

Wayverb: A Graphical Tool for Hybrid Modelling Auralisation

**A thesis submitted to the University of Huddersfield in partial fulfilment of
the requirements for the degree of Master of Arts**

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This is the abstract.

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Introduction

The aim of impulse response synthesis is to simulate the reverberant properties of a space without having to physically build anything. This is useful for a variety of applications: architects need to be able to evaluate the acoustics of a building before construction begins, sound editors for film sometimes need to mix in recordings which were not made on location, electronic musicians like to conjure imaginary or impossible spaces in their music, and virtual-reality experiences must use audio cues to convince the user that they have been transported to a new environment.

Unfortunately, software allowing accurate binaural impulse responses to be synthesised is not currently widely available. Often, software produced for research purposes is never made public. Such software that *is* available generally suffers from one or more of an array of issues.

Most software relies only on fast geometric methods, which are inaccurate, especially at low frequencies. Conversely, programs opting to use more accurate wave-modelling methods require long time periods, on the order of days, or significant computing power to run.

Licensing is also an problem. Most room-acoustics packages are the product of years of combined research by multiple contributors, which is only made viable by releasing the software commercially. However, this inhibits further research, as the code is not freely available. This model also limits users to those able to pay, restricting widespread adoption.

When software is made available freely, often the user experience suffers. Code requires manual compilation, or can only be run from a textual interface, or the project is outdated and unmaintained.

The Wayverb project provides a solution to these problems, by making available a graphical tool for impulse response synthesis. It combines several simulation techniques, providing an adjustable balance between speed and accuracy. It is also free to download, can be run immediately on commodity hardware, and the source code can be used and extended under the terms of the GNU GPL license.

This thesis will begin by examining common methods of room simulation and the software which implements these methods, explaining why particular techniques were chosen for Wayverb. Then, each of the chosen techniques will be explored in depth, along with a description of their implementation. The procedure for producing a single impulse response from the outputs of multiple modelling techniques will be detailed. Two extensions to the basic room acoustics model will be described, namely frequency-dependent reflections at boundaries, and microphone/head-related transfer function (HRTF) simulation. The project will be evaluated, and finally, avenues for future development will be examined.

1 Context

Overview

Room acoustics algorithms fall into two main categories: *geometric*, and *wave-based* (A. Southern, Siltanen, & Savioja, 2011). Wave-based methods aim to numerically solve the wave equation, simulating the actual behaviour of sound waves within an enclosure. Geometric methods instead make some simplifying assumptions about the behaviour of sound waves, which result in faster but less accurate simulations. These assumptions generally ignore all wave properties of sound, choosing to model sound as independent *rays*, *particles*, or *phonons*.

The modelling of waves as particles has found great success in the field of computer graphics, where *ray-tracing* is used to simulate the reflections of light in a scene. The technique works well here because of the relatively high frequencies of the modelled waves. The wavelengths of these waves - the wavelengths of the visible spectrum - will generally be many times smaller than any surface in the scene being rendered, so wave phenomena have little or no effect.

The assumption that rays and waves are interchangeable falls down somewhat when modelling sound. Here, the wavelengths range from 17m to 0.017m for the frequency range 20Hz to 20KHz, so while the simulation may be accurate at high frequencies, at low frequencies the wavelength is of the same order as the wall surfaces in the scene. Failure to take wave effects such as interference and diffraction into account at these frequencies therefore results in noticeable approximation error (Savioja & Svensson, 2015).

In many cases, some inaccuracy is an acceptable (or even necessary) trade-off. Wave-modelling is so computationally expensive that using it to simulate a large scene over a broad spectrum could take weeks on consumer hardware. This leaves geometric methods as the only viable alternative. Though wave-modelling been studied for some time (Smith, 1992), and even applied to small acoustic simulations in consumer devices (such as the Yamaha VL1 keyboard), it is only recently, as computers have become more powerful, that these techniques have been seriously considered for room acoustics simulation.

Given that wave-based methods are accurate, but become more expensive at higher frequencies, and that geometric methods are inexpensive, but become less accurate at lower frequencies, it is natural to combine the two models in a way that takes advantage of the desirable characteristics of each. That is, by using wave-modelling for low-frequency content, and geometric methods for high-frequency content, simulations may be produced which are accurate across the entire spectrum, without incurring massive computational costs.

Characteristics of Simulation Methods

A short review of simulation methods will be given here. For a detailed survey of methods used in room acoustics, see P. Svensson & Kristiansen (2002).

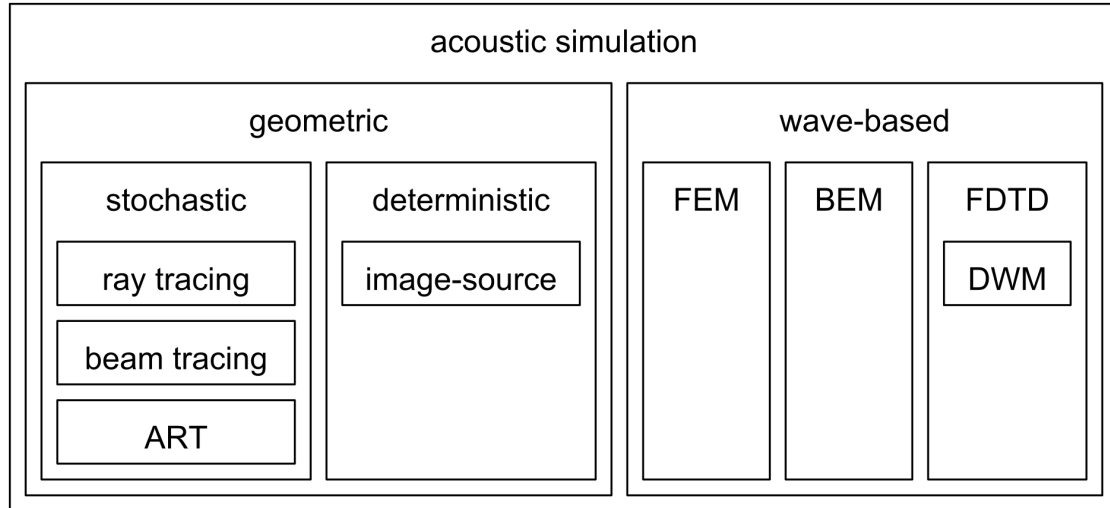


Figure 1.1: An overview of different acoustic simulation methods, grouped by category.

