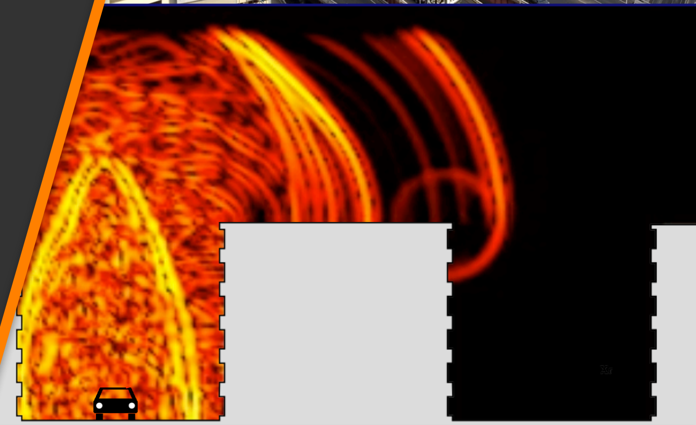
Wave-based modelling in the built environment using the PSTD method: developments and prospects

Maarten Hornikx

07-07-2015



Technische Universiteit **Eindhoven** University of Technology

Short bio

TU/e	1998 - 2004	**M.Sc.** Architecture, Building and Planning Eindhoven University of Technology
	2004 - 2009	**Ph.D.** in Applied Acoustics, Chalmers University of Technology, Göteborg
	2007	University of Mississippi National Center for Physical Acoustics
KATHOLIEKE UNIVERSITEIT LEUVEN	2009 - 2011	**Post-Doc** Aero-Acoustics KU Leuven Individual Marie-Curie IEF fellowship
	2011 - 2013	**Senior Researcher** position Applied Acoustics, Chalmers University of Technology, Göteborg
TU/e	2012- …	**Assistant Professor** in Building Acoustics, Dept. of the Built Environment Eindhoven University of Technology

TU/e Building Acoustics chair

4 Units

AUDE: Architectural Urban Design and Engineering
BPS: Building Physics and Services
SD: Structural Design
USS: Urban Science & Systems

1 Bachelor program
2 Master's programs

- Master Architecture, Building and Planning
- Master Construction Management and Engineering

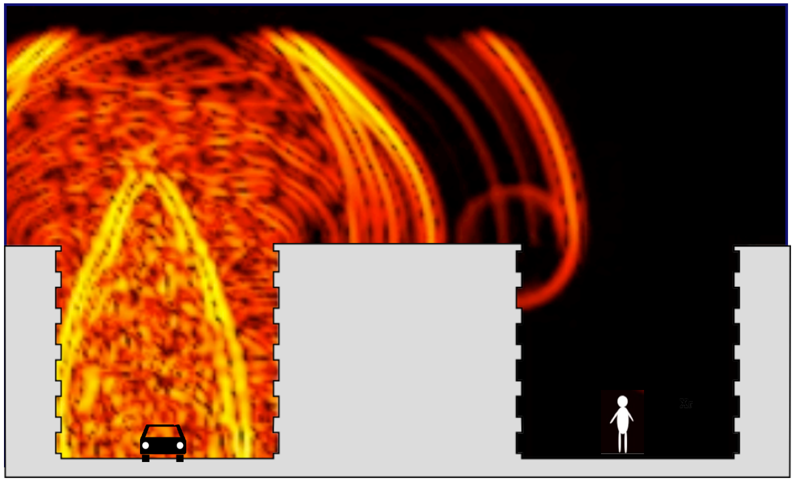
Building Physics and Services

6 Research groups

Building Acoustics
Building Lighting
Building Materials
Building Physics
Building Performance
Building Services

TU/e Building Acoustics chair

Sources → Environment → Receiver



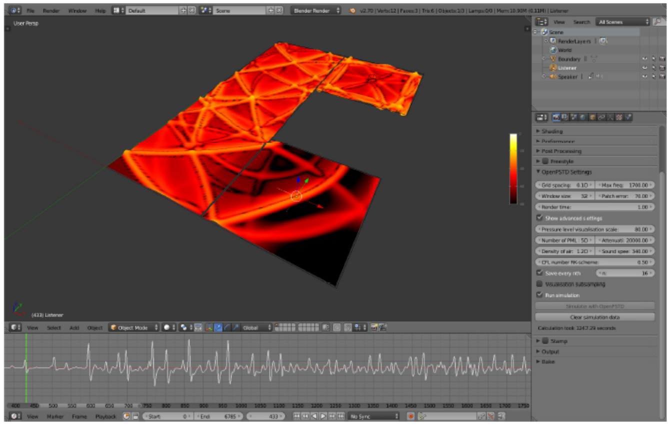
TU/e Building Acoustics chair

Urban Acoustics

Computational methods

Urban propagation effects

Human echolocation



Room and Building Acoustics

Experimental methods

Computational methods

Concert hall and theatre acoustics

Healthy environments

Lightweight structures

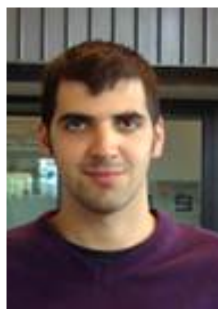
TU/e Building Acoustics chair

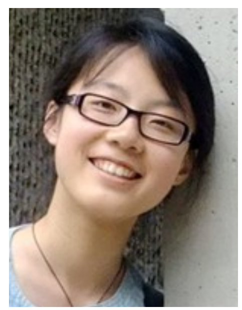

Maarten Hornikx

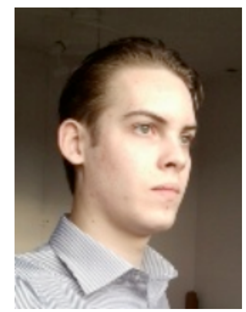

Constant Hak


Remy Wenmaekers


Raúl Pagán


Fotis Georgiou


Chang Liu


Rick de Vos


Michiel Fortuin


Qin Yi**


Ella Braat-Eggen


Indra Sihar


Jikke Reinten


Omar Richardson


Louis van Harten

** From 9/2015

Research vision

We must aim for a high acoustic quality in the built environment at all times, and it must be free from adverse health effects due to noise.

To support this aim, my research is devoted to

- Development of prediction methods to study (fundamental) acoustics and auditory perception of the built environment;
- Using these tools to integrate and optimize acoustics for a sustainable (re)design of the built environment and technical innovations therein.

Research vision

Challenges: Tackle major contemporary problems in acoustics

- Urban noise problem

- Low frequency acoustics related to lightweight buildings

www.sustainabilitymatters.net.au

www.smstimberframe.co.uk

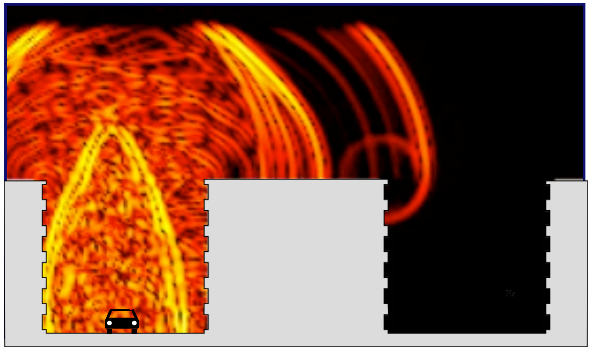
Research vision

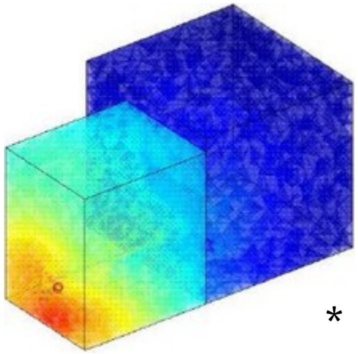
Challenges: Tools

- Design of acoustically realistic Virtual Reality systems

http://www.techmania.nl

- Development and application of open source acoustic prediction methods



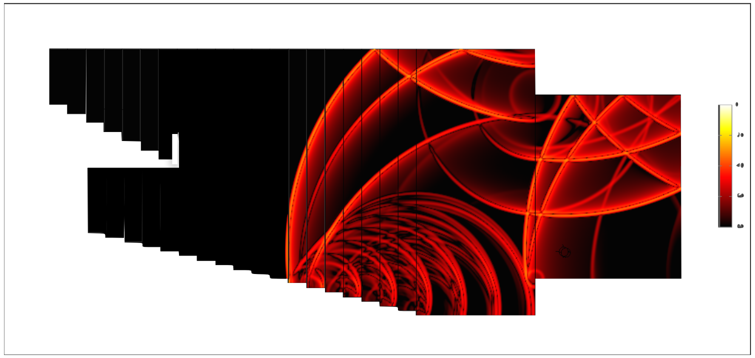


*

*Y. Jing, N. Xiang, On the use of a diffusion equation model for sound energy flow prediction in acoustically coupled spaces, in Proc. of the COMSOL Conference 200,8 Boston

