with room mics, the dry singing and acoustics of the space are intermixed. With the convolution applied artificially after the fact, the acoustics of the space in which the dry tracks were recorded will still appear in the final auralization. By contrast, close-miking allows us to eliminate the acoustics of the recording room as well as stray noises such as traffic sounds from outside the building. Below, we give specific examples of different musical production techniques that are afforded by this approach. These include the possibilities to reposition singers in postproduction, to sculpt and to place reverberation, and to easily overlay multiple rounds of recording.

To produce the stereo mixes, as with the live recording, melodists' and drones' (ison) dry tracks were separately panned, that is, positioned horizontally, across the stereo field. A wet stereo mix was formed by convolving the dry stereo mix with a pair of statistically independent Hagia Sophia impulse responses. The final mix was generated by balancing the wet and dry components.

Surround mixes were generated in a similar manner: each of the eight male chanters' dry signals were panned separately to a location, and clouds of reverberation formed by convolution with a number of statistically independent Hagia Sophia impulse responses were placed about those locations. In our mix of the *prokeimenon*, the eight chanters' dry signals were panned to eight equally spaced locations around the listener. The reverberation clouds were panned tightly about each melodist, in a neighborhood 30 degrees to the left and right and 15 degrees above and below. The isons' reverberation clouds were panned over a wider region, in a neighborhood of 60 degrees to their left and right. This production mix creates the effect of a ring of performers surrounding the listener.

In our mix of the *kontakion*, the dry signals of the thirteen chanters—eight men and five women—were placed on a soundstage in front of the listener, and their associated reverberation clouds were panned about them, so that they shared a wide reverberant stage. This production mix gives the impression of an ensemble playing onstage in front of the listener. The production technique for Psalm 140 was similar to that for the *kontakion*. However, many overdubs were recorded to get the effect of fifty-two singers in a much larger chorus.

Live performance in a virtual Hagia Sophia

We now turn our attention to live auralization of Byzantine chant for performance and recording in which we employ loudspeakers rather than headphones to synthesize the acoustics of Hagia Sophia. The use of loudspeakers both enables presentation to an audience and provides for a more natural interaction among the performers, allowing for freedom of movement and a truly shared performance environment. The use of loudspeakers also presents some technical issues, and in the following we discuss these challenges and outline our solutions. We begin by describing our approach to live loudspeaker-based auralization and finish by discussing live auralization over loudspeakers in three performance halls: the Bing Concert Hall, the CCRMA Stage, and the San Francisco Ritz-Carlton Ballroom.

Our technical approach was driven by the need to perform, rehearse, and record in different spaces that were not preconfigured to present virtual acoustics, and to which we have limited access. This required a virtual acoustics system that was transportable and could be quickly loaded in, installed, configured, and tuned, and also quickly torn down and loaded out. The system hardware is much like that of the headphone-based system described above, again including a set of close microphones to capture the dry voices of individual singers, as well as for recording and postproduction. A set of room microphones records the mix as heard in the space. The system also includes a set of powered full-range loudspeakers and subwoofers to present the simulated acoustics. A digital audio workstation (DAW) connects to the microphones and loudspeakers through a mixing board and audio interface. The DAW processes the close microphone signals to generate live virtual acoustics signals, rendered in the space by the loudspeakers.

The use of loudspeakers raises the issue of feedback: it is possible, particularly when simulating very reverberant spaces such as Hagia Sophia, that loudspeaker signals will find their way back into the performer microphones, forming a feedback loop. This feedback can take a mild form, in which the simulated acoustics is modified, or it can take a severe form, in which particular resonant frequencies grow in amplitude and become unpleasant "whistles."

The approach we take to minimize the possibility of feedback has two components. The first is to use many loudspeakers so that each loudspeaker signal can play a relatively quiet signal, thus minimizing feedback between any given loudspeaker and microphone. The difficulty is that there are a number of microphone–loudspeaker loops running in parallel, and their combination might create feedback if they operate coherently. This possibility is eliminated in our system by using statistically independent impulse responses—in effect, impulse responses that sound the same but do not track each other in any predictable way—to generate the simulated acoustics. Employing this approach, a significant amount of reverberation can be generated without producing perceivable feedback.