Geometric

Geometric methods can largely be grouped into two categories: *stochastic* and *deterministic*.

Stochastic methods are generally based on statistical approximation via some kind of Monte Carlo algorithm. They may be based directly on reflection paths, using *ray tracing* or *beam tracing*, in which rays or beams are considered to transport acoustic energy around the scene. Alternatively, they may use a surface-based technique, such as *acoustic radiance transfer* (ART), in which surfaces are used as intermediate stores of acoustic energy.

These techniques are inherently approximate. They aim to randomly probe the problem space repeatedly, combining the results from multiple samples so that they converge upon the impulse response for a scene. They can be tuned easily, as quality can be traded-off against speed simply by adjusting the number of samples taken. Surface-based methods, especially, are suited to real-time simulations (i.e. interactive, where the listener position can change), as the calculation occurs in several passes, only the last of which involves the receiver object. This means that early passes can be computed and cached, and only the final pass must be recomputed if the receiver position changes.

The main deterministic method is the *image source* method, which is designed to calculate the exact reflection paths between a source and a receiver. For shoebox-shaped rooms, and perfectly rigid surfaces, it is able to produce an exact solution to the wave equation. However, by its nature, it can only model specular (perfect) reflections, ignoring diffuse and diffracted components. For this reason, it is inexact for arbitrary enclosures, and unsuitable for calculating reverb tails, which are predominantly diffuse. The technique also becomes very expensive beyond low orders of reflection. The naive implementation reflects the sound source against all surfaces in the scene, resulting in a set of *image sources*.

Then, each of these image sources is itself reflected against all surfaces. For high orders of reflection, the required number of calculations quickly becomes impractical. For these reasons, the image source method is only suitable for early reflections, and is generally combined with a stochastic method to find the late part of an impulse response.

For a detailed reference on geometric acoustic methods, see Savioja & Svensson (2015).

Wave-based

The main advantage of wave-based methods is that they inherently account for wave effects like diffraction and interference (S. B. Shelley, 2007), while geometric methods do not. This means that they are capable of accurately simulating the low-frequency component of a room impulse-response, where constructive and destructive wave interference form *room modes*. Room modes have the effect of amplifying and attenuating specific frequencies in the room impulse response, and produce much of the subjective sonic ‘colour’ or ‘character’ of a room. Reproducing these room modes is therefore vital for evaluating the acoustics of rooms such as concert halls and recording studios, or when producing musically pleasing reverbs.

Wave-based methods may be derived from the *Finite Element Method* (FEM), *Boundary Element Method* (BEM) or *Finite-Difference Time-Domain* (FDTD) method. The FEM and BEM may be known together as *element methods*.

The FEM is an iterative numerical method for finding natural resonances of a bounded enclosure. It models the air pressure inside the enclosure using a grid of interconnected nodes, each of which represents a mechanical system with a single degree of freedom. The interconnectedness of the nodes leads to a set of simultaneous equations, which can be solved for displacement at each node, and then the solved equations can be used to calculate pressure values at certain elements. The BEM is similar, but models nodes on the surface of the enclosure, instead of within it. This in turn allows it to model unbounded spaces. (D. T. Murphy & Howard, 2000)

The FDTD method works by dividing the space to be modelled into a regular grid, and computing changes in some quantity at each grid point over time. The formula used to update each grid point, along with the topology of the grid, may be varied depending on the accuracy, efficiency, and complexity of required by the application. FDTD methods are generally applied to problems in electromagnetics, but a subclass of the FDTD method known as the *Digital Waveguide Mesh* (DWM) is often used for solving acoustics problems.

The FDTD shares some characteristics with the element methods. They all become rapidly more computationally expensive as the maximum output frequency increases (V. Valimaki, Parker, Savioja, Smith, & Abel, 2012). They also share the problem of discretisation or quantisation, in which details of the modelled room can only be resolved to the same accuracy as the spatial sampling period. If a large inter-element spacing is used, details of the room shape will be lost, whereas a small spacing will greatly increase the computational load.

The FDTD method has one major advantage over element methods: it is run directly in the time domain, rather than producing frequency-domain results, which in turn affords a much simpler implementation.

The main disadvantage of the FDTD method is that it is susceptible to *numerical dispersion*,

in which wave components travel at different speeds depending on their frequency and direction, especially at high frequencies. Several techniques exist to reduce this error, such as oversampling the mesh (G. R. Campos & Howard, 2005), using different mesh topologies (Savioja & Valimaki, 1999; Van Duyne & Smith, 1995), and post-processing the simulation output (Savioja & Valimaki, 2001). Oversampling further increases the computational load of the simulation, while using different topologies and post-processing both introduce additional complexity.

Despite its drawbacks, the FDTD method is generally preferred for room acoustics simulation (V. Valimaki et al., 2012), probably due to its straightforward implementation, intuitive behaviour, and its ability to directly produce time-domain impulse responses.

Existing Software

Searching online and in the literature uncovers a handful of programs for acoustic simulation (this is not an exhaustive list, but it is felt to be representative):

Name	Type	Availability
Odeon (“Odeon,” 2016)	Geometric	Commercial
CATT-Acoustic (“CATT-Acoustic,” 2016)	Geometric	Commercial
Olive Tree Lab (“OTL,” 2016)	Geometric	Commercial
EASE (“EASE,” 2016)	Geometric	Commercial
Auratorium (“Audioborn – Auratorium,” 2016)	Geometric	Commercial
RAVEN (Schröder & Vorländer, 2011)	Geometric	None
RoomWeaver (M. J. Beeson & Murphy, 2004)	Waveguide	None
EAR (“Ear,” 2016)	Geometric	Free
PachydermAcoustic (“Pachyderm Acoustic,” 2016)	Geometric	Free
Parallel FDTD (“ParallelFDTD,” 2016)	Waveguide	Free
i-Simpa (“I-Simpa,” 2016)	Geometric, extensible	Free

All commercial acoustics programs found use geometric techniques, probably because they are fast to run, and can often be implemented to run interactively, in real-time. However, low-frequency performance is a known issue with these programs. For example, the FAQ page for the Odeon software (“Odeon FAQ,” 2016) notes that:

For Odeon simulations as with real measurements, the source and receiver should be at least 1/4th wave length from the walls. But at the very lowest resonance of the room the level can change a lot from position to position without Odeon being able to predict it. For investigation of low frequency behavior (resonances), indeed Odeon is not the tool.