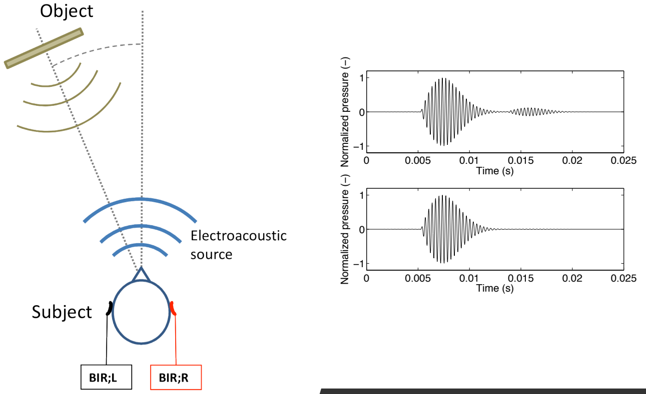
Research agenda

Computational methods

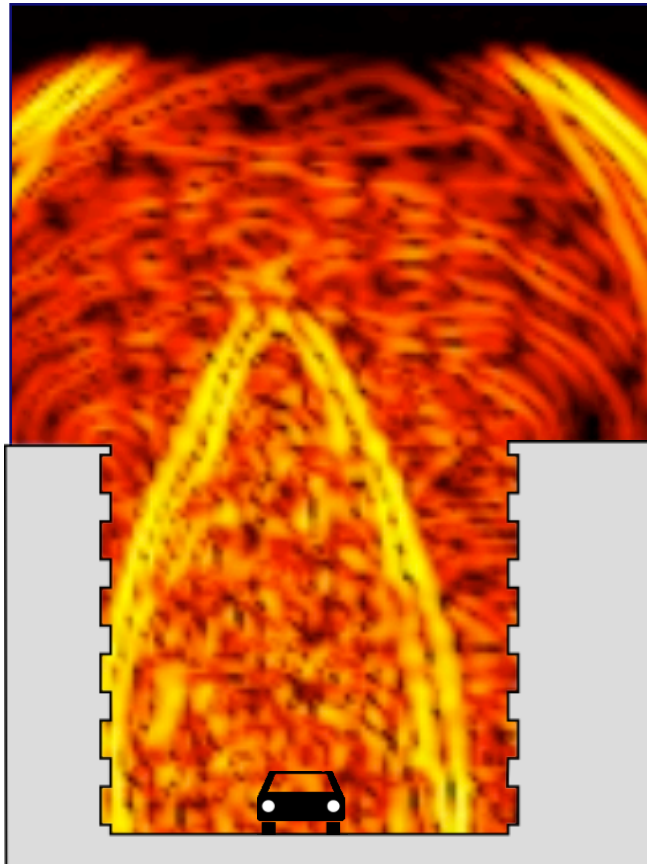


Propagation effects / noise mitigation

Human echolocation / auralization



openPSTD
Marie-Curie CIG grant: 2012-2016

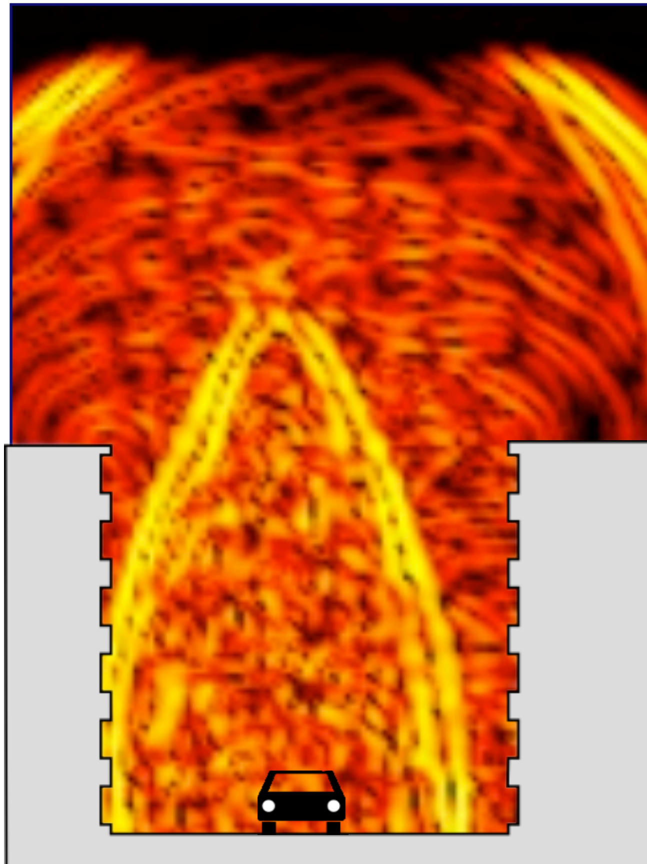


Introduction

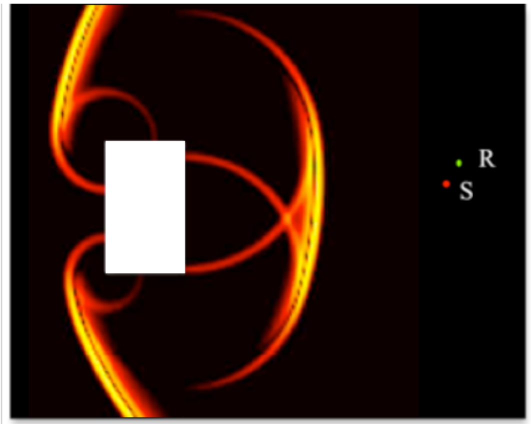
Scope: Modelling of indoor and outdoor acoustic scenarios where wave effects are important

- Meteorological effects
- Complex geometries (including curved surfaces)
- Geometrically shielded environments
- Explicitly modelling of boundary media
- Interference effects (low frequencies)