The second component that helps to eliminate feedback employs directional close microphones. Using microphones with a hypercardioid polar pattern (which is sensitive to sound coming from one particular direction) taped to the foreheads of the singers and pointed down toward their mouths (Figure 10.10) places the singers' voices well within the "main lobes" of the microphones, and therefore they will be accentuated. At the same time, the loudspeaker signals, appearing from the sides and above the singers, will arrive from outside the main lobes of the microphones, and therefore will be suppressed. We have found that this approach is sufficient to eliminate problematic feedback, even when simulating very reverberant environments such as Hagia Sophia and operating in smaller rooms such as the CCRMA Stage, where the loudspeakers are close to the singers.

Two settings were configured for virtual acoustics performance and one for rehearsal and recording. Bing Concert Hall was configured to simulate the acoustics of Hagia Sophia for the "Constantinople" portion of Cappella Romana's February 1, 2013, "From

Figure 10.10 Alexander Lingas, the artistic director of Cappella Romana, being outfitted with a lavalier microphone by Scott Levine for the concert "From California to Constantinople," February 2013, at the Bing Concert Hall, Stanford. The Countryman B2D lavalier microphone has a hypercardioid polar pattern sensitive to sound coming from one particular direction, which helps in minimizing problematic feedback.

Constantinople to California" concert. The San Francisco Ritz-Carlton Ballroom was configured to synthesize the acoustics of Hagia Sophia and of the Church of the Holy Cross in Belmont, California (a medium-sized, reverberant church) for the September 27, 2014, Cappella Romana performance at a Patriarch Athenagoras Orthodox Institute event. In addition, the CCRMA Stage was configured to simulate the acoustics of Stanford's Memorial Church for rehearsal of Cappella Romana's February 2, 2013, "Holy Week in Jerusalem" performance in that space. Finally, the CCRMA Stage was configured to present the acoustics of Hagia Sophia for recording sessions held February 6 and 7, 2013.

We begin with our rendering of the acoustics of Hagia Sophia for live recording on the CCRMA Stage and the preparation of Memorial Church for Cappella Romana's rehearsal for its "Holy Week in Jerusalem" concert. The CCRMA Stage has sixteen full-range loudspeakers and eight subwoofers, all manufactured by ADAM Audio. Eight loudspeakers at ear level and paired subwoofers at floor level, mounted on movable stands, were placed in a ring about the Stage; the remaining eight loudspeakers are affixed to the rafters, in a ring above the singers (Figure 10.11).

The Stage's acoustics are somewhat configurable; velour and felt damping materials were deployed to reduce the Stage's inherent reverberation time to less than a third of a second, a relatively "dead" environment. In this way, the reverberant virtual acoustics generated by the loudspeakers is essentially unmodified by the room. For both the rehearsals and the recording sessions, the Cappella Romana singers arranged themselves in a circle, as before. Countryman B2D 2mm-diameter lavalier microphones with a hypercardioid were affixed to their foreheads with medical tape (Figure 10.10). The fifteen microphone signals were recorded and processed using the digital audio workstation Ableton Live, using the plug-in LAConvolver for real-time convolution, running on a laptop computer.

Figure 10.11 Cappella Romana at a CCRMA Stage recording session, February 2013.
Photograph © Dave Kerr, 2013.

