2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 9-11 DEARBORN, MICHIGAN

Real Time Urban Acoustics Using Commercial Technologies

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ABSTRACT

A methodology based on a combination of commercial software tools is developed for rendering complex acoustic scenes in real time. The methodology aims to bridge the gap between real time acoustic rendering algorithms which lack important physics for the exterior urban environment and more rigorous but computationally expensive geometric or wave-based acoustics software by incorporating pre-computed results into a real time framework. The methodology is developed by surveying the best in class commercial software, outlining a general means for accommodating results from each, and identifying areas where supplemental capability is required. This approach yields a real time solution with improved accuracy. Strengths and limitations in current commercial technologies are identified and summarized.

INTRODUCTION

Urban acoustics is an active research area that is receiving increased attention in the literature. There are two primary focus areas that are behind the increased interest in this area. The first area is DoD interest in support of tactical planning, training, and signature reduction. The second is municipal planning in support of understanding how infrastructure improvements will impact noise levels in occupied urban areas. The uses and required results formats are significantly different, but the underlying acoustic propagation challenge is very similar.

The differences in the required acoustic prediction results are tied directly to the end uses. DoD intends primarily to produce training, simulation and evaluation, experiences in an immersive and interactive environment. This requires reproduction of representative sounds enabling the listener to experience an audio environment comparable to an urban battlefield. Municipal planning uses are focused on understanding equivalent daily exposure levels and the presence of noise levels that exceed guidelines and might interrupt sleep schedules, interfere with workplace communications, or result in hearing damage from long term exposure. A typical result is a colored noise map of the area.

These differing results requirements have driven the two focus areas in fundamentally different directions in terms of development of software tools for modeling the acoustic propagation in an urban environment. The DoD community can accept less physically representative propagation models for simulation and training activities in return for real time performance. The noise levels do not need to be accurately calibrated because if the audio reproduction is recognizable it serves its training purpose. Funds continue to be directed at improving the physics, but real time performance is the top priority. As DoD begins to utilize the immersive environment for evaluation of acoustic signature and detection, calibrated levels and accurate propagation algorithms become increasingly important.

Real time performance is not required in urban acoustics for infrastructure noise enabling more computationally expensive and accurate physics incorporation in the propagation models. The majority of software tools for modeling urban acoustics are based on a form of ray tracing. The commercially available tools are generally vague in terms of technical documentation detailing specifics of their algorithm, due to the proprietary nature. Several specifications exist for propagation of road and railway noise as well as published guidelines for acceptable noise levels.

Impressive improvements in computational power, massively parallel architectures, and wave based techniques have extended the realm of possibility for broadband application of finite difference time domain and fast multi-pole boundary element methods to urban scenes. As computing technology and commercial software based on these techniques continue to rapidly improve, wave based methods may replace geometric acoustics as the default method for physically accurate urban acoustic predictions.

Modular Concept for Real Time Urban Acoustics

A flow chart illustrating the steps involved with simulating and displaying urban acoustics is shown below.

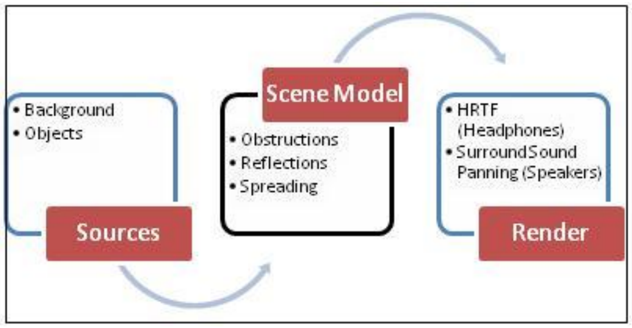

Figure 1: Urban Acoustic Simulation and Display

The primary focus of this paper is in addressing the center section of the above figure. Brief mention is made in relevant sections of tools and techniques specifically tailored for modeling sources as well as a very brief description of the options for acoustic rendering given in the following section.

A framework enabling real time rendering of urban acoustics that facilitates incorporation of results from a variety of computational techniques is desirable. A spatial three dimensional audio design suite that incorporates a modular, filter based approach to acoustic propagation currently exists in a commercial package. This package is called VibeStudio Designer and is available for a modest fee from Vrsonic, Inc [www.vrsonic.com]. The package has been used to develop several DoD simulators [1]. VibeStudio Designer facilitates construction of 3D audio scenes and includes several important propagation physics including spreading loss, atmospheric absorption, material transmission and absorption, reverberation, propagation delays, and rendering for binaural or surround sound display [2].

