A ROOM WITHOUT WALLS: OPTIMIZING AN OUTDOOR MUSIC SHELL TO MAINTAIN VIEWS AND MAXIMIZE REFLECTIONS

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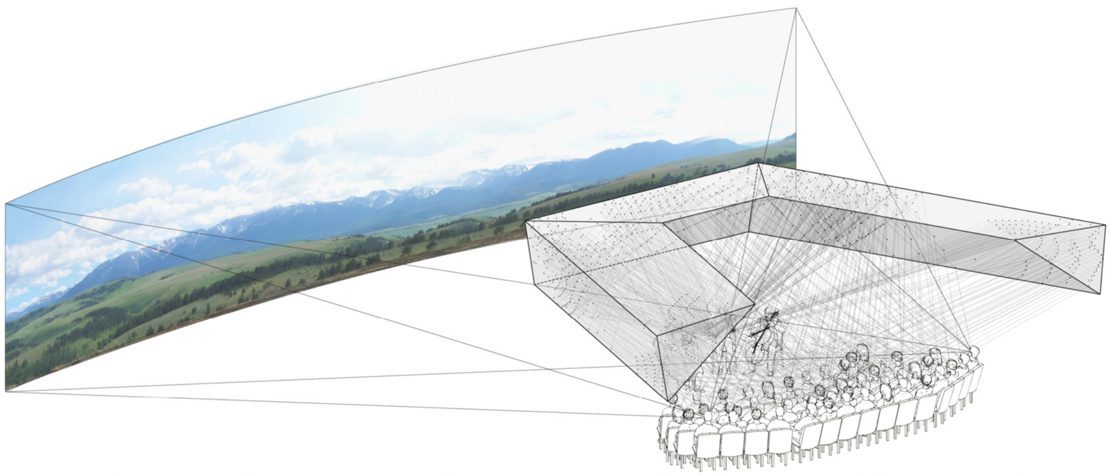

1 INTRODUCTION

In spring 2014, the Tippet Rise Art Center commissioned Arup Acoustics to design an acoustical shell, nicknamed the "Tiara," for hosting outdoor chamber music concerts for an audience of 50-60 people. The shell was intended to be temporary, demountable and transportable to different locations across the art center's site, spread across 11,000 acres of rugged, rolling ranchland in south central Montana (fig. 1). The clients wanted to allow audience members and performers to engage visually with the site's natural surroundings while enjoying the acoustical intimacy of a small room. To balance the dual requirements of exposure and enclosure, we developed a concept for a "room without walls," beginning with a simple box, cutting out surfaces to open views of the surrounding valleys and mountains and optimizing the remaining corners to provide an enveloping array of reflections to the performers and audience.

Most outdoor sound-enhancing structures follow one of two models, as identified by Jaffe.[1] First are shells that surround the performers on stage, capturing sound energy and projecting it to an audience sitting in an amphitheater or on a lawn. Examples include the Hollywood Bowl; the Minnie Guggenheimer Shell, an adjustable, demountable stage enclosure designed by Jaffe for the New York Philharmonic's summer concerts in Central Park; and the Soundforms mobile performance stage, a collaboration between BFLS Architects and Arup Acoustics.[2] This type of shell improves acoustic conditions for performers by providing early reflections from multiple directions so they can hear themselves and each other, and improves the acoustics for audience members by amplifying and enlarging the source image. The second type of structure is a "shed," open at the back and sides and covered by a roof, which protects audience members from the elements and allows reverberation to build up. Sheds often include a stage enclosure and overhead reflector to give

Figure 1: The initial Tippet Rise Tiara site before construction.

musicians stage support and to increase the level of clarity and early sound energy for audience members. The Koussevitzky Music Shed, which features a tessellated stage wall and semi-open canopy of triangular panels designed by Beranek, is a pioneering example.[3]