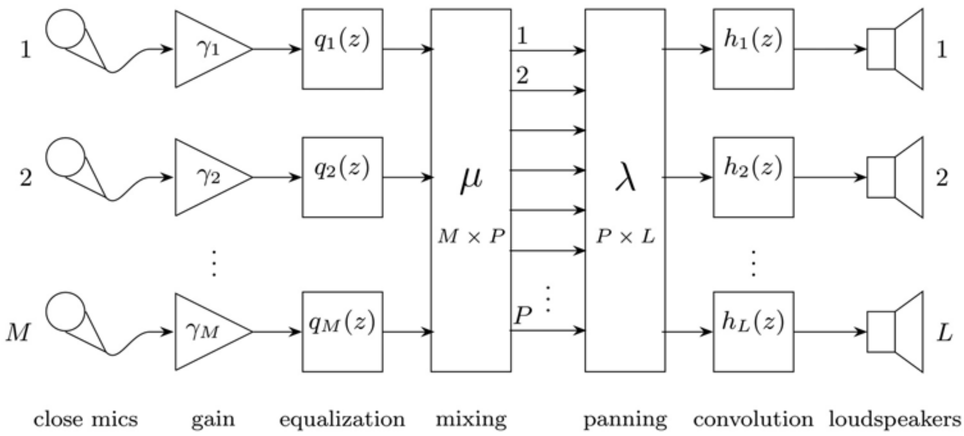

Figure 10.12 Live auralization over loudspeakers signal flow architecture, employing statistically independent loudspeaker impulse responses.

Diagram by Kurt James Werner and Jonathan S. Abel, 2016.

Each of the singer microphone channels was panned among sixteen real-time convolution channels running statistically independent Hagia Sophia impulse responses. In turn, each convolution output drove a different loudspeaker (Figure 10.12). The rafter-mounted loudspeaker signals were modestly delayed, as were the ear-level loudspeaker signals closest to the singers. The purpose was to roughly match the first reflection arrival times from the various directions about the singers. In this way, the chanters heard singing from each of the other chanters directly, as well as through the virtual acoustics of Hagia Sophia played out over the sixteen loudspeakers. The panning of the dry signals and the resulting reverberation was done in such a way as to envelop the performers in a reverberant soundfield. As with the 2011 recording session, the performers warmed up and then individually sang so that microphone levels and equalization could be adjusted. Then, with Cappella Romana chanting, the reverberation level was set, immersing them in the reverberant acoustics of Hagia Sophia.

A similar configuration was used for Cappella Romana's September 27, 2014, performance in the San Francisco Ritz-Carlton Ballroom. Our virtual acoustics system created both a virtual Hagia Sophia and a virtual Church of the Holy Cross in Belmont. The performance took place in a large ballroom venue roughly measuring 120 feet wide by 80 feet deep, with a relatively low 14-foot-high ceiling, carpeted floor, and two mirrored walls. While the mirrored walls set off a bit of flutter echo, the thick carpet produced a short reverberation time. For this concert, we arranged twelve loudspeakers on stands about the room, four across the front and back of the venue, and two on each of the sides. The performers were again outfitted with the Countryman B2D 2mm-diameter lavalier microphones, this time with radio transmitters to send the signals to the mixing board.

To generate the virtual acoustics, the singer microphone signals were first panned among the twelve loudspeakers to provide a dry signal for the venue. Another panning of the microphone signals among the twelve channels was imprinted with the needed acoustics via convolution and rendered through the loudspeakers to provide the wet signal (Figure 10.13). A challenge in configuring the system is choosing the loudspeaker wet–dry mixes to compromise among performer and audience preferences. As with the Stage and Bing performances, the choir director and some melody singers preferred a drier mix, while the ison chanters favored a wetter mix. Their differing preferences could be accommodated to a degree by reducing the wet signal level for the loudspeakers near the stage. The room was rather shallow, and we delayed the rear loudspeaker signals to give the illusion of a deeper room. In addition, we aimed a number of the loudspeakers toward the chandeliers in the ceiling in an attempt to equalize the sound level across the room, as well as to produce a modest sense of height, hoping that the dense, inverted dome-shaped chandeliers would effectively scatter sound. So as to prevent feedback, the dry signal was suppressed in the loudspeakers immediately adjacent to the stage. It turns out that this processing was rather effective, creating a sense of a much taller, enveloping space.

For Cappella Romana's "From Constantinople to California" concert, held in Bing Concert Hall just two weeks after the hall opened in January 2013, we devised a virtual Hagia Sophia using twenty-four full-range loudspeakers and six subwoofers.[45] Twelve of the loudspeakers were arranged around the perimeter of the hall and twelve were hung from the ceiling, forming a "dome" of loudspeakers (Figures 10.14, 10.15). The fifteen performers, twelve melody chanters and three ison chanters, were outfitted with B2D microphones and radio transmitters to provide dry chanter signals; for recording, there were eight room mics manufactured by DPA Microphones, two on stage and six flown in the hall.

