The Spatial Sonic Network is a proposal for a series of parabolic acoustic mirrors that collect, focus, and translate sound. Computational tools were used extensively throughout the project, to realize algorithmic logic, to integrate acoustic performance into the architectural design process, and to link design models to fabrication machinery. While conceptually straightforward, the design of acoustic mirrors, also known as sound mirrors, raised several challenges in terms of network design, geometry definition, acoustic performance simulation, prototyping, and measuring. The research and results that emerged from these challenges is the focus of this paper.

Keywords: Architectural Acoustics, Performance Simulation, Prototyping

INTRODUCTION
Spatial Sonic Network is an architectural installation that re-examines physical and sensorial infrastructure required for communication. It is a proposal for a series of parabolic acoustic mirrors that collect, focus, and translate sound. Spatial Sonic Network is both a series of architectural urban devices that invite investigation and habitation, and an invisible passive acoustic network that creates both the possibility of communication without the aid of amplification. The project is designed to enliven an urban site, inviting passersby into a participatory space that opens channels for communication that are imminent to, but not immediately apparent, amidst its networks of footpaths, sight lines, and digital webs of communication. The final design of this spatial and acoustic logic manifests itself as a seven-node network of sound-mirroring structures. Benches are placed at acoustic focal points, a short distance from the sound reflecting portions of each node’s surface, enabling visitors to sit and have a conversation either locally with those sitting next to them nearby, or through the effect of the acoustic mirror, with those at the opposing node.

Knowledge of the architectural form’s capacity to reflect and focus sound stretches back at least as far as antiquity (Helfer 2009). In the 1920s, Wallace Sabine speculated that the most famous architectural examples of parabolic sonic reflection-The Ear of Dionysius at Syracuse, or the whispering gallery of St. Paul’s Cathedral in London-were likely accidents (Sabine 1964).
During WWI to the early years of WWII, devices were constructed that enabled the acoustic detection and location. While some of these devices were essentially large, steerable horns, some of the best-known examples of the phenomenon were of an architectural scale, see Figure 1. These building-size acoustic mirrors dotted the English coast (Helfer, 2009) and before they were eclipsed by radar, these monolithic, concrete structures were built to detect incoming enemy aircraft. As Ganchrow (2009) notes, acoustic mirrors enable users - through “tactile perception” to literally physically collide with the acoustic phenomenon of the incoming aircraft, where the spaces “close-at-hand and the far-off momentarily coincide.” While the Spatial Sonic Network draws inspiration from this history of sonic surveillance, the project is equally rooted in architectural geometry’s ability to enable communication across significant distances without electrical amplification. Popular in science centers and playgrounds, acoustic mirrors enable spatially separate areas to be acoustically fused into a single arena and offer a benign lesson in acoustics (Blesser and Salter 2007). The acoustic mirror has been investigated by artists and architects (Crow 2007 and Peters et al. 2011) however, the Spatial Sonic Network extends the singular form of the surveillance dish to a multitude of architectural geometries that enable networked communication. At the work’s core lies a paradox: any technology that extends communication also affords new possibilities for surveillance.

METHODS
The project brief called for the design of an urban installation that created “a social meeting space be inserted into the already complex network of movement, vegetation, infrastructure, furniture, and architecture.” (Making Models, 2018) Our team’s solution of a network of acoustic mirrors demanded the solving of several design challenges. The first challenge was placement of acoustic mirror nodes on the site - a site that brought with it complex existing conditions that both limited design options, yet still suggested a limitless number of potential configurations. The exploration of the network topologies to determine the “best” solution suggested computational investigation. To explore this large design space a computer program was developed in Processing. The brief dictated restrictions in terms of build-able areas in relation to buildings, paths, trees, and street furniture. Our generative algorithmic approach, as illustrated in Figure 2, used site data as input, found the build-able regions, computed arrays of random points in the different regions, and output arrangements of acoustic mirror networks. These different networks were analyzed both visually and using the computer program for things like: number of nodes, angles, distances, and topological arrangement.