In designing the Tiara, we wanted to achieve the same degree of amplification, source enlargement and stage support as in the best existing outdoor venues but with a less frontal, more enveloping sound impression and a unified acoustical environment for performers and audience members to share. To this end we looked to two *indoor* spaces as benchmarks, the Schloss Schwetzingen Rokokotheater, a 450-seat baroque opera house, and the Esterházy Palace (Fertőd) Music Room, which seats about 60 people. The Rokokotheater's acoustics are noteworthy for being intimate and enveloping despite a short reverberation time compared to other opera theaters of the period. 3D impulse responses recorded by Bassuet reveal that the room owes its surrounding acoustical qualities to strong early reflections off the proscenium, side walls, ceiling and curved balcony undersides, which compensate for the lack of reverberant energy (fig. 2).[4] Because the reflections arrive from multiple directions and in quick succession after the direct sound, they do not result in image shift but rather blend with the direct sound, giving listeners the impression that the opera singer's voice fills the entire space. The Music Room at Esterházy, on the other hand, is remarkable for an immersive, enveloping sound impression that is consistent throughout the entire space. Bassuet found that the uniform spatial distribution of sound energy is largely due to an array of reflections arriving from the upper front and rear corners of the room.[4]

Figure 2: Principle early reflections in the Schloss Schwetzingen Rokokotheater and Esterházy Music Room. (Photographs courtesy Florian Merdes and Esterházy Palace)

2 DESIGN CONCEPT AND OPTIMIZATION

Our initial design concept consisted of a fan-shaped room 22 ft (6.7 m) wide at the front and 32 ft (9.8 m) wide at the back, 25 ft (7.6 m) deep, and 15' (1.5 m) tall, with the middle of each surface removed so that only the corners remained (fig. 3). We intended the corners to function like those of the Esterházy Music Room, reflecting sound to the performers and audience from all directions to create an immersive and unifying sound environment. We also hoped to emulate the beneficial focusing effect of the Rokokotheater's curved balcony undersides by optimizing our corners to return as much energy as possible to the listeners, supporting a psychoacoustical impression of being in a room despite a lack of reverberation.

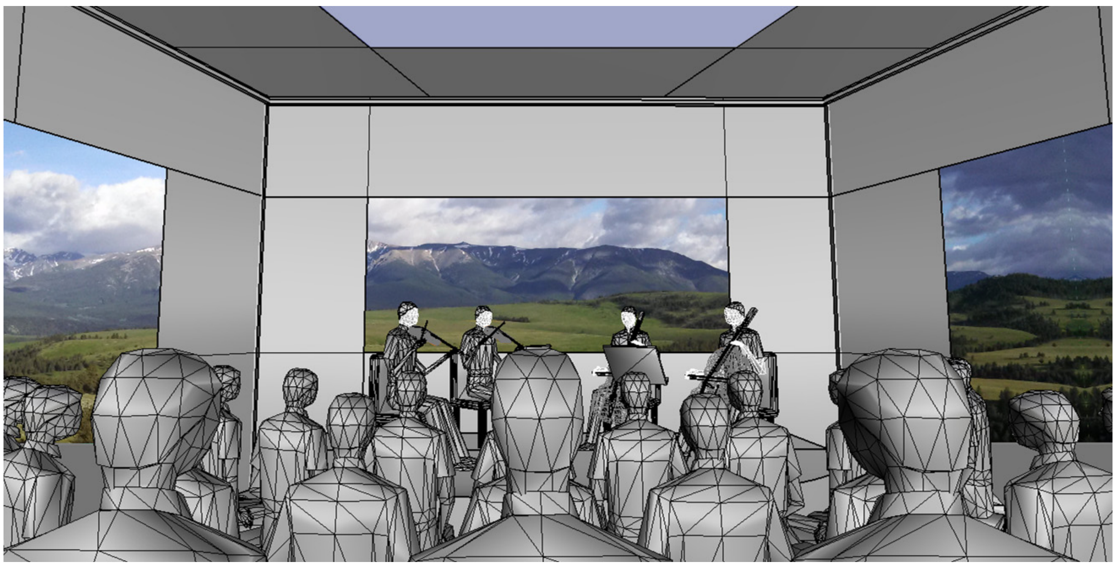

Figure 3: Initial design concept.