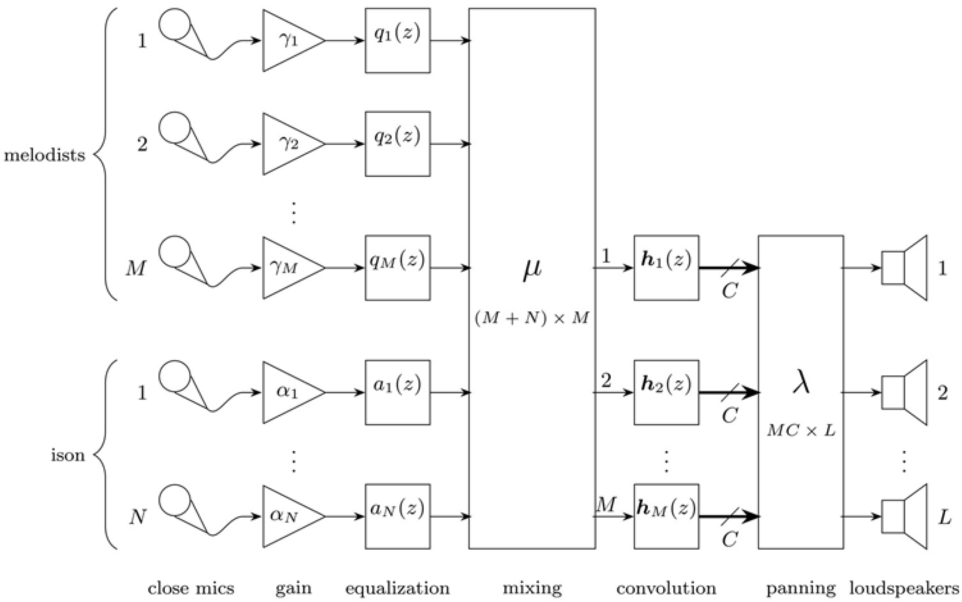

Figure 10.13 Live auralization over loudspeakers signal flow architecture, using statistically independent panned singer reverberation clouds.

Diagram by Kurt James Werner and Jonathan S. Abel, 2016.