Clearly there is a need for acoustics software which can accurately predict low frequency behaviour. However, such software seems to be somewhat rarer than geometric acoustics software. Of the two wave-modelling programs listed, only one is generally available, which must additionally be run from Python or Matlab scripts. This is a good approach for research software, but would probably not be straightforward for users with limited programming experience.

As of December 2016, it appears that no generally-available (commercially or otherwise)

piece of software has taken the approach of combining wave-modelling and geometric methods, although this technique is well-known in the literature (Aretz, Nöthen, Vorländer, & Schröder, 2009; D. Murphy, Beeson, Shelley, Moore, & Southern, 2008; A. Southern & Siltanen, 2013; A. Southern et al., 2011; Southern, Siltanen, Murphy, & Savioja, 2013; Vorlander, 2009).

Research Aims

With all this in mind, it appears that there is a requirement for a program which combines geometric and wave-based methods to produce simulations which are accurate across the audible spectrum. Rather than focussing on performance, or interactive simulation (which is already implemented in the commercial software above), such a program should strive towards accuracy first, and performance second. To be useful to end-users, the program should have a graphical interface, though a scripting or library interface might be provided for research purposes. Finally, the program would ideally be free and open-source, to maximise adoption and to aid future research and collaboration. The goal of the Wayverb project was to produce a program which satisfied these requirements.

Strategy

Chosen Simulation Techniques

As the image-source method is well-suited to finding early reflections, and stochastic methods are reasonably accurate at computing the more diffuse late reflections, it made sense to combine these two methods for high-frequency simulation. Specifically, a simple ray tracing method was chosen over a phonon- or surface-based method for the late-reflection simulation, for two reasons. Firstly, ray tracing is broadly discussed in the literature (Alpkocak & Sis, 2010; Krokstad, Strom, & Sørsdal, 1968; Kuttruff, 2009; Schröder, 2011; Vorländer, 2007), so would not require a great deal of experimentation to implement. Secondly, ray tracing has the property of being an *embarrassingly parallel* algorithm, because each individual ray can be simulated entirely independently, without requiring communication or synchronisation. By running the algorithm on graphics hardware, which is inherently parallel, all rays could be simulated in one go, yielding much greater performance than processing each ray sequentially.

A logistical reason for choosing the image-source and ray tracing solution for high-frequency modelling was that the author had previously implemented such a system for an undergraduate project. It was hoped that much of the code from that project could be re-used, but it transpired that much of the code was unsuitable or incorrect (!), so that the majority was completely re-written. The author was, however, able to re-use much of the knowledge and experience gained from the previous project, which would not have been possible if a completely new stochastic method had been introduced.

For low-frequency simulation, a FDTD-based DWM model was chosen. There is a great deal of writing on this method (G. R. Campos & Howard, 2005; Kowalczyk & Walstijn, 2011; D. T. Murphy & Howard, 2000; Savioja, Lokki, & Välimäki, 2014; Van Duyne & Smith III, 1996), it is relatively simple to implement, and shares with ray tracing the characteristic of being embarrassingly parallel. Each element in the waveguide mesh can

be updated individually and simultaneously, which it was hoped would yield performance benefits.

An in-depth description of the algorithms implemented will be given in the [Image-Source](#), [Ray Tracer](#), and [Waveguide](#) sections.

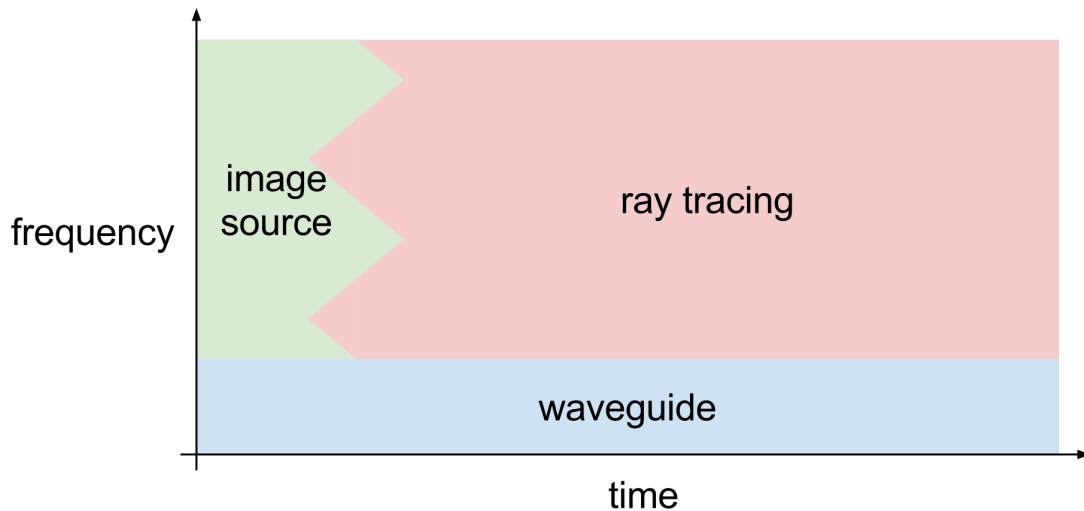


Figure 1.2: The structure of a simulated impulse response.

Deciding on the simulation techniques led to three questions:

- To produce a final output, the three simulations must be automatically mixed in some way. How can this be done?
- Binaural simulation requires some method for direction- and frequency-dependent attenuation at the receiver. How can receivers with polar patterns other than omnidirectional be modelled consistently in all three simulation methods?
- The reverb time and character depends heavily on the nature of the reflective surfaces in the scene. How can frequency-dependent reflective boundaries be modelled consistently in all methods?

These questions will be discussed in the [Hybrid](#), [Microphone Modelling](#), and [Boundary Modelling](#) sections respectively.

Chosen Technology

The programming language chosen was C++. For acceptable performance in numerical computing, a low-level language is required, and for rapid prototyping, high-level abstractions are necessary. C++ delivers on both of these requirements, for the most part, although its fundamentally unsafe memory model does introduce a class of bugs which don't really exist in languages with garbage collection, borrow checking, or some other safety mechanism.

OpenCL was chosen for implementing the most parallel parts of the simulation. The OpenCL framework allows a single source file to be written, in a C-like language, which can target either standard *central processing units* (CPUs), or highly parallel *graphics processing units* (GPUs). The main alternative to OpenCL is CUDA, which additionally

can compile C++ code, but which can only target Nvidia hardware. OpenCL was chosen as it would allow the final program to be run on a wider variety of systems, with fewer limitations on their graphics hardware.