We assessed the efficacy of each corner in the concept diagram by carrying out an image-source method (ISM) analysis[5,6] of the geometry. We found that while reflections off the upper corners covered a substantial part of the audience, reflections off the lower vertical corners covered only a narrow band of audience members. We therefore removed the lower corners from the concept diagram, further opening the view. Reducing the diagram to surfaces exclusively above the heads of musicians and audience members presented some risk of image shift, but we estimated that the risk could be minimized by ensuring that each musician and audience member receive reflections from multiple directions. Following the model of the Rokokotheater, a broad spread of early energy could enlarge rather than displace the source. An ISM analysis for a single, central listening position in our revised concept diagram indicated that a broad spread of incidence angles was possible, with second and third-order reflections arriving from the front, back and sides (fig. 4).

Extending our ISM analysis to the entire audience and stage areas in the revised concept diagram, we found that right-angled corners were not optimally reflecting sound back to the audience. To maximize the quantity and directional spread of reflections arriving at each musician and audience member, we optimized the corner angles of our concept diagram by pairing our ISM analysis algorithm with the Galapagos genetic algorithm plugin for Grasshopper. Our optimization exercise builds off a growing body of research on room acoustic optimization. Sato et al. were the first to apply genetic algorithms to room acoustic geometry optimization, finding an ideal concert hall shape by weighting four orthogonal parameters—strength (G), initial time delay gap (ITDG), reverberation time (RT) and inter-aural cross-correlation coefficient (IACC).[7] Six papers on room acoustic

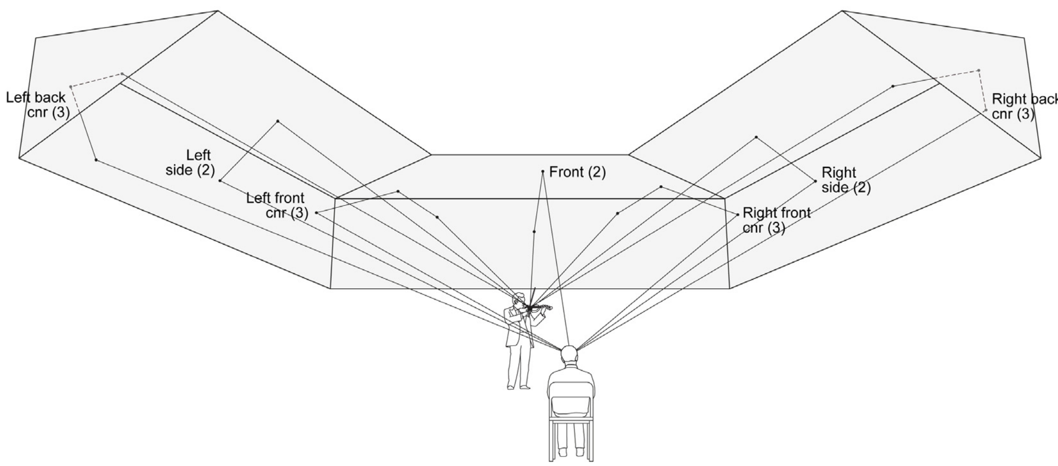

Figure 4: Revised concept diagram showing seven ideal reflection paths.

optimization were presented at the International Symposium on Room Acoustics (ISRA) 2013 alone. Among them, Palma et al. used stochastic raytracing and a genetic algorithm to optimize an outdoor acoustical shell with the aim of maximizing energy distribution over an audience plane.[8]

We parametrized the geometry of our concept diagram to undergo six transformations (fig 5):

1. The bottom edge of the side walls moved in and out in the xy plane.
2. The bottom edge of the stage wall moved in and out on the xy plane.
3. The inner edge of the stage and side ceilings moved up and down along the z axis.
4. The upper back corners moved in and out parallel to the inner edges of the ceiling.
5. The lower back corners moved in and out parallel to the lower edges of the side walls.
6. The inside back corners moved in and out parallel to the upper edges of the side walls.