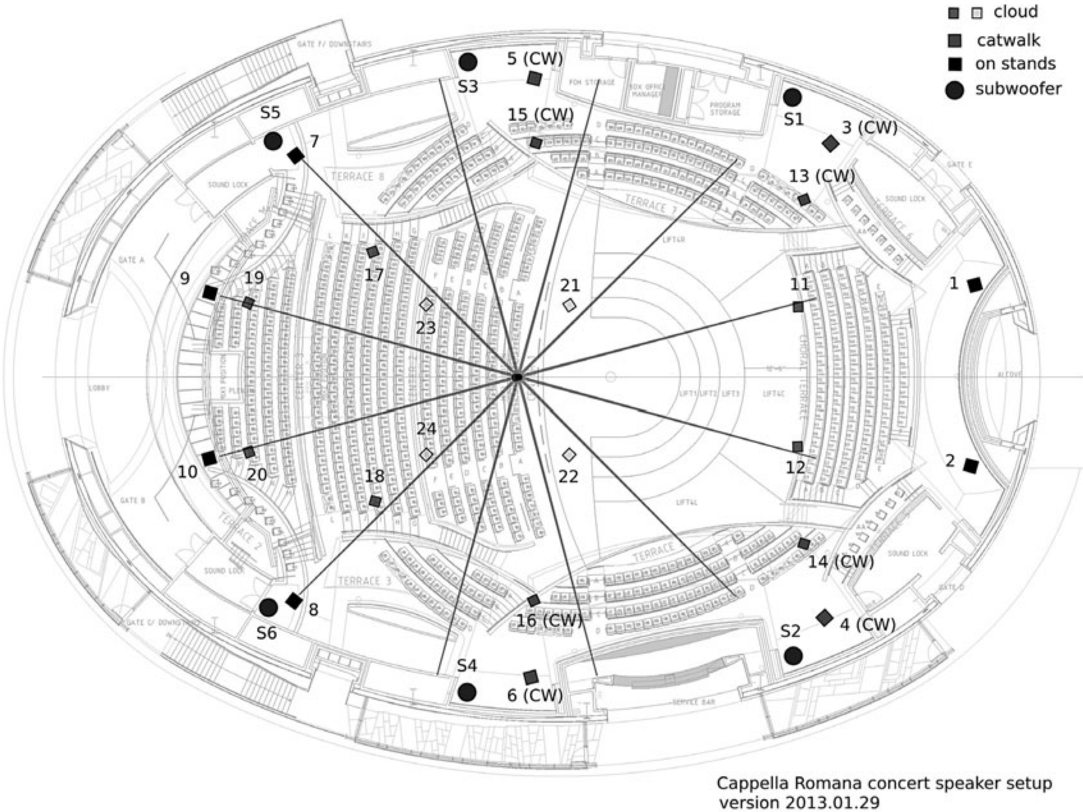

Figure 10.14 Bing Concert Hall, Stanford University, live auralization loudspeaker layout for the performance "From Constantinople to California," February 2013.

Diagram by Fernando Lopez-Lezcano, 2016.

Figure 10.15 Cappella Romana at a dress rehearsal for the concert “From Constantinople to California” at Bing Concert Hall, showing selected loudspeakers (Figure 10.14).
Photograph © Dave Kerr, 2013.

A slightly different virtual acoustics processing approach was employed for the Bing performance. To begin with, Bing Concert Hall is a rather reverberant space, having a 2.5-second-long reverberation time with its dampening curtains deployed. Accordingly, the auralizing impulse responses were adjusted so that the resulting acoustics—the actual acoustics of Bing Concert Hall combined with the virtual acoustics presented over the loudspeakers in the concert hall—produced a faithful rendering of Hagia Sophia.

Second, rather than panning the dry microphone signals among a set of loudspeaker Hagia Sophia convolutions as above, a set of Hagia Sophia impulse responses was imprinted on each dry signal, forming a “cluster” of reverberated signals for each performer. These clusters were then placed about the venue to create a set of overlapping regions in space for the performers’ reverberated singing. Specifically, the virtual acoustics were generated by separately processing each of the twelve melody chanters’ dry microphone signals. Four statistically independent Bing-corrected Hagia Sophia impulse responses were employed to form a wet (that is, reverberation) signal cluster for each melody chanter. These clusters were then sized and positioned about the hall according to the singers’ onstage arrangement using Ambisonics.[46] Each of the three ison chanters was associated with a group of four melody chanters. Their singing was auralized by simply mixing their dry microphone signals with that of the four associated melody chanters prior to convolution and Ambisonics processing. In this way, their bass contribution would occupy a large region in space, as tends to happen with low-frequency sounds. The result was a reverberant soundfield placed about and above the audience, with the men and women of the group layered about the dome of loudspeakers.

We now give an account of the experience of performing and listening in the virtual environments we created, as reported by Cappella Romana and concert reviewers. In the CCRMA Stage rehearsal and recording sessions, the performers found the live auralization over loudspeakers to be significantly better and more natural than the auralization over headphones. The ison chanters particularly enjoyed singing in the virtual Hagia Sophia, saying that it was very easy to find the building's resonances and grow a "wave" of reverberated ison. We should note that the ison singers preferred a wet-dry mix that was wetter than that preferred by the director, and likely somewhat wetter than that in the actual building. They also were enthusiastic about the rich, clear set of high-frequency harmonics they could generate and "play" with, reporting that the virtual building responded in a "very natural" manner. Perhaps in part owing to the significance of the simulated venue, the ison chanters described singing in the virtual Hagia Sophia as a deep, emotional, and transporting experience. A number of Cappella Romana members volunteered that the virtual Hagia Sophia sounded and responded like a real space, in contrast with their prior experiences with artificial reverberation. Many group members also commented that the virtual Hagia Sophia "held its pitch."