The only deployment target was macOS. This was mainly to ease development, as maintaining software across multiple platforms is often time-consuming. macOS also tends to have support for newer C++ language features than Windows. Visual Studio 2015 for Windows still doesn't support all of the C++11 language features ("Visual Studio support for C++ language features," 2016), while the Clang compiler used by macOS has supported newer C++14 features since version 3.4 ("Clang support for C++ language features," 2016), released in May 2014 ("Download LLVM releases," 2016). Targeting a single platform avoids the need to use only the lowest common denominator of language features. As far as possible, the languages and libraries have been selected to be portable if the decision to support other platforms is made in the future. Once Windows fully supports C++14, it should be possible to port the program with a minimum of effort.

The following additional libraries were used to speed development. They are all open-source and freely available.

- *GLM*: Provides vector and matrix primitives and operations, primarily designed for use in 3D graphics software, but which is useful for any program that will deal with 3D space.
- *Assimp*: Used for loading and saving 3D model files in a wide array of formats, with a consistent interface for querying loaded files.
- *FFTW3*: Provides Fast Fourier Transform routines. Used mainly for filtering and convolution.
- *Libsndfile*: Used for loading and saving audio files, specifically for saving simulation results.
- *Libsamplerate*: Provides high-quality sample-rate-conversion routines. Waveguide simulations are often run at a relatively low sample-rate, which must then be adjusted.
- *Gtest*: A unit-testing framework, used to validate small individual parts of the program, and ensure that changes to one module don't cause breakage elsewhere.
- *Cereal*: Serializes data to and from files. Used for saving program configuration options.
- *ITPP*: A scientific computing library. Used for its implementation of the Yule-Walker method for estimating filter coefficients for a given magnitude response.
- *JUCE*: Provides a framework for building graphical applications in C++. Used for the final application.

The project uses Cmake to configure its build, and to automatically download project dependencies. Python and Octave were used for running and automating tests and generating graphs.

This documentation is written in Markdown, and compiled to html and to pdf using Pandoc. The project website is generated with Jekyll.

2 Image-source

Coming soon.

3 Ray Tracer

Coming soon.

4 Waveguide

Coming soon.

5 Microphone Modelling

Coming soon.

6 Boundary Modelling

Coming soon.

7 Evaluation

Coming soon.

8 The Future

Coming soon.

References

This list contains all items cited in the text. It also contains some items not directly mentioned, but which nonetheless guided the development of the project, or might shape its future.

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- Allard, J.-F., & Champoux, Y. (1992). New empirical equations for sound propagation in rigid frame fibrous materials. *The Journal of the Acoustical Society of America*, 91(6), 3346–3353. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/91/6/10.1121/1.402824>
- Allen, J. B., & Berkley, D. A. (1979). Image method for efficiently simulating small-room acoustics. *The Journal of the Acoustical Society of America*, 65(4), 943–950. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/65/4/10.1121/1.382599>
- Alpkocak, A., & Sis, M. (2010). Computing impulse response of room acoustics using the ray-tracing method in time domain. *Archives of Acoustics*, 35(4), 505–519. Retrieved from <http://www.degruyter.com/view/j/aoa.2010.35.issue-4/v10168-010-0039-8/v10168-010-0039-8.xml>
- Amanatides, J., Woo, A., & others. (1987). A fast voxel traversal algorithm for ray tracing. In *Eurographics* (Vol. 87, pp. 3–10). Retrieved from <http://www.cse.chalmers.se/edu/year/2015/course/TDA361/grid.pdf>
- Antoni, J. (2010). Orthogonal-like fractional-octave-band filters. *The Journal of the Acoustical Society of America*, 127(2), 884–895. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/127/2/10.1121/1.3273888>
- Aretz, M., Nöthen, R., Vorländer, M., & Schröder, D. (2009). Combined broadband impulse responses using FEM and hybrid ray-based methods. In *EAA Symposium on Auralization*. Retrieved from https://www.researchgate.net/profile/Dirk_Schroeder/publication/258098666_Combined_Broadband_Impulse_Responses_Using_FEM_and_Hybrid_Ray-Based_Methods/links/54fd4d80cf2c3f52424436f.pdf
- Audioborn. (2016). Retrieved from <http://www.audioborn.com>
- Bass, H. E., Bauer, H.-J., & Evans, L. B. (1972). Atmospheric absorption of sound: Analytical expressions. *The Journal of the Acoustical Society of America*, 52(3B), 821–825. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/52/3B/>

- Beeson, M. J., & Murphy, D. T. (2004). RoomWeaver: A digital waveguide mesh based room acoustics research tool. In *Proc. COST G6 Conf. Digital Audio Effects (Naples, Italy, October 2004)* (pp. 268–73). Retrieved from http://www.mirlab.org/conference_papers/International_Conference/DAFx%202004/Proc/P_268.pdf
- Bertram, M., Deines, E., Mohring, J., Jegorovs, J., & Hagen, H. (2005). Phonon tracing for auralization and visualization of sound. In *VIS 05. IEEE Visualization, 2005.* (pp. 151–158). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1532790
- Bilbao, S. (2009). Grid Functions and Finite Difference Operators in 2D. In *Numerical Sound Synthesis* (pp. 287–304). John Wiley & Sons, Ltd. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1002/9780470749012.ch10/summary>
- Bilbao, S. (2013). Modeling of complex geometries and boundary conditions in finite difference/finite volume time domain room acoustics simulation. *IEEE Transactions on Audio, Speech, and Language Processing*, 21(7), 1524–1533. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6494263
- Borish, J. (1984). Extension of the image model to arbitrary polyhedra. *The Journal of the Acoustical Society of America*, 75(6), 1827–1836. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/75/6/10.1121/1.390983>
- Campos, G. R., & Howard, D. M. (2005). On the computational efficiency of different waveguide mesh topologies for room acoustic simulation. *IEEE Transactions on Speech and Audio Processing*, 13(5), 1063–1072. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1495487
- Campos, G., & Howard, D. (2000). A parallel 3D digital waveguide mesh model with tetrahedral topology for room acoustic simulation. In *Proceedings of the COST G-6 Conference on Digital Audio Effects (DAFx), (Verona, Italy)* (pp. 73–78). Retrieved from ftp://nic.funet.fi/pub/sci/audio/dafx/2000/profs.sci.univr.it/%257Edafx/Final-Papers/pdf/Campos_g_DAFx.pdf
- CATT-Acoustic. (2016). Retrieved from <http://www.catt.se/>
- Christensen, C. L., & Rindel, J. H. (2005). A new scattering method that combines roughness and diffraction effects. In *Forum Acousticum, Budapest, Hungary.* Retrieved from http://www.cs.yorku.ca/course_archive/2005-06/W/6335/feb20/CLC%20fa2005.pdf
- Clang support for C++ language features. (2016). Retrieved from http://clang.llvm.org/cxx_status.html
- Deines, E., Bertram, M., Mohring, J., Jegorovs, J., Michel, F., Hagen, H., & Nielson, G. M. (2006). Comparative visualization for wave-based and geometric acoustics.