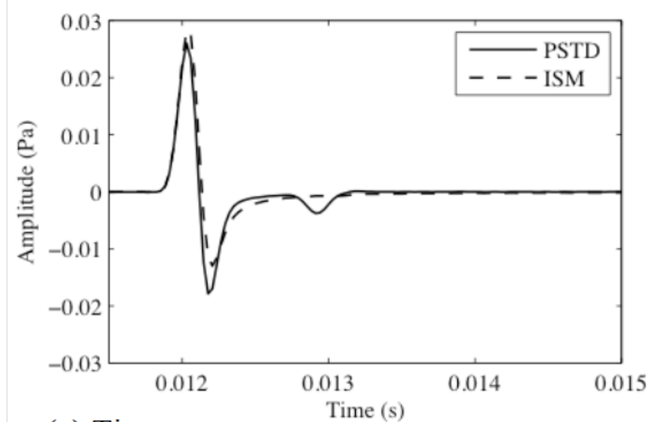
-> Wave-based acoustics



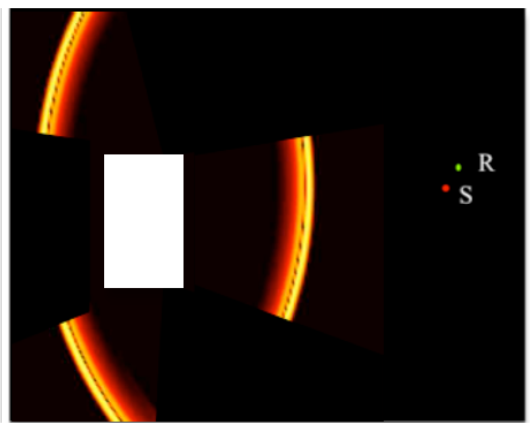
Introduction



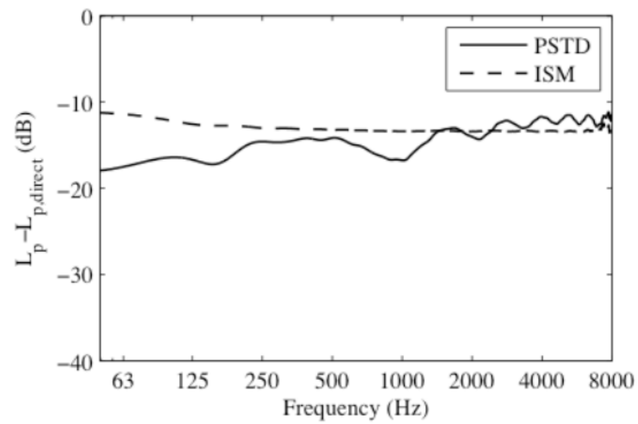
(a) PSTD



(c) Time responses



(b) ISM

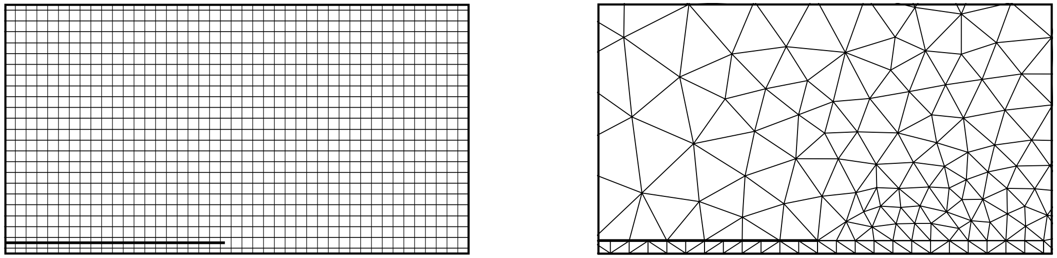


(d) Frequency spectra

Introduction

Solution methods wave-based acoustics (see[1] for references)

- Finite Element Method (mesh (b)) (FEM)
- Discontinuous Galerkin method (mesh (b)) (DG)
- Finite-Difference Time-Domain method (mesh (a)) (FDTD)
- Pseudo-Spectral Time-Domain method (mesh (a)) (PSTD)



(a) (b)

Challenge: efficient wave-based acoustic method

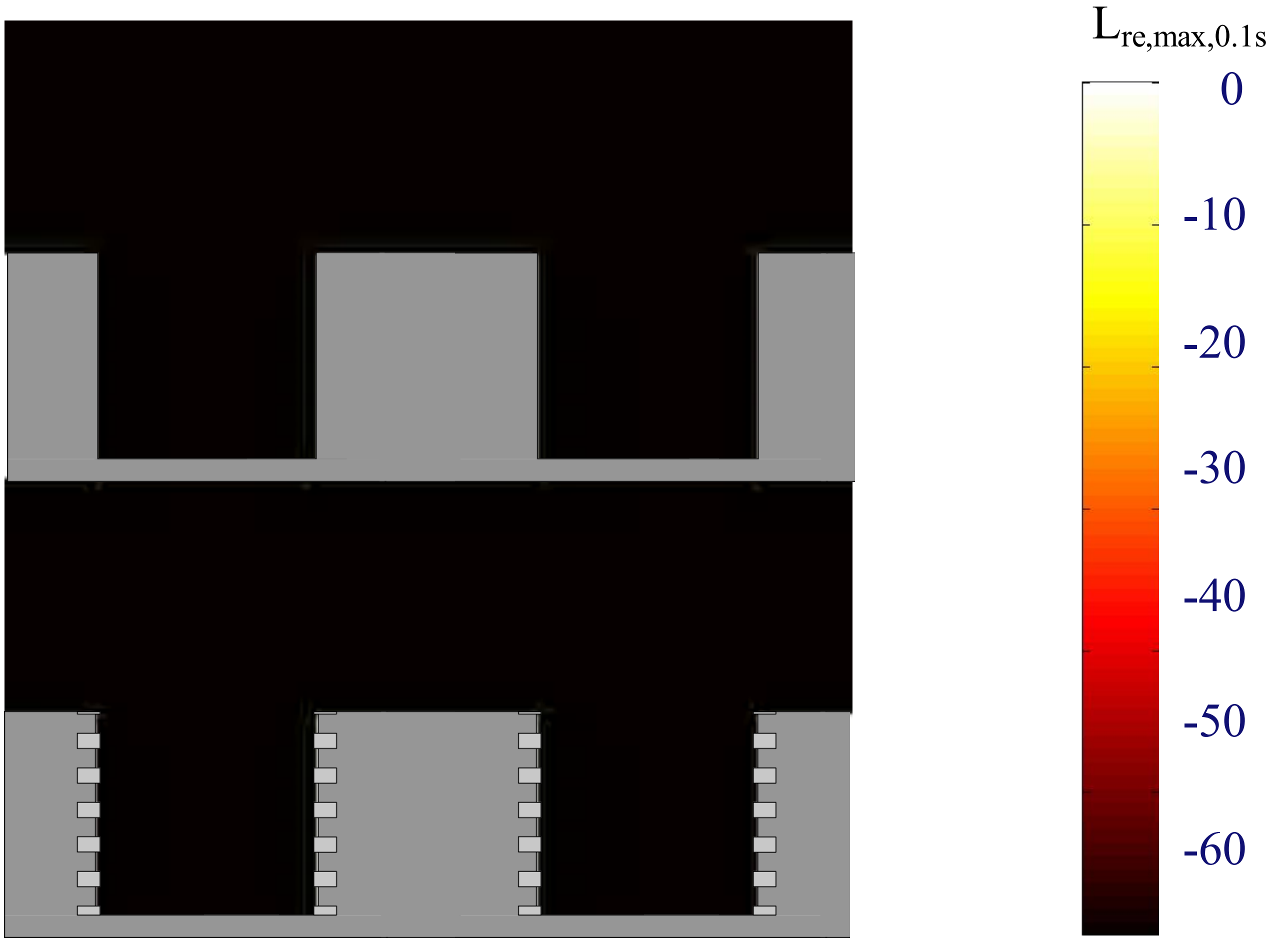
PSTD is most efficient method, but some developments are left to utilize its efficiency for generic situations

[1]Hornikx, M. Numerical modeling of sound propagation to closed urban courtyards. (2009). ISBN 978-91-7385-298-2. Department of Civil and Environmental Engineering, Division of Applied Acoustics, Vibroacoustics Group, Chalmers University of Technology, Sweden.