For the performance in the Ritz-Carlton Ballroom, Cappella Romana had about an hour to acclimate to the two virtual environments, Hagia Sophia and Belmont's Church of the Holy Cross. Despite the lack of rehearsal time, their performance was spectacular, particularly in the virtual Holy Cross. The performance and virtual acoustics were very well received; a number of audience members had the sense of being completely immersed and swept up in the performance. It is interesting that though we did not disclose the identity of the "medium-sized church" (Holy Cross) to the audience, Fr. Peter Salmas, Holy Cross's priest, recognized its acoustic signature.

For the "Constantinople" portion of the Bing concert, Cappella Romana performed selections from the Divine Liturgy at Hagia Sophia and chanted in the acoustic simulation of Hagia Sophia described above. Cappella Romana performers and several of their board members, as well as composers attending the concert, reported that the space sounded and reacted in a very natural way; they found it easy to forget that the acoustics were simulated. The ison chanters again thoroughly enjoyed the responsiveness of the virtual Hagia Sophia to high-frequency harmonics and the ease with which the drone could be built and sustained.

During the performance of the liturgy selections, the audience was asked to hold its applause so as to create and sustain an immersive experience. As Jason Serinus related in his concert review for *San Francisco Classical Voice*:[47]

> It is impossible to describe the experience objectively; to even attempt to do so would miss the point of a sensual experience meant to induce a transcendent state. Throwing all caution to the winds, as it were, the "performance" was the closest to lift-off I have experienced short of chemically enhanced listening sessions or the final hours of a seven-days meditation intensive.
>
> Closing my eyes, it was not hard to imagine that the singers' voices were actually reverberating back and forth through Hagia Sophia's enormous sanctuary and remarkable 50-meters high dome. The constant bass drone heard in much of the music helped ground an experience that sent the senses soaring, as the entire space seemed to fill with voices proclaiming the glories of the Christian God.

To the skeptical, or those allergic to computer-simulated environments, this may sound like so much caca or the hallucinations of an aging ’60s tripper. But I know no other way to describe an experience that, in Pentcheva’s words, was intended “to create the sensation that you were standing in a space that was neither in this world nor in heaven, that you were hovering in between.” Even without the additional visual and olfactory elements of the church—the incense, glittering walls, stunning mosaics, now absent tapestries, and floors of marble whose bookmatched pieces suggest the uninterrupted waves of the sea—the sonic environment was unique. Working in consort, the team of Abel, Pentcheva, and Lingas created an experience that is sure to make history, and spearhead further projects on multiple continents in the years ahead.

Conclusion

In this chapter, we have detailed several approaches to auralizing Byzantine chant in a virtual Hagia Sophia, bringing its acoustic response to recorded audio and real-time performance applications. Responses to these systems have been positive. The performers of Cappella Romana found the virtual acoustics presented over loudspeakers to be natural and to “feel like a real space.” The interactive nature of the real-time auralization was also well received; performers reported that it “responds like a real room.” Ison singers asserted, “It’s easy to find resonances,” also noting that it “holds its pitch.”

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Glossary

akolouthiai. Musical manuscripts recording the order and performance of primarily the proper chants of vespers, *orthros*, and the three Divine Liturgies, emerging in Late Byzantium. They are written in the Middle Byzantine intervallic notation.

anechoic. Sound with a nearly imperceptible amount of reverberation; it bears minimal acoustic imprint because the space in which it was propagated was extremely dry or the sound was recorded through close-miking, that is, the microphones were set very close to the sound source.

apēchēmata. A simple or elaborate intonation formula in a given mode that precedes a chant in the same mode.

apolytikon. Dismissal hymn sung at vespers, *orthros*, or after the Eucharist in the Divine Liturgy.

asmatic syllables. Nonsemantic vocalisms inserted to extend and beautify the chanted texts of the cathedral rite.

asmatikon. Choir book for the *ekklēsiastēs* (cathedral rite of Constantinople) that contained the chants for the elite choir of Hagia Sophia.

auralization. The process of re-creating the aural experience of a particular space. It includes the rendering of audio data by digital means in order to achieve a virtual three-dimensional sound space.

automela. See *heirmologion*.