- IEEE Transactions on Visualization and Computer Graphics*, 12(5), 1173–1180. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4015479
- Delany, M. E., & Bazley, E. N. (1970). Acoustical properties of fibrous absorbent materials. *Applied Acoustics*, 3(2), 105–116. Retrieved from <http://www.sciencedirect.com/science/article/pii/0003682X70900319>
- Dimitrijevic, B., Nikolic, B., Aleksic, S., & Raicevic, N. (2015). Optimization of Excitation in FDTD Method and Corresponding Source Modeling. *RADIOENGINEERING*, 24(1), 11. Retrieved from https://dSPACE.vutbr.cz/bitstream/handle/11012/38723/15_01_0010_0016.pdf?sequence=1
- Download LLVM releases. (2016). Retrieved from <http://llvm.org/releases/>
- Durany, J., Mateos, T., & Garriga, A. (2015). Analytical Computation of Acoustic Bidirectional Reflectance Distribution Functions. *Open Journal of Acoustics*, 5(04), 207. Retrieved from <http://www.scirp.org/journal/PaperInformation.aspx?paperID=62211>
- Ear. (2016). *GitHub*. Retrieved from <https://github.com/aothms/ear>
- EASE. (2016). Retrieved from <http://ease.afmg.eu/index.php/features.html>
- Escolano-Carrasco, J., & Jacobsen, F. (2006). A physical interpretation of frequency dependent boundary conditions in a digital waveguide mesh. In *Proceedings of Thirteenth International Congress on Sound and Vibration*. Retrieved from <http://www.forskningsdatabasen.dk/en/catalog/108083221>
- Fontana, F., & Rocchesso, D. (2001). Signal-theoretic characterization of waveguide mesh geometries for models of two-dimensional wave propagation in elastic media. *IEEE Transactions on Speech and Audio Processing*, 9(2), 152–161. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=902281
- Foteinou, A., Van Mourik, J., Oxnard, S., & Murphy, D. (2014). Hybrid Acoustic Modelling of Historic Spaces Using Blender. In. *Forum Acusticum*. Retrieved from <http://wlv.openrepository.com/wlv/handle/2436/605729>
- Fu, Z.-h., & Li, J.-w. (2016). GPU-based image method for room impulse response calculation. *Multimedia Tools and Applications*, 1–17. Retrieved from <http://link.springer.com/article/10.1007/s11042-015-2943-4>
- Funkhouser, T., Carlbom, I., Elko, G., Pingali, G., Sondhi, M., & West, J. (1998). A beam tracing approach to acoustic modeling for interactive virtual environments. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques* (pp. 21–32). ACM. Retrieved from <http://dl.acm.org/citation.cfm?id=280818>
- Furse, C. M., Roper, D. H., Buechler, D. N., Christensen, D. A., & Durney, C. H.

- (2000). The problem and treatment of DC offsets in FDTD simulations. *IEEE Transactions on Antennas and Propagation*, 48(8), 1198–1201. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=884487
- Gedney, S. D. (2011). Introduction to the finite-difference time-domain (FDTD) method for electromagnetics. *Synthesis Lectures on Computational Electromagnetics*, 6(1), 1–250. Retrieved from <http://www.morganclaypool.com/doi/abs/10.2200/S00316ED1V01Y201012CEM027>
- Gorzel, M., Kearney, G., Boland, F., & Rice, H. (2010). Virtual acoustic recording: An interactive approach. In *Proc. of the 13th international conference on Digital Audio Effects (DAFX)*. Graz, Austria. Retrieved from https://www.researchgate.net/profile/Marcin_Gorzel/publication/228998533_Virtual_acoustic_recording_an_interactive_approach/links/09e4150742ba370bbf000000.pdf
- Hacihabiboglu, H., Gunel, B., & Kondo, A. M. (2008). On the accuracy of first-order numerical derivatives in multidimensional digital waveguide mesh topologies. *IEEE Signal Processing Letters*, 15, 9–12. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4418392
- Hacihabiboglu, H., Gunel, B., & Kondo, A. M. (2008). Time-domain simulation of directive sources in 3-D digital waveguide mesh-based acoustical models. *IEEE Transactions on Audio, Speech, and Language Processing*, 16(5), 934–946. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4494749
- Hacihabiboglu, H., Günel, B., & Cvetkovic, Z. (2010). Simulation of directional microphones in digital waveguide mesh-based models of room acoustics. *IEEE Trans. on Audio, Speech and Language Process*, 18(2), 213–223. Retrieved from https://www.researchgate.net/profile/Huseyin_Hacihabiboglu/publication/224504323_Simulation_of_Directional_Microphones_in_Digital_Waveguide_Mesh-Based_Models_of_Room_Acoustics/links/0c960519e803aee931000000.pdf
- Hadi, M. F., & Almutairi, N. B. (2010). Discrete finite-difference time domain impulse response filters for transparent field source implementations. *IET Microwaves, Antennas & Propagation*, 4(3), 381–389. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5430362
- Hamilton, B. (2013). Sampling and Reconstruction on a Diamond Grid and the Tetrahedral Digital Waveguide Mesh. *IEEE Signal Processing Letters*, 10(20), 925–928. Retrieved from <https://www.infona.pl/resource/bwmeta1.element.ieee-art-000006558503>
- Heinz, R. (1993). Binaural room simulation based on an image source model with addition of statistical methods to include the diffuse sound scattering of walls and to predict the reverberant tail. *Applied Acoustics*, 38(2), 145–159. Retrieved from <http://www.sciencedirect.com/science/article/pii/0003682X9390048B>
- Howarth, M. J. (1998). *The application of advanced computer models to the prediction*