VibeStudio does not include propagation effects of reflections, diffusion, or refraction. However, it incorporates two important aspects of real time acoustic propagation, an advanced scheduling and prioritizing algorithm that insures real-time performance and a method for filter coefficient interpolation that eliminates artifacts as sources or listeners move throughout the scene. User defined filters that include additional propagation physics can be incorporated into the pipeline and any of the individual propagation filters can be disabled. This modular framework provides the flexibility to include results based on pre-computations and post-processing of various types of models, including ray and wave based techniques. An image of the propagation pipeline control in VibeStudio is included below to illustrate the default filter components. Additional filters are incorporated as software plug-ins. All scene descriptions are stored in an open XML format allowing nearly unlimited user control of all aspects of a scene.

An additional benefit is support of the open sound control (OSC) protocol into VibeStudio. The OSC protocol is an open standard developed in support of communication between computers, sound synthesizers, and multimedia devices that is optimized for modern networking technology [3]. The OSC protocol makes control and synchronization of multimodal immersive environments possible.

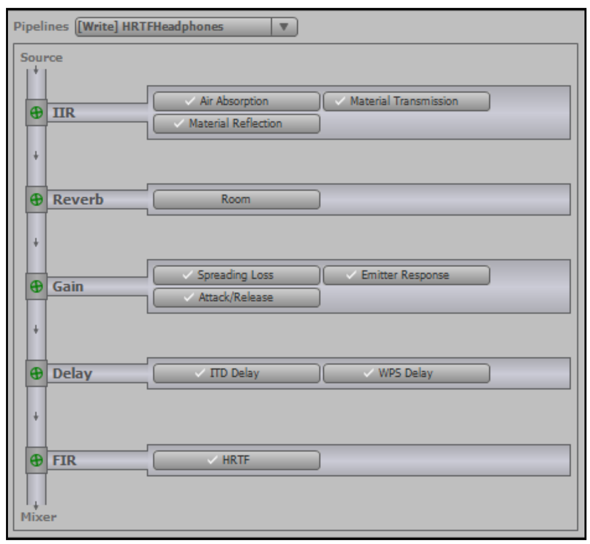

Figure 2: Modular propagation pipeline

Real Time Acoustic Rendering

The real time rendering is the least challenging aspect of the real time acoustics problem. Several commercial tools are available for rending both binaural headphones displays as well as standard and arbitrary surround sound formats. For this reason, minimal detail is provided in this paper and the reader is referred to [2]. An image illustrating a binaural display scenario and a typical surround sound setup are included below.

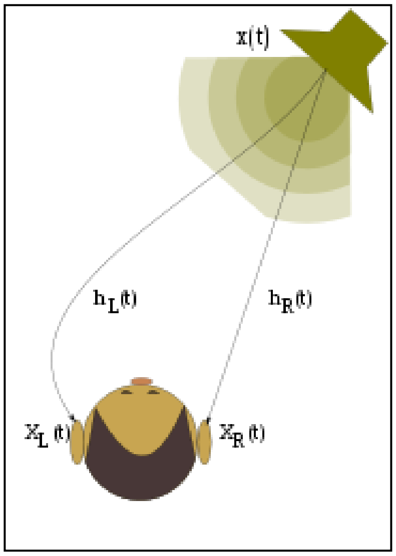

Figure 3: Binaural rendering

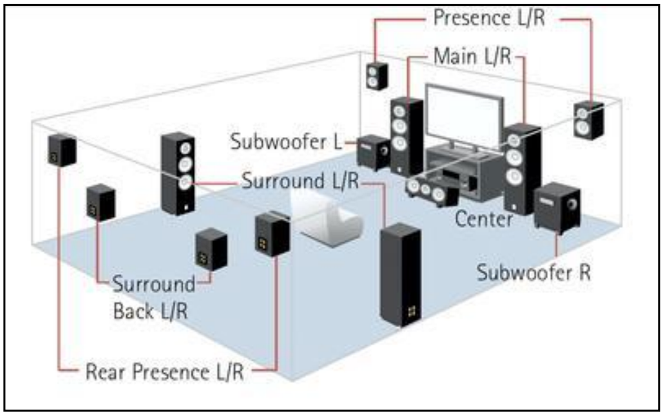

Figure 4: Dolby Surround 10.2

Real Time Propagation in a Complex Environment Based on Pre-Compuation and Filter Fitting