We imposed limits on the transformation ranges to prevent the geometry from obstructing views of the mountain horizon and to keep within the dimensional limits allowable by a structural diagram developed by the multidisciplinary design team.

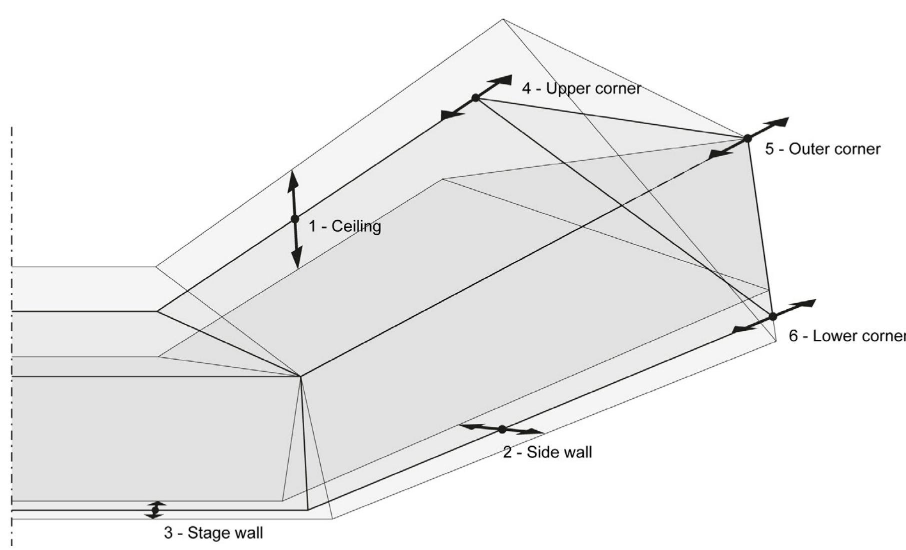

Figure 5: Optimization parameters.

The six independent transformations created a solution space too large to exhaust by brute force, so we deployed the Galapagos evolutionary solver to seek out optimal combinations of parameter values.[9] Each geometric iteration was analyzed by ISM to identify specular second and third-order reflections from a source to the 50 receiver positions (fig. 6) and the success or failure of each iteration was evaluated by a fitness function. We developed two different fitness functions, the first a count of the second and third-order reflections reaching all receivers, and the second a count of second and third-order reflections limited to the 12 "poorest" receivers, ie. those receiving the fewest reflections. We found that the first fitness function tended to maximize the total number of reflections at the expense of the poorest receivers, whereas the second fitness function resulted in a more even distribution with the total number of reflections comparable to (or in some cases even *exceeding*) those generated by the first fitness function. We did not incorporate the spread of reflection incidence angles into the fitness functions as we observed a consistently positive correlation between the quantity and directional variety of incident reflections.