openPSTD

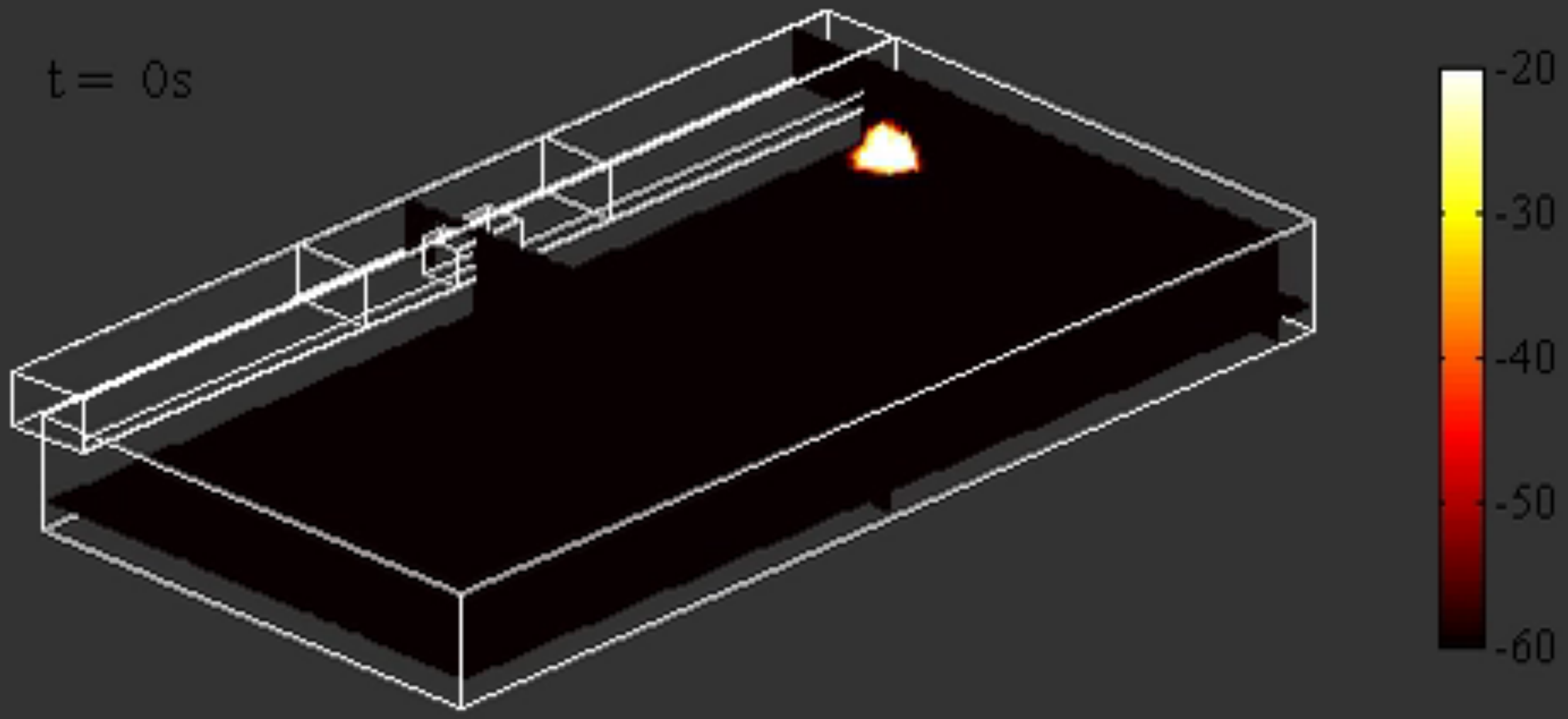
Flat facades

Profiled facades



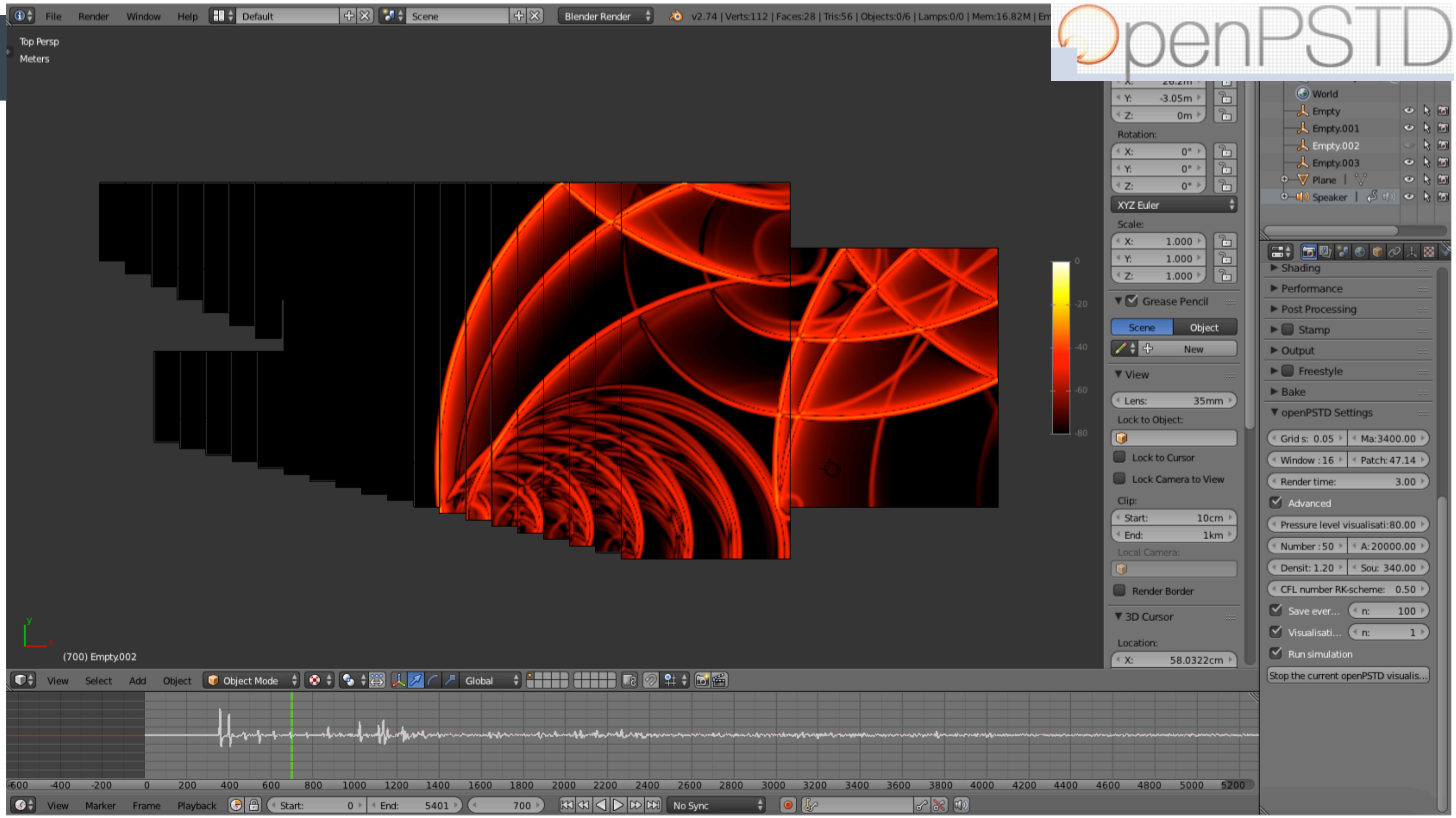
*Hornikx, Numerical modelling of sound propagation to closed urban courtyards. Doctoral thesis, Chalmers Univ. Tech., (2009).

openPSTD



openPSTD

www.openpstd.org



Krijnen, T., Hornikx, M. (2014). openPSTD: the open source implementation of the Pseudo Spectral Time-Domain method, Forum Acusticum, 7-12 September 2014, Krakow, Poland.