- of sound in enclosed spaces* (PhD thesis). University of Salford. Retrieved from <http://usir.salford.ac.uk/id/eprint/14677>
- Huopaniemi, J., Savioja, L., & Karjalainen, M. (1997). Modeling of reflections and air absorption in acoustical spaces: A digital filter design approach. In *IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* (pp. 19–22). Citeseer. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.41.3912&rep=rep1&type=pdf>
- I-Simpa. (2016). *I-Simpa*. Retrieved from <http://i-simpa.ifsttar.fr/>
- Jeong, H., & Lam, Y. W. (2012). Source implementation to eliminate low-frequency artifacts in finite difference time domain room acoustic simulation. *The Journal of the Acoustical Society of America*, 131(1), 258–268. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/131/1/10.1121/1.3652886>
- Karjalainen, M., & Erku, C. (2004). Digital waveguides versus finite difference structures: Equivalence and mixed modeling. *EURASIP Journal on Applied Signal Processing*, 2004, 978–989. Retrieved from <http://dl.acm.org/citation.cfm?id=1289420>
- Kelloniemi, A. (2006). Frequency-dependent boundary condition for the 3-D digital waveguide mesh. In *Proc. Int. Conf. Digital Audio Effects (DAFx'06)* (pp. 161–164). Citeseer. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.440.3197&rep=rep1&type=pdf#page=171>
- Kim, M., & Scavone, G. P. (2009). Domain decomposition method for the digital waveguide mesh. In *2009 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* (pp. 21–24). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5346457
- Koutsouris, G. I., Brunskog, J., Jeong, C.-H., & Jacobsen, F. (2013). Combination of acoustical radiosity and the image source method. *The Journal of the Acoustical Society of America*, 133(6), 3963–3974. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/133/6/10.1121/1.4802897>
- Kowalczyk, K., & Walstijn, M. van. (2008a). Modeling frequency-dependent boundaries as digital impedance filters in FDTD and K-DWM room acoustics simulations. *Journal of the Audio Engineering Society*, 56(7/8), 569–583. Retrieved from <http://www.aes.org/e-lib/browse.cfm?elib=14401>
- Kowalczyk, K., & Walstijn, M. van. (2008b). Modelling Frequency-Dependent Boundaries as Digital Impedance Filters in FDTD Room Acoustic Simulations. In *Audio Engineering Society Convention 124*. Audio Engineering Society. Retrieved from <http://www.aes.org/e-lib/browse.cfm?conv=124&papernum=7430>
- Kowalczyk, K., & Walstijn, M. van. (2011). Room acoustics simulation using 3-D compact explicit FDTD schemes. *IEEE Transactions on Audio, Speech, and Language Processing*, 19(1), 34–46. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all

[jsp?arnumber=5440917](#)

- Krokstad, A., Strom, S., & Sørsdal, S. (1968). Calculating the acoustical room response by the use of a ray tracing technique. *Journal of Sound and Vibration*, 8(1), 118–125. Retrieved from <http://www.sciencedirect.com/science/article/pii/0022460X68901983>
- Kuttruff, H. (2009). *Room Acoustics, Fifth Edition*. CRC Press.
- Lafortune, E. P., Foo, S.-C., Torrance, K. E., & Greenberg, D. P. (1997). Non-linear approximation of reflectance functions. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (pp. 117–126). ACM Press/Addison-Wesley Publishing Co. Retrieved from <http://dl.acm.org/citation.cfm?id=258801>
- Lehmann, E. A., & Johansson, A. M. (2008). Prediction of energy decay in room impulse responses simulated with an image-source model. *The Journal of the Acoustical Society of America*, 124(1), 269–277. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/124/1/10.1121/1.2936367>
- Levy, E. C. (1959). Complex-curve fitting. *IRE Transactions on Automatic Control*, (1), 37–43. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6429401
- Marbjerg, G., Brunskog, J., Jeong, C.-H., & Nilsson, E. (2015). Development and validation of a combined phased acoustical radiosity and image source model for predicting sound fields in rooms. *The Journal of the Acoustical Society of America*, 138(3), 1457–1468. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/138/3/10.1121/1.4928297>
- McGovern, S. (2011). The image-source reverberation model in an N-dimensional space. In *Proc. 14th Int. Conf. Digital Audio Effects, Paris, France* (pp. 11–18). Retrieved from http://recherche.ircam.fr/pub/dafx11/Papers/17_e.pdf
- Miklavcic, S. J., & Ericsson, J. (2004). *Practical implementation of the 3D tetrahedral TLM method and visualization of room acoustics*. Department of Science; Technology (ITN), Campus Norrköping, Linköping University [Institutionen för teknik och naturvetenskap (ITN), Campus Norrköping, Linköpings universitet]. Retrieved from https://www.researchgate.net/profile/Stanley_Miklavcic/publication/268338847_PRACTICAL_IMPLEMENTATION_OF_THE_3D_TETRAHEDRAL_TLM_METHOD_AND_VISUALIZATION_OF_ROOM_ACOUSTICS/links/547411fe0cf245eb436dbd7e.pdf
- Mouchtaris, A., Narayanan, S. S., & Kyriakakis, C. (2002). Efficient multichannel audio resynthesis by subband-based spectral conversion. In *Signal Processing Conference, 2002 11th European* (pp. 1–4). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7072210
- Murphy, D. T., & Beeson, M. (2007). The KW-boundary hybrid digital waveguide mesh for room acoustics applications. *IEEE Transactions on Audio, Speech, and Language*