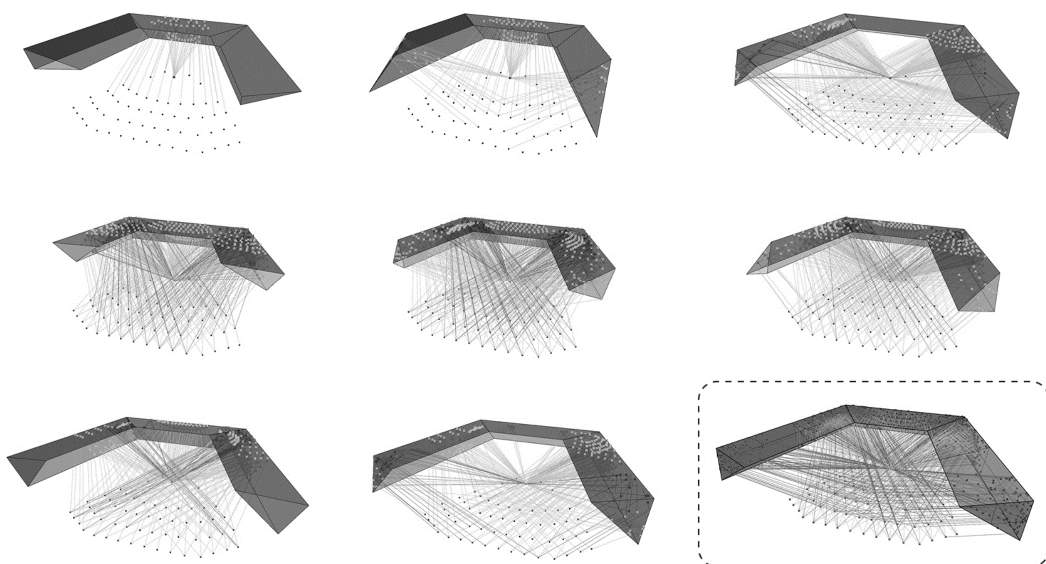

Figure 6: ISM analyses of a small sample of iterations tested by the Galapagos evolutionary solver. The selected scheme is highlighted.

After the first round of optimiziation, transformation parameter values converged on two solution regions with similar quantities and distributions of reflections. The first solution region resulted in a ceiling angled downwards towards the audience, a function of second-order side-wall-to-ceiling reflections. The second solution region resulted in a ceiling angled downwards *away* from the audience, a product of the inverse reflection path, ie. ceiling-to-side-wall. Despite the acoustical similarity between the two solution regions, the design team proceeded with the second outcome as the geometry it produced was easier to support structurally and would give audience members a stronger visual sense of enclosure.

The final geometry we chose to serve as the basis for constructing the Tiara was found to return an average of 5.7 second and third-order reflections to each receiver. We fell short of our goal to provide each receiver the same 7 reflections but managed to provide each a minimum of one reflection from the front, one from the left side and one from the right side.

3 CONSTRUCTION AND VALIDATION

The Tippet Rise Tiara was constructed in July, 2014 and the first concerts were held over the course of the summer (fig. 7). Due to unexpected wind gusts, the inaugural concert began indoors and moved outside once the wind had died down, giving audience members the opportunity to compare the two listening environments. (They expressed a strong preference for the sound in the Tiara.) One member of the Billings Youth Orchestra string quartet remarked, “It helped to be outside, with the wind blowing through your hair … to understand what Dvořak meant, to play this like the bird, and you can feel like a bird flying in the wind.”[10] Other performers have described playing in the Tiara as a “liberating experience.”

Figure 7: The completed Tiara, July 2014.

During the first concerts, we experienced a high degree of consistency in sound strength and envelopment throughout the audience area, indicating that our optimization exercise had been successful. The reflected energy arriving from above was balanced and well-integrated with the direct sound, creating a pleasant enlargement of the source dimensions. Optimizing the structure’s geometry from a single point source risked that some instruments in an ensemble would be “picked up” better than others by the structure’s geometry—indeed, during the first concert, the first violinist and cellist seated downstage were louder and their source images were larger than the second violinist and violist seated upstage. For the second concert, we moved the stage closer to the audience, exposing the upstage musicians to a greater solid angle of the stage wall. This improved the balance considerably for audience members, and musicians reported being able to hear themselves and each other better. Optimization based on ISM analysis, which only identifies specular reflections, also risked an uneven timbral response privileging high frequencies. While reflections did appear to have more high frequency content than low, we heard some responsiveness at bass and mid-frequencies, possibly due to comb filtering caused by reflections arriving within a short time window of each other.