The second challenge was the definition of the acoustic mirror geometry itself. Figure 3 describes the logic of acoustic reflection using rays - that the angle of incidence equals the angle of reflection. The form of acoustic mirrors is relatively well-known (Kaplan 2010, Helfer 2009) and can be described through using the mathematical formulation of the parabola (in 2D) or paraboloid (in 3D). With the parabolic form, incoming parallel rays of sound energy becomes focused at a single point. Parametric modelling describes associative geometrical relationships and this method was found to be an appropriate method for generating the geometry of the acoustic mirror surfaces. The Grasshopper algorithmic modelling environment for CAD software Rhino was used to develop the parametric models of the acoustic mirrors.
The third challenge was to predict the acoustic performance of the mirrors themselves. Historically in architecture and engineering, the use of ray-diagrams is an accepted way of predicting sound reflections (Addis 2009). As illustrated in Figure 4, Grasshopper was used to geometrically verify generated surfaces to verify focus points and the directional characteristics of sound projection.

However, this ray diagram approach is a simplification of the properties of sound and so two other types of computational acoustic simulation were also employed. Acoustic simulation can be categorized into two types of simulation: geometric methods and wave-based methods, and this project used both. Most commercially available acoustic simulation software uses geometric methods (usually a combination of ray-tracing and image source), and in this project the Odeon software was used. Because sound is a wave phenomenon, and to visualize sound waves, a custom computer program using a Finite-Difference Time-Domain (FDTD) solver was used (Peters 2015).

The design and fabrication of two prototype mirrors addressed the fourth challenge - how to construct the proposed acoustic mirrors of the Spatial Sonic Network. Grasshopper was used to develop parametric models that generated the details of the structural fins and panels, as well as generated the drawings and data needed to CNC mill components from plywood material. Though only a 3-axis mill was available, prototyping was used to fabricate the two double-curved acoustic mirrors. These two prototypes were used to test the performance of the acoustic mirror’s parabolic geometry and panelized material configuration. The two digitally-fabricated prototypes were measured using acoustic testing equipment - a Bruele and Kjaer (B&K) 2250 sound level meter and B&K 4720 Echo speech source. These two acoustic mirror prototypes were also installed in the University of Toronto’s Art Museum and were used and experienced by visitors to the museum. The prototypes were both quantitatively and qualitatively examined.
RESULTS

Generative Network Topology

The Spatial Sonic Network consists of a number of nodes. Each node consists of two or more acoustic mirrors enabling many people to interact with the installation simultaneously. From two nodes an “Acoustic-Connection” is established. From three nodes, three “Acoustic-Connections” are created. However, when a larger number of nodes (more than three) is considered, the number of potential “Acoustic-Connections” increases exponentially. The shape and topology of the network becomes harder to visualize. As site restrictions are introduced, designing the network becomes a difficult task due to the multivariable possibilities. An algorithm was developed in Processing to study the possible and desired networks. The algorithm produced balanced networks by calculating the standard deviation of length the “Acoustic-Connections”, see Figure 5. In each network the algorithm attempted to maximize the number of connections to obtain most acoustic mirrors given the minimum-angle allowed between two connections while also considering the site-specific acoustic obstacles. While this installation was designed for a specific site, this algorithm is generalizable for almost any site and scale of network.

Defining Acoustic Mirror Geometry

An algorithm to automatically generate the parabolic mirror surface and node geometry was developed in Grasshopper. Using data exported from the previously described network topology generator, this script automatically generated the geometry of each of the nodes, trimming the surfaces and connecting surfaces with flat faces, shown in Figure 6. The parabolic geometry of the acoustic surface was determined using mathematical formulation combined with acoustic ray diagrams to obtain the exact angle of the reflecting surface to capture all of the sound energy - transferring it as efficiently as possible from node to node. Due to different focal distances a variety of parabolic forms were generated, and as these...
forms are trimmed against each other interesting architectural forms are generated. Hundreds of different node options were studied, a selection of which can be seen in Figure 7. The final design of the seven-node configuration is shown in Figure 8.

Figure 7
Acoustic mirror node design study.