In order to create a general framework for real time acoustic propagation in an urban scene, a filter based approach is outlined. A filter based propagation algorithm lends itself well to real time computation. The propagation calculation is based on convolution of source signals with infinite impulse response (IIR) or finite impulse response (FIR) digital filters. Convolution of many sources with sequential filters is an ideal GPU application and [4] illustrates the ability of the GPU to perform this calculation for real time acoustics. The filter based approach allows any modeling technique, whether geometric or wave based, to fit into the real time propagation framework so long as it can yield impulse or frequency response representations of acoustic propagation between combinations of listener and source positions. All physics, such as direct path, diffraction, and refraction, included in the response function can be captured in its filter representation. The impulse response and frequency response function are time domain and frequency domain representations of the acoustic propagation function. Depending on the modeling technique either is a possible result. Images illustrating each are included below.

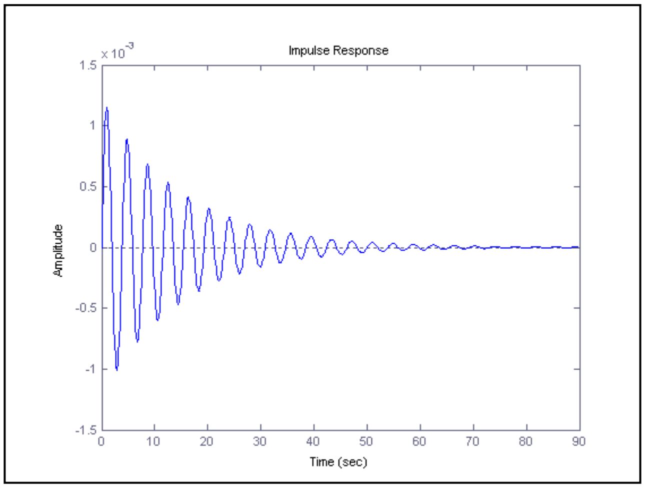

Figure 5: Impulse Response Function – Time Domain

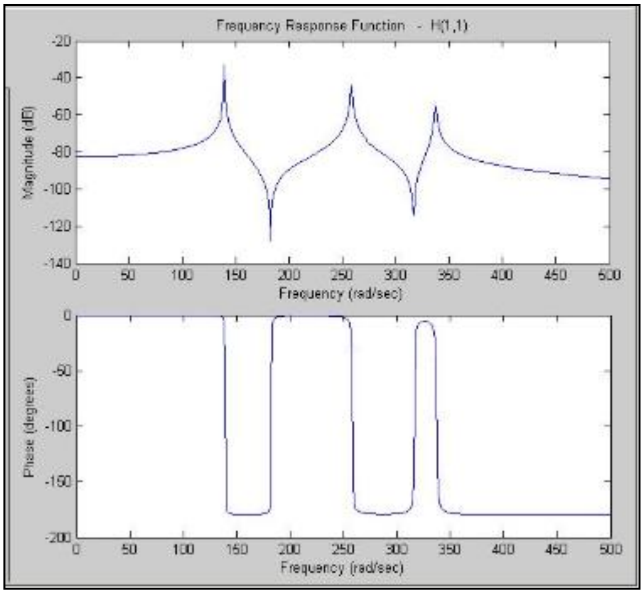

Figure 6: Frequency Response Function – Frequency Domain

A filter of appropriate form and order must be fit to the predicted propagation function. Filter coefficient fitting to arbitrary response functions and order selection can be accomplished using a variety of algorithms, some automatic such as Remez exchange and least P_{th} norm. Advanced filter fitting and order selection algorithms are implemented in commercial software like Matlab or LabView. Options for digital filter fitting include FIR, which is based on current and past input values, and IIR which is based on current and past input values and past output values. Each representation has unique advantages in terms of computational efficiency, required tap counts, and phase response [5]. Difference equation representations of both finite impulse response and infinite impulse response filters are included for reference.