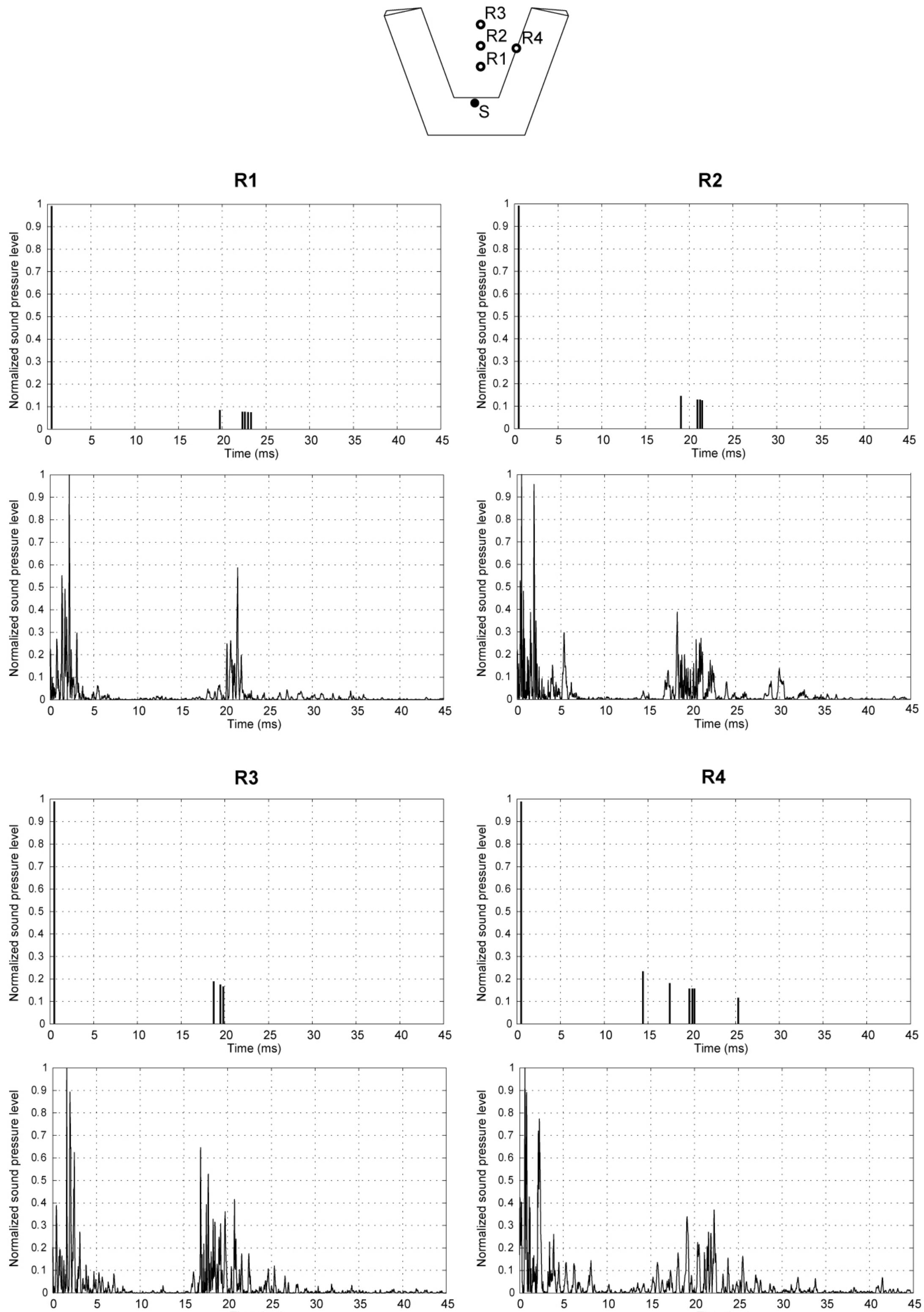

Figure 8: Predicted and measured impulse responses for four receiver positions

We carried out a validation of our acoustical predictions by comparing predicted impulse responses to impulse responses recorded on site. To create a predicted impulse response, we identified reflections from different receiver positions by ISM analysis and recorded their delay time and attenuation due to distance. We recorded impulse responses at the same receiver positions on site by recording balloon pops on a B-Format SoundField microphone and extracting the omnidirectional W channel. Figure 8 shows a comparison of predicted to measured impulse responses, normalized to the direct sound, for four receiver positions. The graphs show good correlation in time between the arrival of reflections in predicted and measured impulse responses. The relative arrival time of reflections from position to position also matches our predictions, with receivers closer to the source receiving reflections later than those further from the source. Measured reflections are more spread out in time than predicted reflections, which may be due in part to diffraction at the panel edges.

4 EXPANSION

After a number of successful concerts in the Tiara, the art center decided to expand the Tiara to accommodate up to 80 audience members. An ISM analysis revealed that simply extending the arms of the structure would not provide adequate coverage to listeners in the middle of the audience area. To ensure coverage in this area, we added a kink to the