Cheroubikon. A hymn accompanying the procession with the Eucharist gifts in the Byzantine rite, introduced at the time of Justinian and ratified in 573–74.

contrafacta. See *heirmologion*.

convolution reverberation. A process for producing artificial reverberation, which uses a software (algorithm) in order to convolve the impulse response of the targeted space being modeled with the incoming audio signal, which can be either an anechoic recording or live sound. *See also* impulse response.

diataxis. A type of liturgical book (*see* typikon), which gives the rubrics regulating the ordinary structure of the services.

ēchēmata. Intonation formulas written in the middle of a chant or in between major sections of longer chants. In the musical manuscripts these are sometimes written out with intervallic neumes or, alternatively, are abbreviated as modal signatures. See also *apēchēmata*.

euchologion. A manuscript containing the priest's prayers for the Divine Services, first surviving in MS Barberini 336 (seventh century; Vatican City, Biblioteca Apostolica Vaticana).

heirmologion. A type of musical manuscript dating as early as the tenth century that functioned as a reference book for heirmoi. It contains automela, or "model melodies," that serve as a model to produce derivatives known as proshomoia or contrafacta texts within the strophic hymn genre of the Kanon.

heirmos. A hymn with a fixed rhythm and melody that is used as the standard rhythmic and melodic pattern for other hymns (*troparia*) in the *Kanon* of the morning office (*orthros*) in the Eastern Church.

hypakoai. Identifying short monostrophic hymns similar to Western responsories. In the cathedral rite (*ecclēsiastēs*), the *hypakoē* (sing.) could be melismatic and lengthy.

Iadgari. The Georgian *tropologion* (i.e., book of *troparia* hymns), which survives in different forms in at least seven codices dating as early as the tenth century, representing fourth-to-ninth-century Greek practices of the Cathedral of the Anastasis in Jerusalem and the Great Lavra of St. Sabas in Palestine.

impulse response. The acoustic signature of a space or the output of a dynamic system (that is, an architectural interior) when presented with a brief input signal such as a pistol shot, a balloon pop, or sinusoidal sweep. Impulse response can be likened to an indexical "snapshot," which records the acoustic signature of a space measured as the decay of –60 dB in seconds of an impulsive signal fired in that space. A broadband sound source is usually used because it produces a wide range of sound waves from low to high frequencies (20 Hz to 40 kHz), thus giving an exhaustive "picture" of the way the particular space imprints itself on sound. *See also* reverberation time *and* convolution reverb.

kalophonic chant. A distinct musical style of Byzantine chant that flourished from the late thirteenth through fifteenth centuries, featuring virtuosic vocal phrases, text troping, and sections of nonsemantic text. See *teretismata* and *kratemata*.

kathisma. One of the meanings of this term identifies the divisions of the Psalter (twenty in all) according to the Rite of the Cathedral of the Anastasis in Jerusalem and, later, the Neo-Sabaitic Rite of Late Byzantium. Each *kathisma* consists of one to five psalms.

kondakar. In Slavonic Church chant tradition, this musical codex of melismatic chants contains the repertory of the Greek models of the *psaltikon* and the *asmatikon*. It is written in Old Church Slavonic notation, which resembles the prediastematic notations found in some *psaltika*.

kontakarion. See *psaltikon* and *kondakar*.

kontakion. Liturgical poems that developed from the fifth through the seventh centuries in Greek-speaking Syria, Palestine, and Constantinople that were sung as "chanted sermons" probably after the morning service and before the Divine Liturgy on great feasts in urban centers. It consists of an introduction (*prooimion*), followed by a varying number of stanzas (*oikoi*), connected to the *prooimion* by a refrain. The *oikoi* are linked by acrostic. A model stanza (*heirmos*), one each for the *prooimion* and the *oikoi*, signals the appropriate melodies to be used in their respective signing.

kratemata. Independent melodic units sung to nonsense syllables known as *teretismata* and used to prolong a hymn. A collection of *kratemata* is called a *kratematarion*. A *kratematarion* held such melodic units arranged according to the eight modes. See also *teretismata* and kalophonic.

melisma. The singing of many notes on a single syllable.