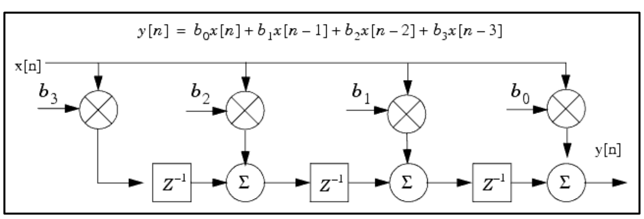

Figure 7: FIR Type Filter

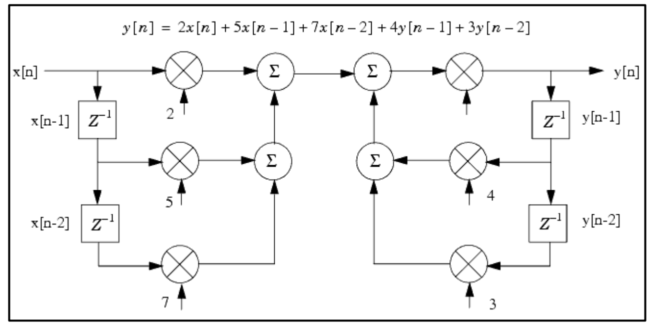

Figure 8: IIR Type Filter

Important Propagation Physics for Detection and Localization of Sounds in Urban Scenes

Several important propagation physics contribute to the ability to detect and localize sound sources in an urban environment. These include reflections, diffractions, and refractions and the influence of the wavelength of sounds. Each is discussed in detail in order of importance with regards to realistic auralization of urban acoustics. The direct path contribution is omitted due to its straightforward nature.

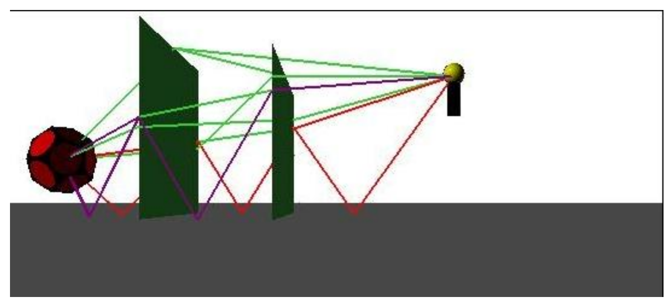

Figure 9: Diagram of combinations of reflection and diffraction points between a single point source and receiver

Reflections

Early (low order) reflections are an extremely important aspect of realistic urban acoustics. Early reflections can be nearly equal in magnitude to the direct path contribution, as illustrated in the following figure, and can cause a listener to localize the sound source to an early reflection location. The material properties of the reflective surface influence the scattering, absorption, and resulting energy of the reflected wave as shown below. Reflection is implicitly included in wave based methods when considering point to point propagation and forms the basis for ray based methods.

However, when auralization is required, extensions of both ray and wave based methods are required to recreate the spatial effects of the reflection point, especially when no direct path exists. In order to capture this important spatial effect, a method for identifying low order reflection positions and including additional coherent sources at these positions based on image source methods can be used [6]