- Processing*, 15(2), 552–564. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4067045
- Murphy, D. T., & Howard, D. M. (2000). *Digital waveguide mesh topologies in room acoustics modelling* (PhD thesis). Citeseer. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.723.1750&rep=rep1&type=pdf>
- Murphy, D. T., & Mullen, J. (2002). Digital waveguide mesh modelling of room acoustics: Improved anechoic boundaries. In *Proc. DAFX* (Vol. 2, pp. 163–168). Retrieved from http://ant-s4.unibw-hamburg.de/dafx/papers/DAFX02_Murphy_Mullen_waveguide_mesh_modeling.pdf
- Murphy, D. T., Southern, A., & Savioja, L. (2014). Source excitation strategies for obtaining impulse responses in finite difference time domain room acoustics simulation. *Applied Acoustics*, 82, 6–14. Retrieved from <http://www.sciencedirect.com/science/article/pii/S0003682X14000401>
- Murphy, D., Beeson, M., Shelley, S., Moore, A., & Southern, A. (2008). Hybrid room impulse response synthesis in digital waveguide mesh based room acoustics simulation. In *Proceedings of the 11th International Conference on Digital Audio Effects (DAFx-08)* (pp. 129–136). Retrieved from <http://core.ac.uk/download/pdf/21721150.pdf>
- Nelson, G., Pfeifer, L., & Wood, R. (1972). High-speed octave band digital filtering. *IEEE Transactions on Audio and Electroacoustics*, 20(1), 58–65. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1162338
- O’Rourke, J. (1985). Finding minimal enclosing boxes. *International Journal of Computer & Information Sciences*, 14(3), 183–199. Retrieved from <http://link.springer.com/article/10.1007/BF00991005>
- Odeon. (2016). Retrieved from <http://www.odeon.dk/>
- Odeon FAQ. (2016). Retrieved from <http://www.odeon.dk/faq-page#t16n151>
- OTL. (2016). Retrieved from <http://www.olivetreelab.com/Room>
- Oxnard, S., O’Brien, D., Mourik, J. van, & Murphy, D. (2015). Frequency-Dependent Absorbing Boundary Implementations in 3D Finite Difference Time Domain Room Acoustics Simulations. Retrieved from http://www.conforg.fr/euronoise2015/output_directory/data/articles/000112.pdf
- Pachyderm Acoustic. (2016). *GitHub*. Retrieved from <https://github.com/PachydermAcoustic>
- ParallelFDTD. (2016). *GitHub*. Retrieved from <https://github.com/juuli/ParallelFDTD>
- Revelles, J., Urena, C., & Lastra, M. (2000). An efficient parametric algorithm for octree

- traversal. Retrieved from <https://otik.uk.zcu.cz/handle/11025/15821>
- Rindel, J. H. (1993). Modelling the angle-dependent pressure reflection factor. *Applied Acoustics*, 38(2), 223–234. Retrieved from <http://www.sciencedirect.com/science/article/pii/0003682X93900539>
- Rindel, J. H. (2000). The use of computer modeling in room acoustics. *Journal of Vibroengineering*, 3(4), 41–72. Retrieved from https://www.researchgate.net/profile/Jens_Rindel/publication/2461601_The_Use_of_Computer_Modeling_in_Room_Acoustics/links/542027af0cf241a65a1b0999.pdf
- Savioja, L., & Lokki, T. (2001). Digital waveguide mesh for room acoustic modeling. *CAMP-FIRE*, 6(3), 13. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.398.8067&rep=rep1&type=pdf#page=23>
- Savioja, L., & Svensson, U. P. (2015). Overview of geometrical room acoustic modeling techniques. *The Journal of the Acoustical Society of America*, 138(2), 708–730. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/138/2/10.1121/1.4926438>
- Savioja, L., & Valimäki, V. (1999). Reduction of the dispersion error in the interpolated digital waveguide mesh using frequency warping. In *Acoustics, Speech, and Signal Processing, 1999. Proceedings., 1999 IEEE International Conference on* (Vol. 2, pp. 973–976). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=759858
- Savioja, L., & Valimäki, V. (2001). Interpolated 3-D digital waveguide mesh with frequency warping. In *Acoustics, Speech, and Signal Processing, 2001. Proceedings.(ICASSP'01). 2001 IEEE International Conference on* (Vol. 5, pp. 3345–3348). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=940375
- Savioja, L., Karjalainen, M., & Takala, T. (1996). DSP formulation of a finite difference method for room acoustics simulation. In *Proceedings of NORSIG'96 IEEE Nordic Signal Processing Symposium* (pp. 455–458). Retrieved from https://www.researchgate.net/profile/Tapio_Takala/publication/239443426_DSP_Formulation_of_a_Finite_Difference_Method_for_Room_Acoustics_Simulation/links/004635371a9f6b175f000000.pdf
- Savioja, L., Lokki, T., & Välimäki, V. (2014). The interpolated 3-D digital waveguide mesh method for room acoustic simulation and auralization. *Ultrasonics: The International Journal of Acoustics*, 48(3), 48–52. Retrieved from http://www.academia.edu/download/30718688/savioja_nam02.pdf
- Schneider, J. B., Wagner, C. L., & Broschat, S. L. (1998). Implementation of transparent sources embedded in acoustic finite-difference time-domain grids. *The Journal of the Acoustical Society of America*, 103(1), 136–142. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/103/1/10.1121/1.50888>

- Schröder, D. (2011). *Physically based real-time auralization of interactive virtual environments* (Vol. 11). Logos Verlag Berlin GmbH. Retrieved from https://books.google.com/books?hl=en&lr=&id=HtDxSt0jcRkC&oi=fnd&pg=PR17&dq=+Dirk+Schro+%CC%88der+Physically+Based+Real-Time+Auralization+of+Interactive+Virtual+Environments&ots=CCbCVBNlmn&sig=CAIxZysU-fxjnSkG_X1_dffQ72o
- Schröder, D., & Vorländer, M. (2011). RAVEN: A real-time framework for the auralization of interactive virtual environments. In *Forum Acusticum*. Retrieved from https://www2.ak.tu-berlin.de/~akgroup/ak_pub/seacen/2011/Schroeder_2011b_P2_RAVEN_A_Real_Time_Framework.pdf
- Schroeder, M. R. (1965). New Method of Measuring Reverberation Time. *The Journal of the Acoustical Society of America*, 37(3), 409–412. doi:10.1121/1.1909343
- Sheaffer, J. (2013). *From source to brain: Modelling sound propagation and localisation in rooms* (PhD thesis). Citeseer. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.662.9774&rep=rep1&type=pdf>
- Sheaffer, J., & Fazenda, B. M. (2010). FDTD/K-DWM simulation of 3D room acoustics on general purpose graphics hardware using compute unified device architecture (CUDA). *Proc. Institute of Acoustics*, 32(5). Retrieved from http://usir.salford.ac.uk/11568/?utm_source=twitterfeed&utm_medium=twitter
- Sheaffer, J., Van Walstijn, M., Rafaely, B., & Kowalczyk, K. (2015). Binaural reproduction of finite difference simulations using spherical array processing. *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, 23(12), 2125–2135. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7194789
- Sheaffer, J., Walstijn, M. van, & Fazenda, B. (2014). Physical and numerical constraints in source modeling for finite difference simulation of room acoustics. *The Journal of the Acoustical Society of America*, 135(1), 251–261. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/135/1/10.1121/1.4836355>
- Sheaffer, J., Webb, C., & Fazenda, B. M. (2013). Modelling binaural receivers in finite difference simulation of room acoustics. In *Proceedings of Meetings on Acoustics* (Vol. 19, p. 015098). Acoustical Society of America. Retrieved from <http://scitation.aip.org/content/asa/journal/poma/19/1/10.1121/1.4800195>
- Shelley, S. B. (2007). *Diffuse boundary modelling in the digital waveguide mesh*. University of York. Retrieved from http://www-users.york.ac.uk/~dtm3/Download/SBS_Thesis.pdf
- Shelley, S., & Murphy, D. T. (2005). Diffusion modelling at the boundary of a digital waveguide mesh. In *Signal Processing Conference, 2005 13th European* (pp. 1–4). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=