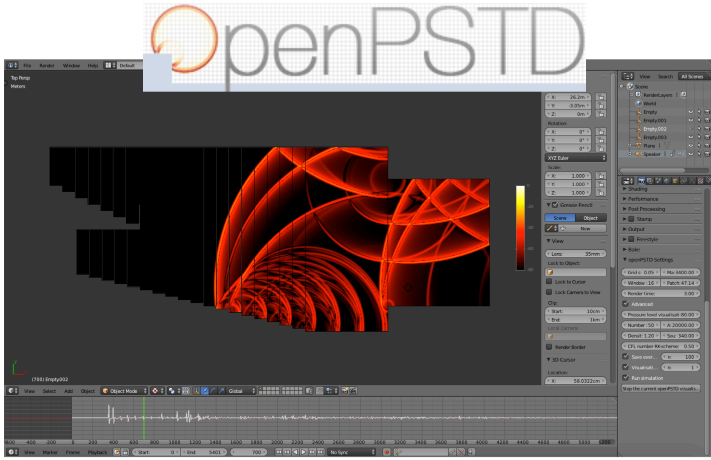
Maarten Hornikx

openPSTD

www.openpstd.org

openPSTD v1.0

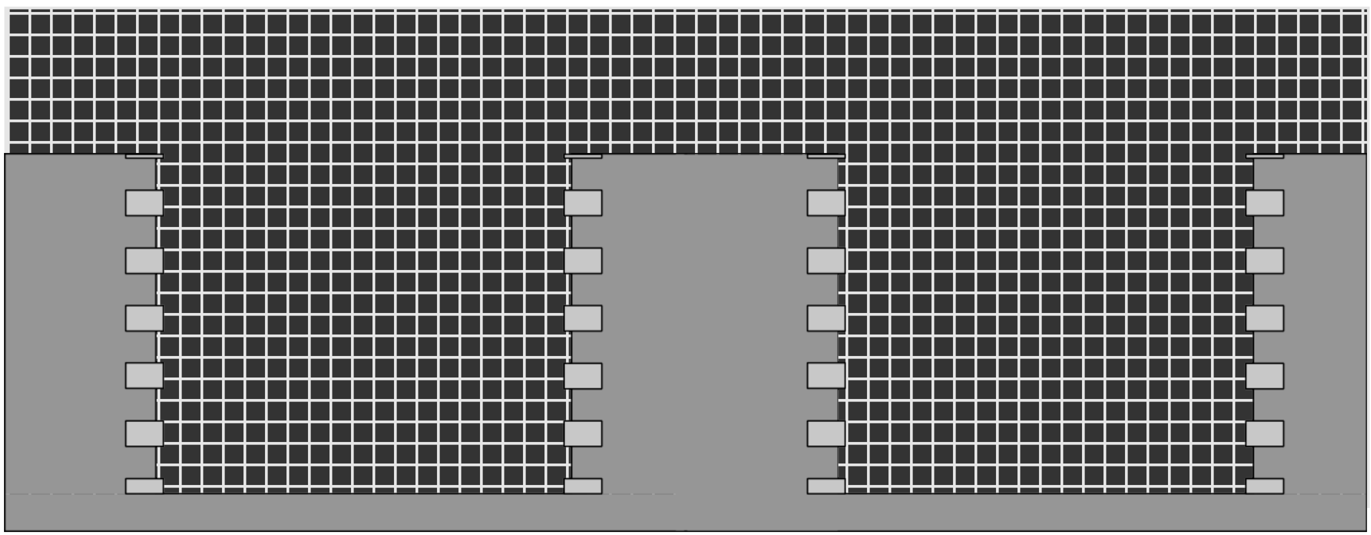
- 2D implementation
- Boundaries with real valued frequency independent impedance values
- Computation of impulse responses
- Postprocessing with program of your choice (Matlab, Python…)
- GPU acceleration



Krijnen, T., Hornikx, M. (2014). openPSTD: the open source implementation of the Pseudo Spectral Time-Domain method, Forum Acusticum, 7-12 September 2014, Krakow, Poland.

PSTD method, mesh

Cartesian grid, solution sought at all grid points



- Example: 3D environment: 180m x 63m x 40m, f_{upper} = 500 Hz
  PSTD: Δx = 0.32 m, around 14•10^6 computational cells
  Compare with
  FDTD: Δx = 0.06 m, around 1.75•10^9 computational cells

PSTD method, time-derivative

- The linearized Euler equations (LEE)

$$\frac{\partial p'}{\partial t} = -\rho_0 c^2 \nabla \boldsymbol{u}' - (\boldsymbol{u_0} \cdot \nabla) p'$$

$$\frac{\partial \boldsymbol{u}'}{\partial t} = -(\boldsymbol{u}' \cdot \nabla)\boldsymbol{u_0} - (\boldsymbol{u_0} \cdot \nabla)\boldsymbol{u}' - \frac{1}{\rho_0}\nabla p'$$

$$\frac{\partial \boldsymbol{q}'}{\partial t} = -L\boldsymbol{q}'$$

$$\boldsymbol{q}' = \left[p' \; u_x' \; u_y' \; u_z' \right]^T$$

- Time-derivative with explicit low-storage 6-stage Runge-Kutta (RKo6s) method*

$$\boldsymbol{q}'(\boldsymbol{x}, t_0) = \boldsymbol{q}'(\boldsymbol{x}, t)$$

$$\boldsymbol{q}'(\boldsymbol{x}, t_i) \approx \boldsymbol{q}'(\boldsymbol{x}, t_0) - \gamma_i \Delta t \left(L\boldsymbol{q}'(\boldsymbol{x}, t_{i-1}) \right)$$

$$for \quad i = 1 \ldots 6,$$

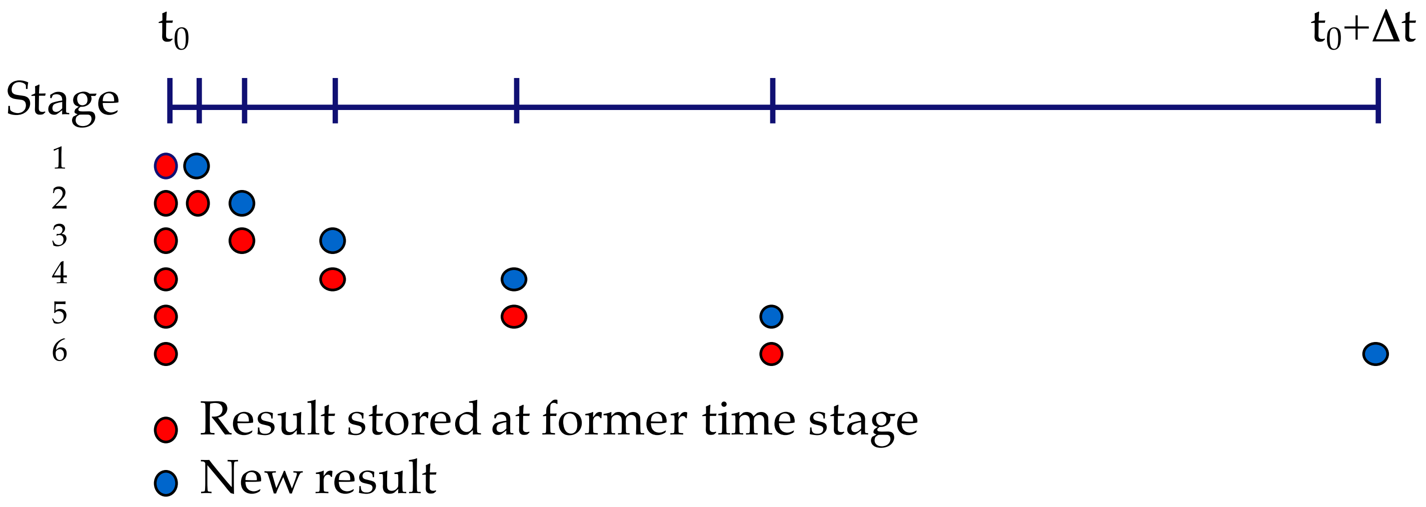
$$\boldsymbol{q}'(\boldsymbol{x}, t + \Delta t) \approx \boldsymbol{q}'(\boldsymbol{x}, t_6)$$

*Bogey, C., Bailly, C., A family of low dispersive and low dissipative explicit schemes for flow and noise computation," J. Comput. Phys. 194, 194–214 (2004).

PSTD method, time-derivative

- Time-derivative with Runge-Kutta (RKo6s) method*
- Explicit -> no matrix inversion

  Efficient but more sensitive to stability then implicit schemes
- Multistage method (6 stages), but low storage capacity: only 2 former stage needs to be stored



*Bogey, C., Bailly, C., A family of low dispersive and low dissipative explicit schemes for flow and noise computation," J. Comput. Phys. 194, 194–214 (2004).

Developments

PSTD method, spatial derivatives

- The linearized Euler equations (LEE)

$$\frac{\partial p'}{\partial t} = -\rho_0 c^2 \nabla \boldsymbol{u}' - \left(\boldsymbol{u_0} \cdot \nabla\right) p'$$

$$\frac{\partial \boldsymbol{u}'}{\partial t} = -\left(\boldsymbol{u}' \cdot \nabla\right)\boldsymbol{u_0} - \left(\boldsymbol{u_0} \cdot \nabla\right)\boldsymbol{u}' - \frac{1}{\rho_0}\nabla p'$$

$$\frac{\partial \boldsymbol{q}'}{\partial t} = -L\boldsymbol{q}'$$

$$\boldsymbol{q}' = \left[p' \; u'_x \; u'_y \; u'_z\right]^T$$

- Extended Fourier pseudospectral method* to solve $L\boldsymbol{q}'$

*Hornikx, M., Waxler, R., Forssén, J., (2010). The extended Fourier pseudospectral time-domain method for atmospheric sound propagation, J. Acoust. Soc. Am., 128(4), 1632-1646.