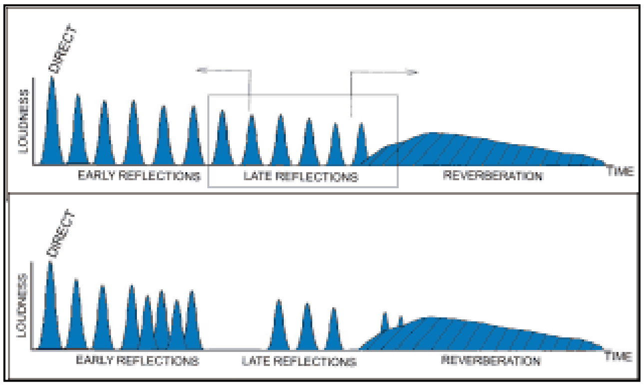

Figure 10: Audio Effect of Reflections and Diffusion

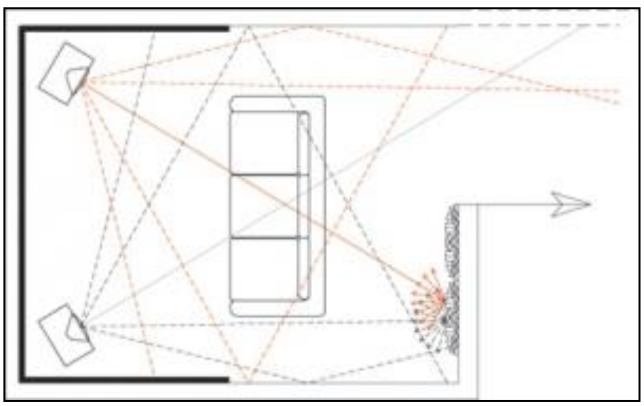

Figure 11: Diffusion - Acoustic Scattering

Fresnel zones influence reflections by influencing the energy participating in the reflection and expanding the area where the impinging sound wave can reflect. The 1st Fresnel zone contains the majority of the available signal energy and forms a 3 dimensional ellipsoid containing all points where the additional path length is less than the sounds wavelength/2. Energy adjustments for the Fresnel effect can be accommodated in ray based methods based on the work by Clay and Medwin [7, 8]. Image is included below illustrating the shapes of Fresnel zone orders and a reflection from a Fresnel zone.

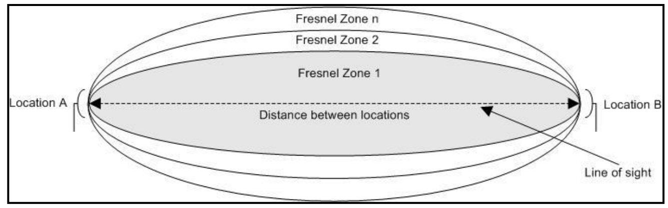

Figure 12: Fresnel Zone Shapes

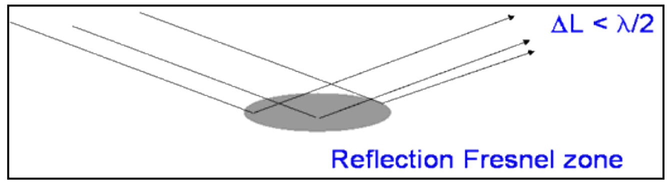

Figure 13: Fresnel zone effect on reflections

Diffraction

Depending on the density of obstructions and the source frequency characteristics, diffraction can also be an important propagation mechanism associated with urban acoustics. Its effect on detection and localization is exaggerated in an urban environment.

Diffraction is implicitly included in wave based methods, but must be included in ray based methods using approximate models such as Pierce, Hadden-Pierce, or Biot-Tolstoy-Medwin. Please refer to [9 - 26] for further details.

When auralization is required, extensions of both ray and wave based methods are required to recreate the spatial effects of the diffraction points, especially when no direct path exists. In order to capture this important spatial effect, a method for identifying low order diffraction positions and including additional coherent sources at these positions based on image source methods can be used.

Images showing typical diffraction scenarios in an urban environment are included below.

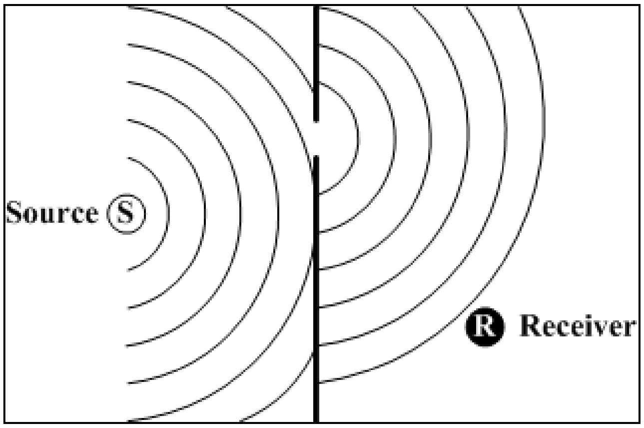

Figure 14: Example of Diffraction of Sound

Fresnel zones influence diffraction by influencing the energy participating in the diffraction. The size of the 1st Fresnel zone increases with frequency and provide a mechanism to influence the energy contained in the diffracted path and predict the efficient diffraction at low frequencies. This is illustrated in the following figure.