- Siltanen, S., Lokki, T., & Savioja, L. (2010). Rays or waves? Understanding the strengths and weaknesses of computational room acoustics modeling techniques. In *Proceedings of the International Symposium on Room Acoustics*. Melbourne, Australia. Retrieved from https://www.researchgate.net/profile/Tapio_Lokki/publication/236169416_Rays_or_Waves_Understanding_the_Strengths_and_Weaknesses_of_Computational_Room_Acoustics_Modeling_Techniques/links/00463538f7bd84469a000000.pdf
- Siltanen, S., Lokki, T., Kiminki, S., & Savioja, L. (2007). The room acoustic rendering equation. *The Journal of the Acoustical Society of America*, 122(3), 1624–1635. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/122/3/10.1121/1.2766781>
- Siltanen, S., Lokki, T., Tervo, S., & Savioja, L. (2012). Modeling incoherent reflections from rough room surfaces with image sources. *The Journal of the Acoustical Society of America*, 131(6), 4606–4614. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/131/6/10.1121/1.4711013>
- Siltanen, S., Southern, A., & Savioja, L. (2013). Finite-difference time domain method source calibration for hybrid acoustics modeling. In *2013 IEEE International Conference on Acoustics, Speech and Signal Processing* (pp. 166–170). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6637630
- Smith, J. O. (1992). Physical modeling using digital waveguides. *Computer Music Journal*, 16(4), 74–91. Retrieved from <http://www.jstor.org/stable/3680470>
- Southern, A., & Murphy, D. (2007a). Methods for 2 nd Order Spherical Harmonic Spatial Encoding in Digital Waveguide Mesh Virtual Acoustic Simulations. In *2007 IEEE Workshop on Applications of Signal Processing to Audio and Acoustics* (pp. 203–206). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4392993
- Southern, A., & Murphy, D. T. (2007b). 2nd order spherical harmonic spatial encoding of digital waveguide mesh room acoustic models. In *Proceedings of the 10th International Conference on Digital Audio Effects (DAFx07), Bordeaux, France* (pp. 101–108). Citeseer. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.384.295&rep=rep1&type=pdf>
- Southern, A., & Siltanen, S. (2013). A hybrid acoustic model for room impulse response synthesis. In *Proceedings of Meetings on Acoustics* (Vol. 19, p. 015113). Acoustical Society of America. Retrieved from <http://scitation.aip.org/content/asa/journal/poma/19/1/10.1121/1.4800212>
- Southern, A., Siltanen, S., & Savioja, L. (2011). Spatial room impulse responses with a hybrid modeling method. In *Audio Engineering Society Convention 130*. Audio Engineering Society. Retrieved from <http://www.aes.org/e-lib/browse.cfm?elib=>

- Southern, A., Siltanen, S., Murphy, D. T., & Savioja, L. (2013). Room impulse response synthesis and validation using a hybrid acoustic model. *IEEE Transactions on Audio, Speech, and Language Processing*, 21(9), 1940–1952. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6516012
- Summers, J. E., Takahashi, K., Shimizu, Y., & Yamakawa, T. (2004). Assessing the accuracy of auralizations computed using a hybrid geometrical-acoustics and wave-acoustics method. *The Journal of the Acoustical Society of America*, 115(5), 2514–2515. Retrieved from <http://scitation.aip.org/content/asa/journal/jasa/115/5/10.1121/1.4809339>
- Svensson, P., & Kristiansen, U. R. (2002). Computational modelling and simulation of acoustic spaces. In *Audio Engineering Society Conference: 22nd International Conference: Virtual, Synthetic, and Entertainment Audio*. Audio Engineering Society. Retrieved from <http://www.aes.org/e-lib/browse.cfm?elib=11119>
- Valimaki, V., Parker, J. D., Savioja, L., Smith, J. O., & Abel, J. S. (2012). Fifty years of artificial reverberation. *IEEE Transactions on Audio, Speech, and Language Processing*, 20(5), 1421–1448. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6161610
- Van Duyne, S. A., & Smith III, J. O. (1996). The 3D tetrahedral digital waveguide mesh with musical applications. In *Proceedings of the 1996 International Computer Music Conference* (pp. 9–16). The International Computer Music Association. Retrieved from <https://dialnet.unirioja.es/servlet/articulo?codigo=569975>
- Van Duyne, S. A., & Smith, J. O. (1995). The tetrahedral digital waveguide mesh. In *Applications of Signal Processing to Audio and Acoustics, 1995., IEEE ASSP Workshop on* (pp. 234–237). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=482998
- Visual Studio support for C++ language features. (2016). Retrieved from <https://msdn.microsoft.com/en-us/library/hh567368.aspx>
- Vorlander, M. (2009). Simulation and auralization of broadband room impulse responses. In *Tecniacústica 2009*. Retrieved from <https://dialnet.unirioja.es/servlet/articulo?codigo=4680242>
- Vorländer, M. (2007). *Auralization: Fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality*. Springer Science & Business Media. Retrieved from <https://books.google.com/books?hl=en&lr=&id=CuXF3JkTuhAC&oi=fnd&pg=PA1&dq=auralization+vorlander&ots=EXlinTIK9W&sig=d2t3k2YLLPA1FWvfH15gw1QSi7M>
- Warren, G. S., & Scott, W. R. (1998). Numerical dispersion in the finite-element method using three-dimensional edge elements. *Microwave and Optical Technology Letters*,

18(6), 423–429. Retrieved from http://users.ece.gatech.edu/~wrscott/Papers/1998-8_MOTL_Numerical_Dispersion_3D.pdf

Zhang, C., & Chen, T. (2001). Efficient feature extraction for 2D/3D objects in mesh representation. In *Image Processing, 2001. Proceedings. 2001 International Conference on* (Vol. 3, pp. 935–938). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=958278