PSTD method, spatial derivatives

- Example for *dp*/*dx* (1D Fourier transforms)

$$\left.\frac{\partial p}{\partial x}\right|_{n\Delta x} = F_x^{-1}\left(jk_x F_x\left[p\right]\right)$$

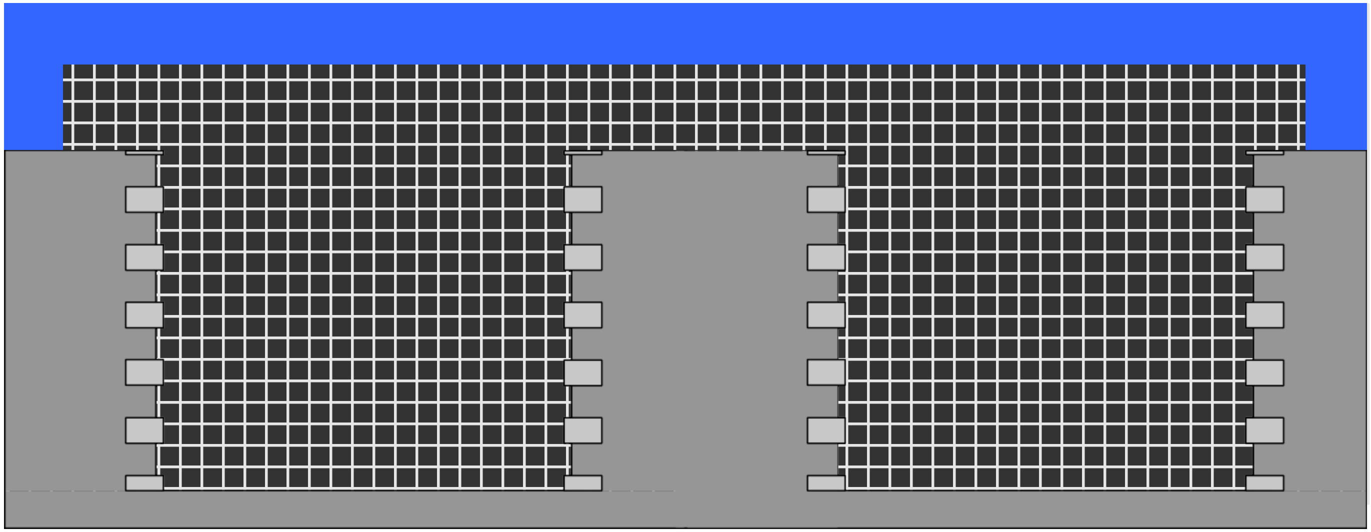
Consequences of PSTD method

- Acoustic variables should spatially be periodic
- Spectral accuracy down to 2 spatial points (Δx) per wavelength

Hornikx, M., Waxler, R., Forssén, J., (2010). The extended Fourier pseudospectral time-domain method for atmospheric sound propagation, J. Acoust. Soc. Am., 128(4), 1632-1646.

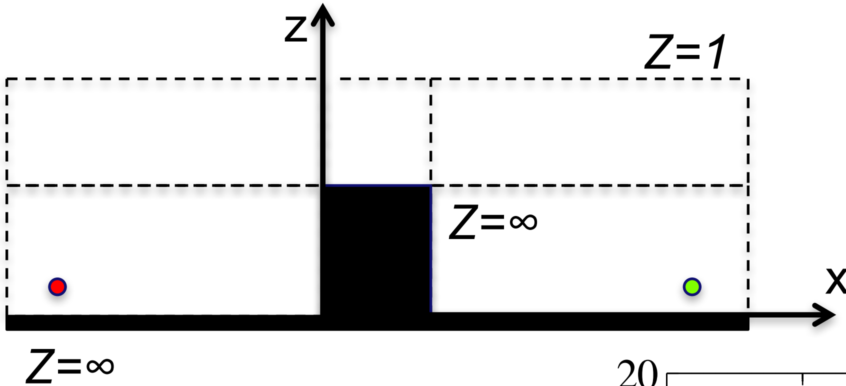
PSTD method, mesh

- Non-reflecting boundaries modelled by an absorbing layer (PML)
- Materials modelled by a media with different densities
- Acoustic source (initial values or source function) and receiver positions assigned