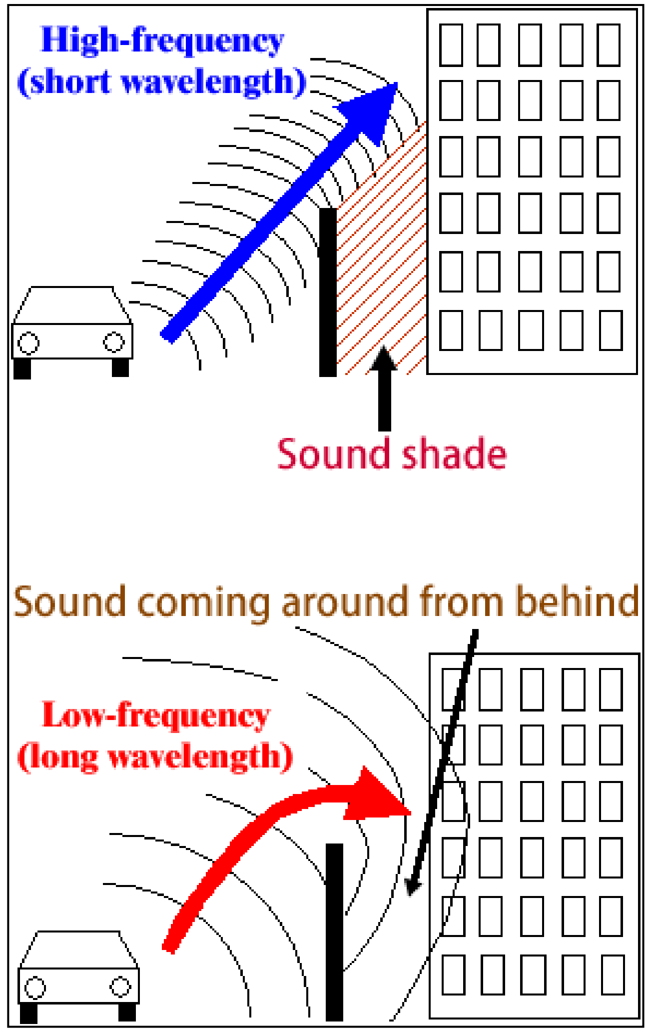

Figure 15: Wavelength Effect on Diffraction

Refraction

Atmospheric refraction can occur due to a number of factors including thermal gradient, wind, and changes in density. Refraction can be very important depending on the scene. Its importance grows as the scene becomes larger and with decreased density of obstructions. Urban scenes present specific challenges in predicting refraction due to local effects of buildings on wind and thermal gradients.

Refraction is not typically implemented in ray based or wave based methods. Implementation in ray based methods can be accomplished using a variety of methods, including curved rays. Please refer to [6, 27] for details. An image illustrating a curved ray is included below. The radius of curvature is dependent on meteorological parameters and the distance between sources. Wave based methods that include a volume mesh may accommodate local densities and velocities that would enable modeling of refraction effects. Some advances have been made to include meteorological and refraction effects into surface meshed model (BEM). Please refer to [28] for details.

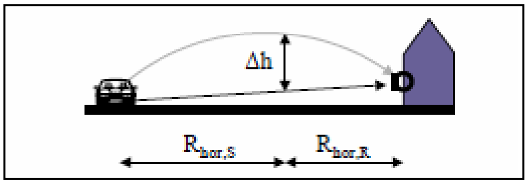

Figure 16: Curved Ray Model

The image below shows how atmospheric refraction can reinforce sound and create shadow zones. The classic example of this effect is the ability to hear voices from across a lake at night but not during the day due to inversion of the thermal gradient and associated atmospheric refraction.

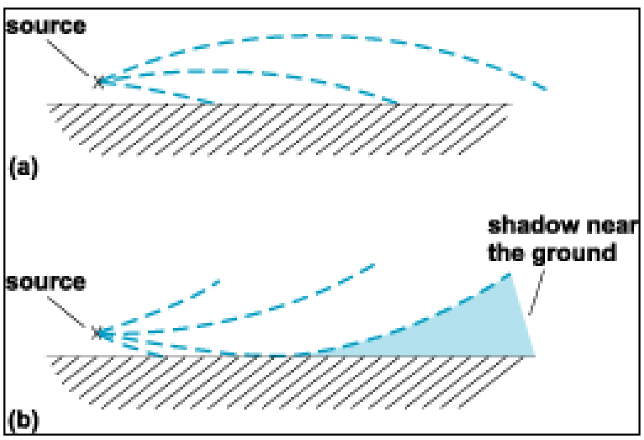

Figure 17: Atmospheric Refraction

Review of Commercial Software

Numerous commercial tools exist for constructing engineering models of acoustics problems. Some are better suited than others for exterior propagation problems, and a select few lend themselves to accurately and efficiently modeling exterior acoustics in an urban environment. These tools can be grouped into two general categories, geometric and wave methods.