Missal (Roman). The liturgical book that contains the texts and rubrics for the celebration of the Mass in the Roman rite of the Catholic Church.

mode. See *octoechos*.

neumes. Early system of musical notation designating single pitches or small clusters of notes.

octoechos. The eight modes in Byzantium start with the four authentic (Gk. *kyrios*, "dominant") followed by the four plagal (Gk. *plagios*, "oblique") modes; the third plagal is also known as *barys* (Gk., "heavy," "deep"). Ascribing a melody to a specific mode is based not on a specific scale structure, but on the application of a specific set of melodic formulas, considered to belong to one mode in one of the chant genres.

The eight musical modes (*octoechos*) are derived from the recitation of the Resurrection account of the four Gospels, each split into two parts for the resulting succession of eight weeks. Tenth-century Georgian manuscripts, purporting to preserve eight-century evidence from Greek liturgical manuscripts recording the Jerusalem rite, offer model psalms sung according to each musical mode. In the Byzantine rite, the Resurrection Gospel readings increase from eight to eleven, and a further eleven hymns, or *troparia heothina*, were added to the celebration of *orthros*. This new hymnody has been attributed to Emperor Leo VI (866–912).

orthros. Morning office or matins, celebrated at daybreak to consecrate the day to God. Along with the evening office (*hesperinos* or vespers), *orthros* was one of the two principal hours of the cathedral and monastic offices.

pannychis. Vigil service.

periēgēsis. The structure of ekphrasis of a building organized as a tour around and a journey though it.

prokeimena. These chants (melismatic in the cathedral rite of Constantinople) precede the readings from the Epistle in the Divine Liturgy (Eucharist rite) or introduce the Old Testament readings at *hesperinos* (vespers) or the New Testament at *orthros* (morning service). They correspond to the place of the gradual in the Roman rite.

proshomoia. Contrafacta melodies based on a musical-poetic model (*automelon*). See also *heirmologion*.

psaltikon. Also known as the *kontakarion*, the book for the precentor or soloist, which contains the most virtuosic chants of the cathedral rite of Constantinople.

reverberation time (RT). The time elapsed after an impulsive signal has been fired and its energy has decayed by –60 dB from its initial level. It is only measured in the interval –5 dB to –35 dB and doubled to match measurements over a decay of –60 dB in seconds. It could thus be described as RT T_{30}.

stational liturgy. Peripatetic liturgy exemplified with stages of the rite celebrated at different churches along a preserved urban itinerary, with Mass celebrated at a selected church, known as the *statio* of the liturgy for that day. The richest evidence for the stational liturgy comes from Rome and Constantinople.

sticheraria. Musical manuscripts dating to the eleventh century containing (mostly) proper chants called *stichera idiomela* for the liturgical feasts of the calendar year. *Stichera idiomela* are chants that have their "own melody," that is, they are not modeled after other melodies.

sticheron. A hymn genre performed at the morning (*orthros*) or evening (*hesperinos*) services as inserts in the recitation of the psalms. *Stichera* are further divided into *sticheron idiomelon*, hymns that have their own melody, as opposed to *stichera proshomoia*, which are new texts composed to a melody from a limited repertoire of well-known models.

synaxarion. A church calendar for the fixed (proper) feasts, with the appropriate readings indicated for each one, but no further texts.

teretismata. Musical vocalizations set to the nonsemantic syllables *te te te*, *to to to*, and *ri ri ri*, which appeared in certain thirteenth-century manuscripts and flourished in the fourteenth century as fundamental components of the *kalophonic* chant idiom. They recall the earlier practice of intercalating aspiratory nonsemantic syllables.

tituli. The specific churches in Rome, which claim to have their origins as house-churches of the pre-Constantinian era.

Trisagion. One of the central chants of the Divine Liturgy, praising the Trinity and chanted before the Apostle and Gospel readings. It is testified to as early as the fourth century.

troparion. The word *troparion* typically identifies a hymn, but it can also refer to a refrain.

typikon (liturgical). A typikon constitutes one of the two books regulating the services (see *diataxis*). It functions as a liturgical calendar with instructions for the propers for each day. In Byzantium there were three types of typika: that of Hagia Sophia; that of the monastic Sabaitic rite; and that of the monastic Neo-Sabaitic rite.

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