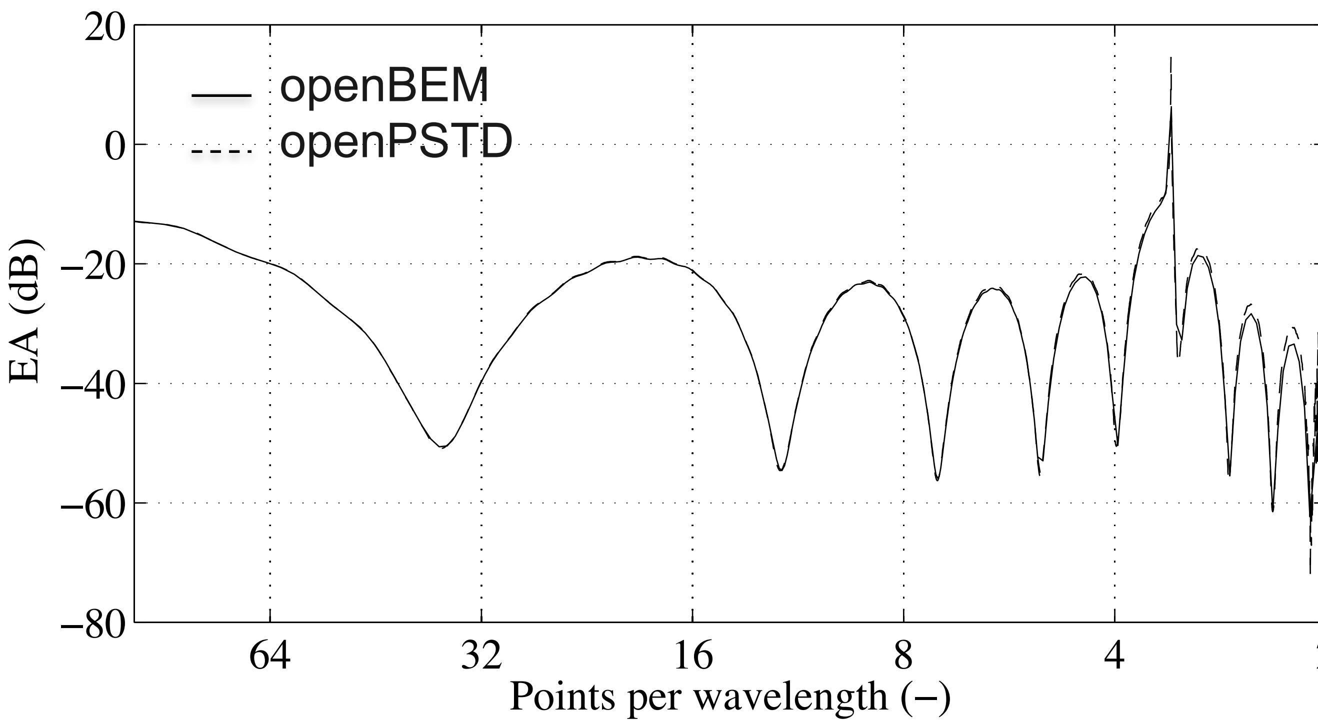


Developments

Subdomains



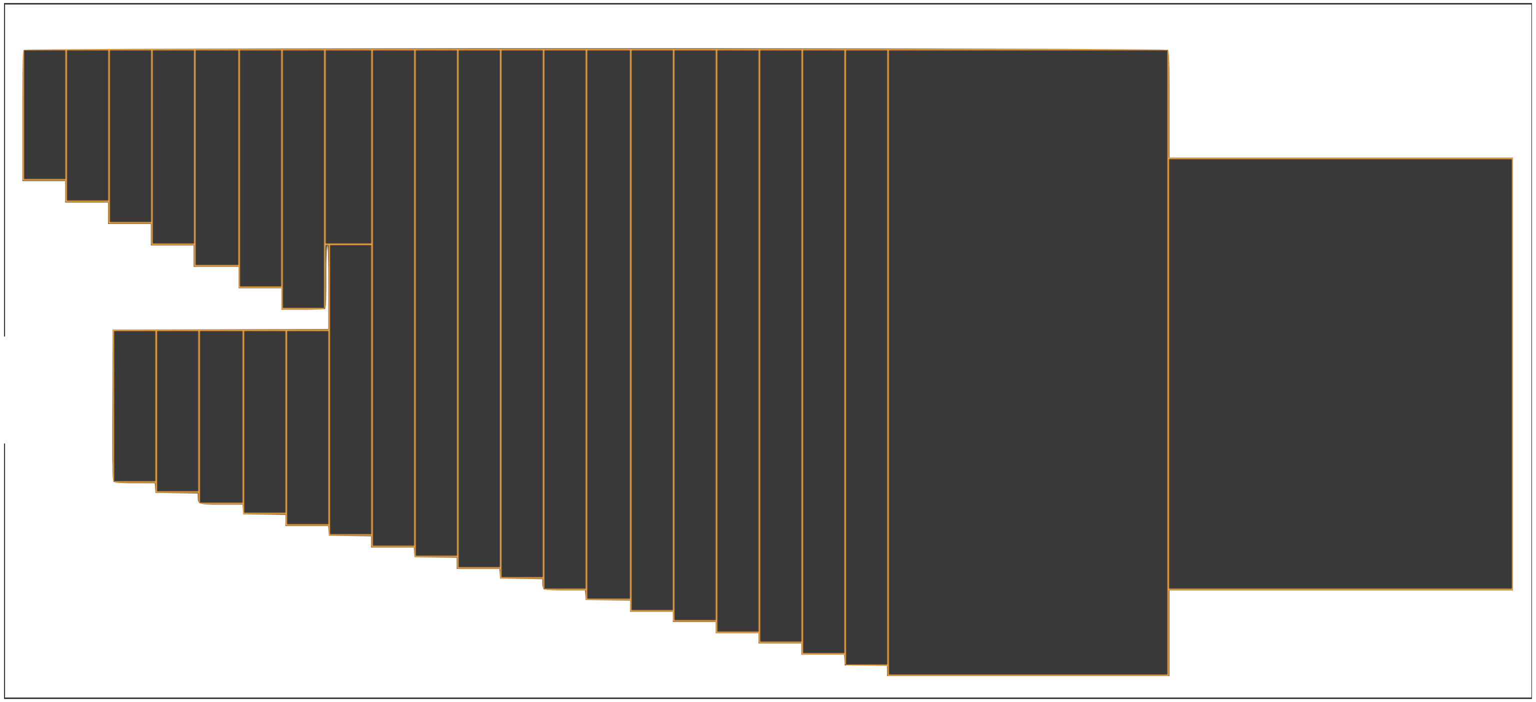
(x_{source},z_{source}) = (-10 m, 1 m)
(x_{rec},z_{rec}) = (14 m, 1 m)
Barrier, 4 m wide, 5 m tall



Hornikx, M., Krijnen, T., van Harten, L. (2015). openPSTD: the open source pseudospectral time-domain method for acoustic propagation, Computer Phsysics Communications. Manuscript in progress for submission