Geometric acoustics are prevalent in architectural and infrastructure domains. They see broad use in design of auditoriums and other listening spaces. They are also used extensively in modeling noise in and around urban infrastructure such as railways, highways, and airports.

Wave based methods enjoy broad use in major industry such as automotive, aerospace, off highway, and consumer products. Wave based methods are particularly suited to modeling problems in detail and typically include the ability to model vibration and acoustics, i.e. fluid-structure interaction.

Each of the two broad categories is discussed in further detail below. Specific commercial packages are identified and strengths, weaknesses, and applications to the urban acoustics problem are summarized.

Geometric Acoustic Technology

Geometric acoustics encompasses numerous tracing techniques as well as image source methods. These methods have the ability include the effects reflection and diffraction for the case of time averaged results. Image source methods form the basis for accurate auralization of these advanced physics. Low frequency accuracy for reflections and diffraction is an on-going challenge. Inclusion of Fresnel zones improves performance in the low frequency ranges where vehicle typically operate. A list of variations of ray and particle tracing is included below.

- Ray Tracing
- Cone Tracing
- Frustum Tracing
- Beam Tracing
- Image Source Method

This approach to acoustics has many similarities to techniques used in visual rendering problems. Several commercial packages available:

- Sound plan
- Odeon
- OTL Terrain
- Catt
- Ease

An image illustrating a typical scene modeled in a ray-tracing package is included below. Rays illustrating reflection and diffraction points are visible.

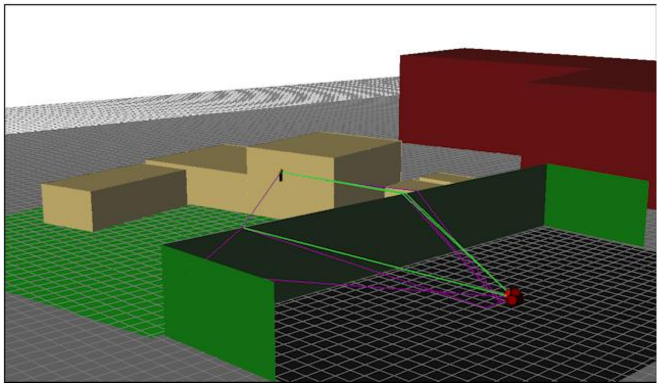

Figure 18: Representative Exterior Software

Finite Element Method (FEM)

Finite element based acoustics have enjoyed broad application in industry both at the component level and at the vehicle level. The method is best suited for detailed source modeling and most commercial packages can easily handle fluid structure interactions in order to model both acoustics and vibration. Computational burden grows rapidly (N^2) with increased element count. As structures and cavities grow larger and more complex, modal densities increase quickly and the deterministic methods like FE and BEM become less useful in practice. Statistical energy analysis (SEA) and hybrid methods are typically paired with FE acoustics models to achieve broadband performance.

Several Commercial packages are available:

- VAOne
- VNoise
- LMS Virtual.Lab
- Actran

An image illustrating a FEM based engine noise radiation solution is shown below. This is a typical application for FEM acoustics.

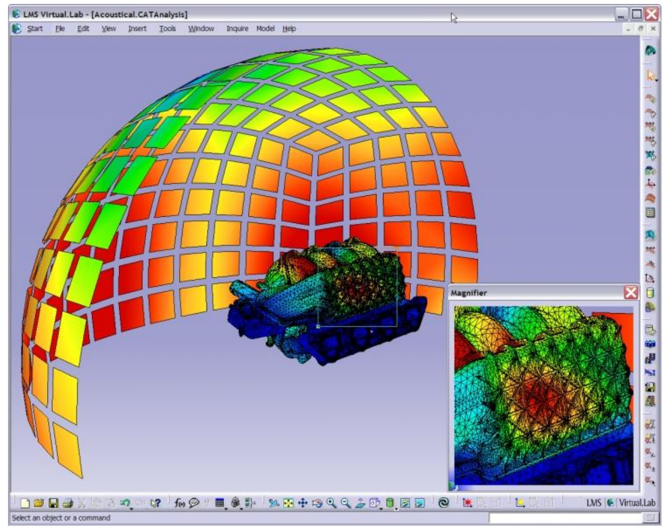

Figure 19: FEM Acoustic Model of Engine Radiation

Boundary Element Method (BEM)

Recent improvements have made large broadband simulations more realistic on standard hardware. Specifically the development of fast multi pole BEM algorithms has rapidly improved BEM capabilities to solve large models capable of broadband acoustic predictions. Additional significant improvements are likely as these algorithms transition to GPU platforms. Acoustic BEM may very well be the default method within the near future for large urban scenes. At a minimum, it is currently efficient enough to improve predictions at low frequencies where ray based methods offer questionable accuracy. Several commercial packages available:

- VAOne
- VNoise
- FastBEM
- Coustyx
- LMS Virtual Lab

An image below shows a calculated sound field for an urban scene using a fast multi pole algorithm.