**Simulation Results**
Once digital CAD models were generated, the acoustic performance of the acoustic mirrors were simulated using both ray-tracing methods and wave-based methods. A computer program was developed in Processing that utilized the FDTD method (Cox 2009, Peters 2015) for simulating the physics of acoustic waves. A script was written in Rhinoscript that exported a 2D grid of data defining solid-void relationships. This 2D grid was written in text file format and imported into the Processing FDTD program. This workflow essentially takes discretized 2D sectional information from Rhino and then visualizes the sound waves and the efficiency of the sound energy transfer across the acoustic connection between acoustic mirrors. Figure 9 shows results from this wave visualization: first, how the first parabolic acoustic mirror creates a planar reflected wave front, and second, how this sound energy is then focussed to a single point with the second mirror.

Acoustic simulation software Odeon was used to simulate the performance of the acoustic mirrors. Both point receiver (at the focus point) as well as grid receiver (across a wide area of study) simulations were carried out. The simulations were done to prove that the Spatial Sonic Network nodes would actually work as communication devices - that there would be sufficient sound level at “acoustically connected” nodes that people could understand each other. Sound level is an important component to speech intelligibility. The simulations demonstrated that sound levels were amplified between the acoustic mirrors. As shown in Figure 10, sound pressure level (dB) was extremely variable due to the impact of the acoustic mirror geometry, and reverberation time remained consistent throughout the area of study.

**Prototyping**
To build the acoustic sound mirrors a general construction strategy was developed that used the input parabolic acoustic surface, and from this generated a set of notched ribs and triangulated panels, see Figure 11. The digital fabrication workflow used Rhino 3D, Grasshopper, RhinoCAM, and a 3-axis CNC milling machine.

Two identical 1:1 prototypes of parabolic acoustic mirrors were built to test the functionality of the sonic network, see Figure 12. These prototypes were installed at the University of Toronto’s Art Museum as part of the invited “Making Models” exhibition. The input surface was cropped from a revolved parabolic surface with a focus point 600mm from the surface, and at a vertical (sitting) height of 1165 mm. The acoustic mirror prototypes were eight feet in height and had a width of one meter. The trimmed surface geometry was subdivided into 60 quads, each then triangulated, creating 120 triangular panels for each mirror. Because of the increase of curvature at the centre of the parabola, the panel subdivisions became smaller as they approached the focus; this was done using the decay curve of a power function. Horizontal ribs were oriented parallel to the x-y plane, and vertical ribs were oriented perpendicular to the tangent of the horizontal parabola of revolution. The edge of the horizontal ribs approximating the parabolic section was tapered - the parabolic geometry meant that any given horizontal rib would only be sloped in one direction, thereby not requir-
ing any 5-axis CNC operations or flip milling. Triangulated panels were CNC-cut from 9.5mm plywood, painted white, and a 3mm deep profile was milled to express the panelization and to hide nails.

**Acoustic Measurements**

The constructed 1:1 prototypes offered a perceptual confirmation of the unique acoustic communication properties of the parabolic surface. The prototypes were measured using acoustical testing equipment. For measurements, a B&K 2250 sound level meter and B&K 4720 Echo sound source were used to test the efficiency of the acoustic mirrors at transferring sound energy from node to node. While several acoustic mirrors have been built and published in the past, very few have been simulated and/or measured for their performance. This experiment provides a starting point for measuring and understanding in greater detail the actual performance of the parabolic surface for collecting and transmitting sound. The B&K Echo sound source output pink noise and was set to “elevated level”. The sound source is directional and was placed facing into the acoustic mirror with the speaker directly at the 60 cm focal point. Similarly, the microphone of the sound level meter faced the acoustic mirror. Measurements were carried out in a large,
Figure 9
FDTD Wave Simulation of Sound Source (left) and Sound Receiver (right) demonstrating how the first parabolic acoustic mirror creates a planar reflected wave front that is then focussed to a single point using the second mirror.
reverberant room at the University of Toronto’s architecture building. The sound source produced a general level of 67.8 dB in the room.