structure's arms and re-optimized the structure along the same lines as the optimization described above. The final form returns an average of 5.6 reflections to each receiver inside the structure, about the same as in the initial construction but with a broader distribution of third-order reflections (fig. 9). The expanded shell was constructed in the spring of 2015 and three concerts have been held to date. It is likely that the Tiara could continue to be scaled up to a certain extent. We note, however, that as a growing number of audience members pushes the structure further from the source, the larger the corners will need to become to reflect sound back to the majority of the stage and audience area (and the weaker those reflections will become).

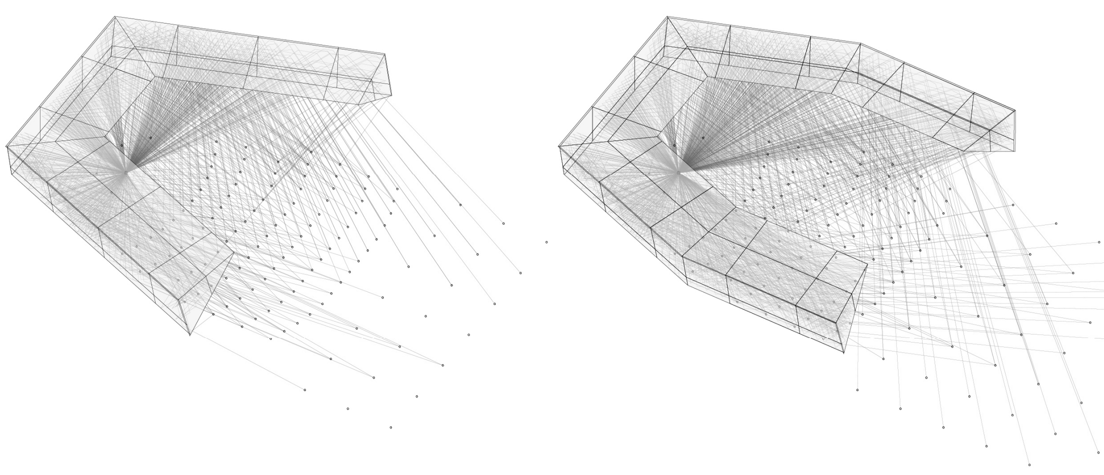

Figure 9: Image source analysis of original and expanded shells with the same receiver layout in both.

Figure 10: Expanded Tiara, August 2015.

At its current scale, the Tippet Rise Tiara creates an open yet intimate performance space where musicians and audience members share the same enveloping acoustical environment. The Tiara heightens engagement between performers and listeners while at the same time inviting contemplation of the relationship between music and the natural environment. Because the Tiara is demountable and transportable, it can be reconstructed in different locations across the Tippet Rise site, and in each location, new relationships will become visible and audible.

5 ACKNOWLEDGMENTS

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