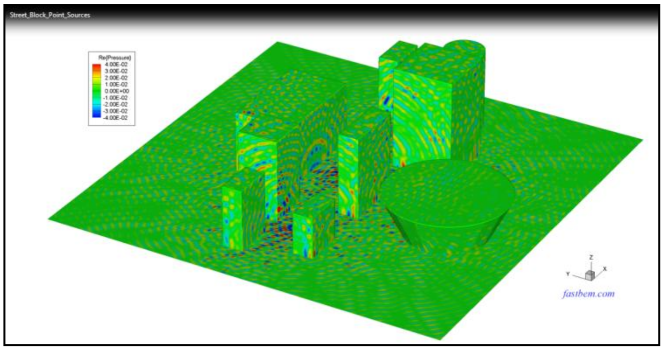

Figure 20: Fast Multi-pole BEM Model of a City Block

Finite Difference Time Domain (FDTD)

Although FDTD methods are extremely powerful for modeling acoustics problems, they are not yet commercially available in a package intended for acoustics. The FDTD approach is well suited for implementation on a GPU platform. This technique is promising for high fidelity simulation of transient acoustics as computing power continues to rapidly increase.

An image below illustrates a wave front calculation executed with a user contributed Matlab package for FDTD acoustics. [29]

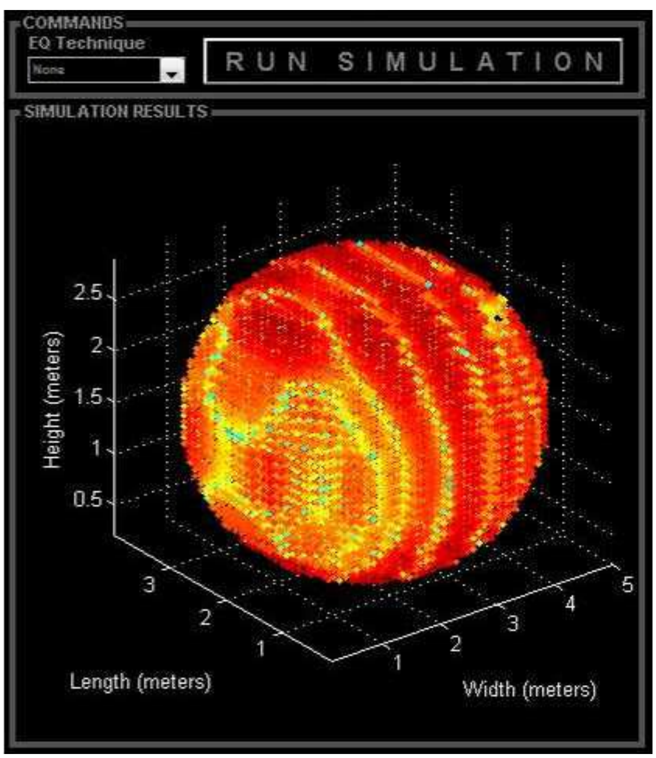

Figure 21: Screen shot of FDTD Simulation Toolbox

CONCLUSION

A methodology is outlined that capitalizes on existing commercial technologies to improve the accuracy of real time urban acoustic simulations. The methodology is flexible in its ability to incorporate results from a variety of computational acoustic methods in the form of digital filter approximations. Improvements can be incorporated into the real time urban simulations as myriad acoustic modeling tools improve in the area of accurately modeling the physics associated with urban scenes. The outlined methodology minimizes the required development by eliminating the need to build a complete solution tailored specifically for real time urban acoustics that includes advanced propagation features like diffraction and atmospheric refraction. This approach reduces the effort to adaptation of results from commercially available packages with minimal supplement in capability where absolutely necessary, while improving the quality of real time urban acoustic environments.

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