DISCUSSION AND CONCLUSION
The relationship of performance to geometry, and in particular the variations in parabolic form, is a key driving concept in the design of the acoustic mirrors. As such, parametric design tools played an important role in the project, encoding the geometric relationships and enabling the straightforward exploration of variation. Underlying the associative systems of the acoustic mirrors, is the algorithms that define the network of nodes on the site. Processing proved to be an adaptable tool to generate and evaluate the site strategies for the project. The generation and importing of text files enabled the network definition routine in Processing to link to the node generation script in Grasshopper.

While architects are comfortable with designing for visual criteria, acoustic conditions are more challenging. Acoustic performance needs to be integrated into the architecture design process and similar to previous work, simulation played an important role in enabling designers to understand the acoustic effects of their geometric moves (Peters 2015). Two different types of simulation were used: geometric methods and wave-based visualization. While normally geometric methods produce excellent results and are the only simulation tool needed for many architectural acoustic design scenarios, in this case the results coming out of the geometric simulations did not capture the amplification of sound at the focus point of the receiver. While, it did predict an amplification of sound all along the axis between sound source and sound receiver. The experiment demonstrates that while reverberation time is a key driver for much of architectural acoustics, it is not as relevant in a discussion of acoustic mirrors. The geometric methods fail to identify the focal points, do not accurately predict the sound levels. However, while the FDTD wave-based simulation was used primarily as a visualization tool, it proved to be immensely useful. It demonstrated clearly the creation of a planar wave front, the multiple sound waves incident upon the sound receiver, and the clear focussing effects of the parabolic geometry. The wave-based visualization also clearly demonstrates the time-based nature of the sonic event.

1:1 prototyping was a key design tool, and the full-scale prototype demonstrated again the ability to enable the perceptual verification of the sonic experience (Peters et al. 2011). There were many issues with the smoothness of the acoustic surface that

<table>
<thead>
<tr>
<th>Distance from Mirror (cm)</th>
<th>Sound Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>83.3</td>
</tr>
<tr>
<td>50</td>
<td>87.3</td>
</tr>
<tr>
<td>60</td>
<td>94.4</td>
</tr>
<tr>
<td>70</td>
<td>89.2</td>
</tr>
<tr>
<td>80</td>
<td>83.1</td>
</tr>
<tr>
<td>90</td>
<td>79.2</td>
</tr>
<tr>
<td>100</td>
<td>77.3</td>
</tr>
<tr>
<td>120</td>
<td>75.7</td>
</tr>
<tr>
<td>150</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Table 1
Sound level measured at various distances on axis between acoustic mirror focal points.

Figure 10
Acoustic simulation. Odeon predicts that sound pressure level will be at a maximum between acoustic mirrors (left) while reverberation remains constant throughout the space (right).

Figure 11
Waffle structure and panelization strategy for acoustic mirror fabrication.
could have impacted its performance: the discretization into panels, panels did not fit perfectly, and there was minor surface articulation. These all add up to an imperfect reflector, and it is speculated that the use of more advanced fabrication techniques could result in more acoustically efficient reflectors.

The acoustic measurements confirmed the simulations. A focus distance of 60 cm was predicted and verified. Tables 1 and 2 illustrate just how significant the focussing effects of the acoustic mirrors are, and the measured effects are consistent with the FDTD visualization. On-axis the sound level varies from about 75 dB to 94.4 dB, about a 20 dB difference. According to Long (2006) while a 6 dB increase is substantial a 10 dB increase is a doubling of sound level; therefore, a 20 dB increase would be a doubling again of the sound level. The focus point produces a sound about 4 times as loud as the sound only a short distance away. Interestingly, the focus point perceptually becomes a virtual sound source, radiating sound from the focus point. This effect would likely become even more pronounced if a smoother surface was fabricated.

REFERENCES
Addis, B 2009 ‘A brief history of design methods for building acoustics’, Third international congress on construction history, University of Technology Cottbus Germany, pp. 20-24
Blesser, B and Salter, L 2007, Spaces speak, are you listening?, MIT Press, Boston, USA
Helfer, M 2009 ‘Sound source localisation with acoustic mirrors’, *NAG/DAGA International Conference on Acoustics*, Rotterdam