Subdomains

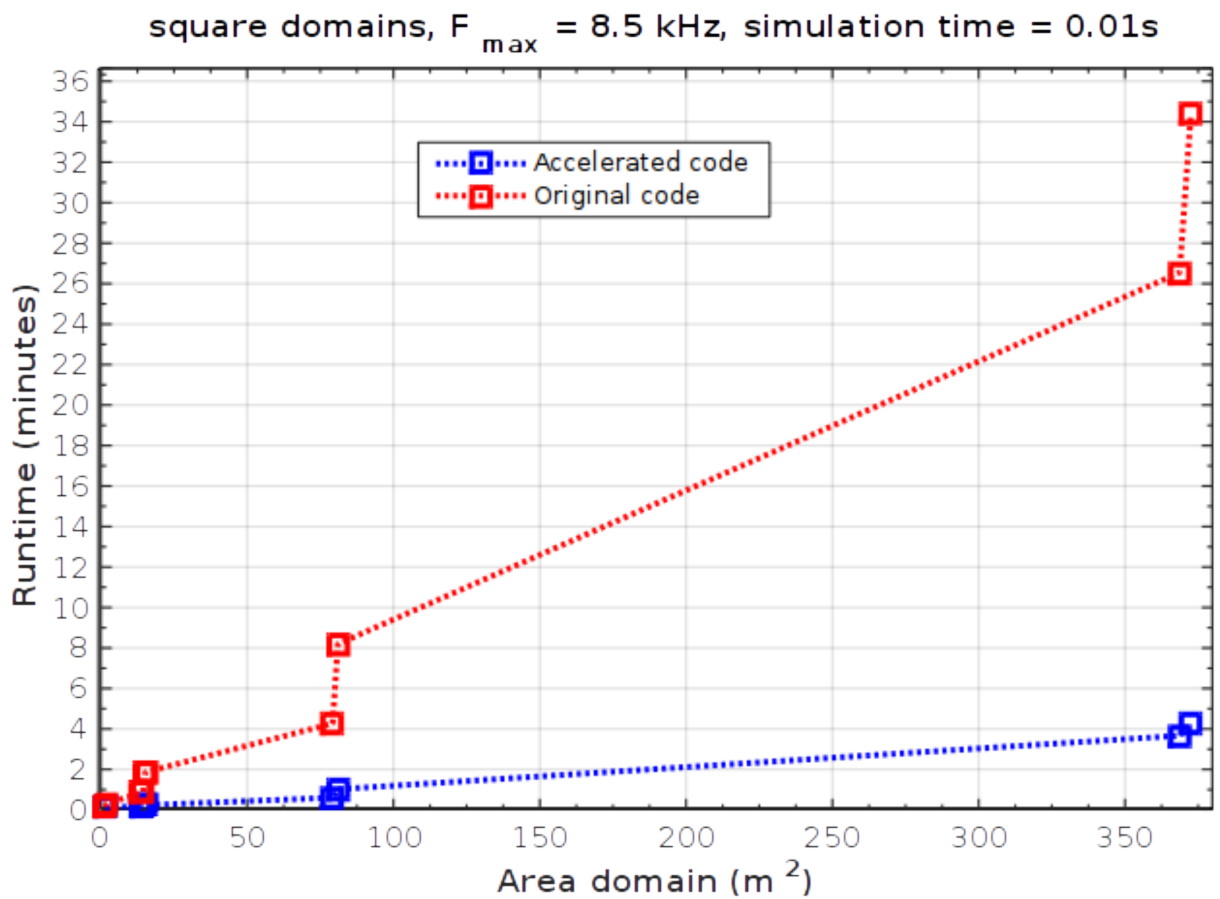
Domain decomposition



GPU acceleration

Developments

GPU acceleration

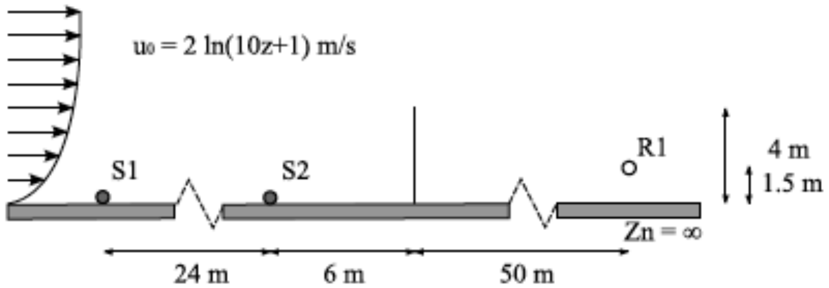


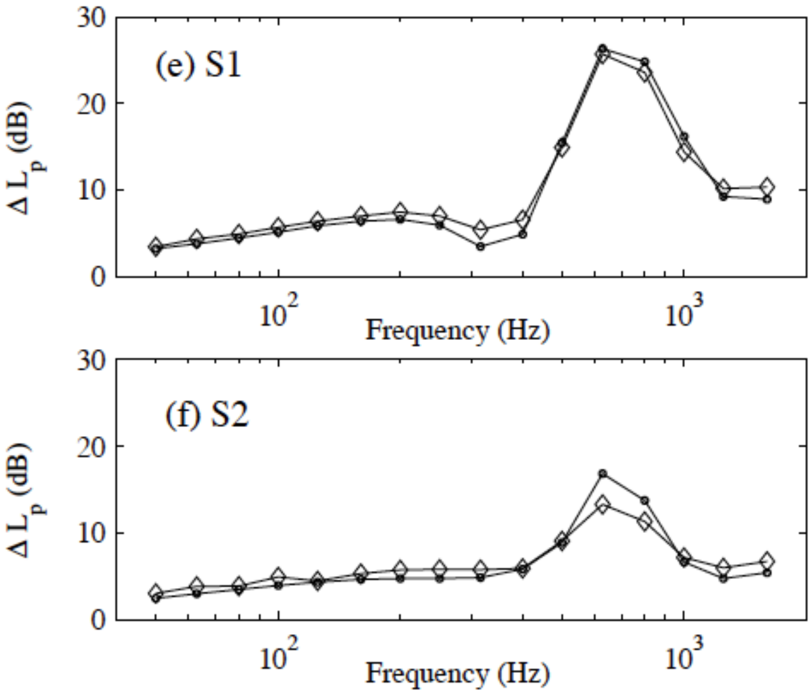
Louis van Harten

Developments

Boundaries and inhomogeneous moving medium

- Downward refraction due to wind or temperature gradients



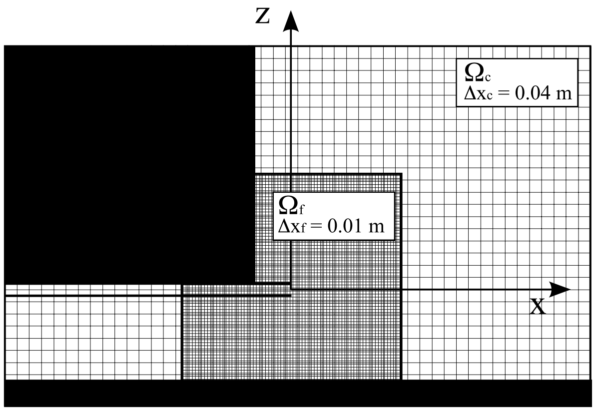


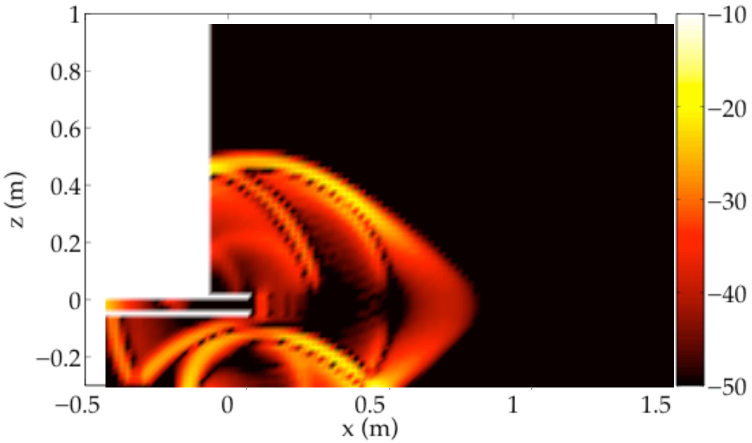
Diamonds: PE method;
Open circles: extended Fourier PSTD method

Hornikx, M., Waxler, R., Forssén, J., (2010). The extended Fourier pseudospectral time-domain method for atmospheric sound propagation, J. Acoust. Soc. Am., **128**(4), 1632-1646.

Developments

Local grid refinement



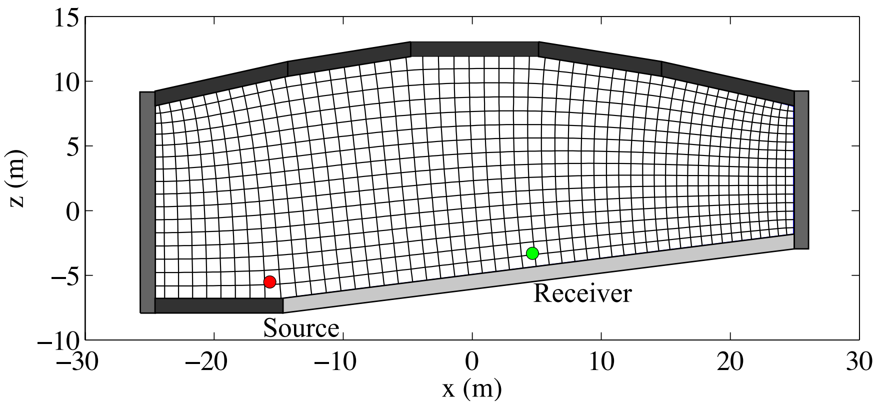


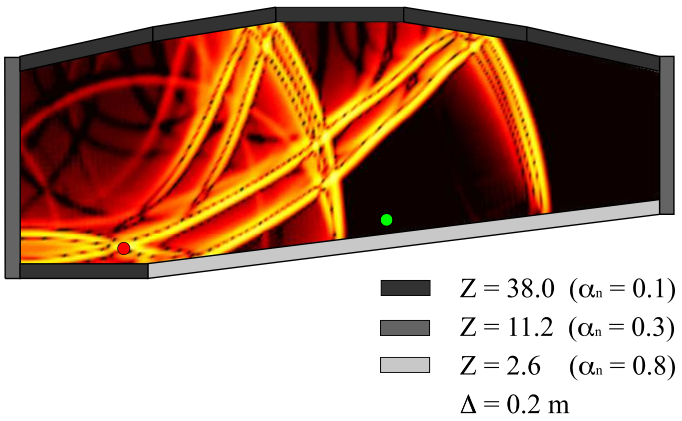
Hornikx, M., De Roeck, W., Desmet, W. (2012). A multi-domain Fourier pseudospectral time-domain method for the linearized Euler equations. J. Comp. Phys., **231**(14), 4759-4774.

Hornikx, M., De Roeck, W., Toulorge, T., Desmet, W. (2015). Flow and geometrical effects on radiated noise from exhaust pipes computed by the Fourier pseudospectral time-domain method, Computers and Fluids, 116, 176-191.

Developments

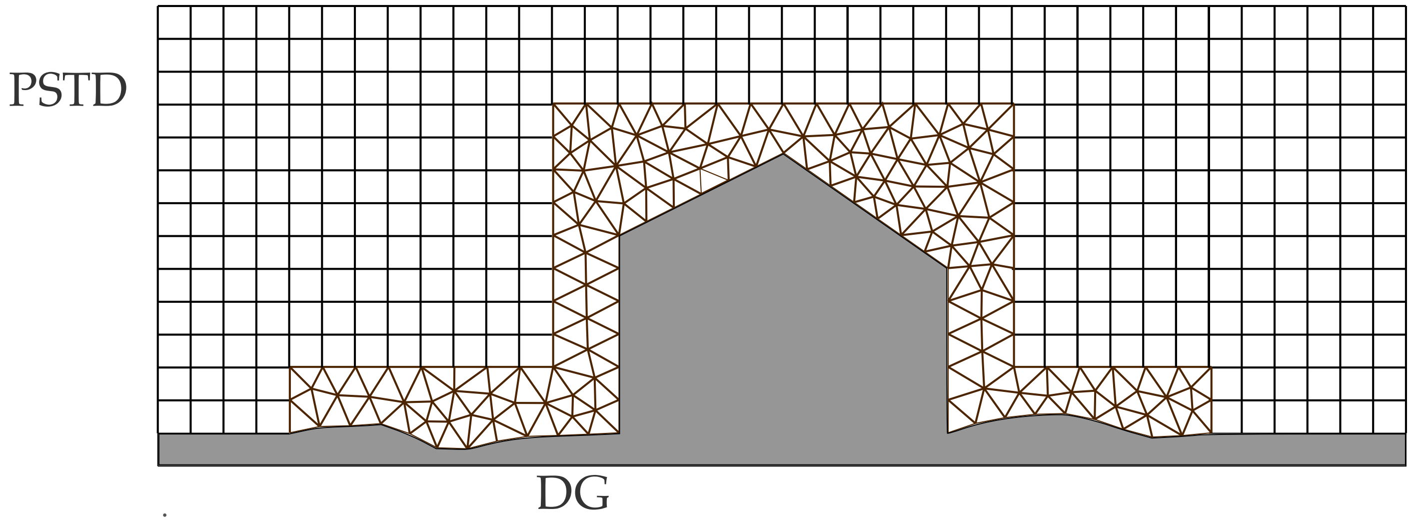
Curvilinear implementation





Hornikx, M., Dragna, D. (2015). Application of the Fourier pseudo spectral time-domain method in orthogonal curvilinear coordinates for near-rigid moderately curved surfaces, J. Acoust. Soc. Am. 138(1).

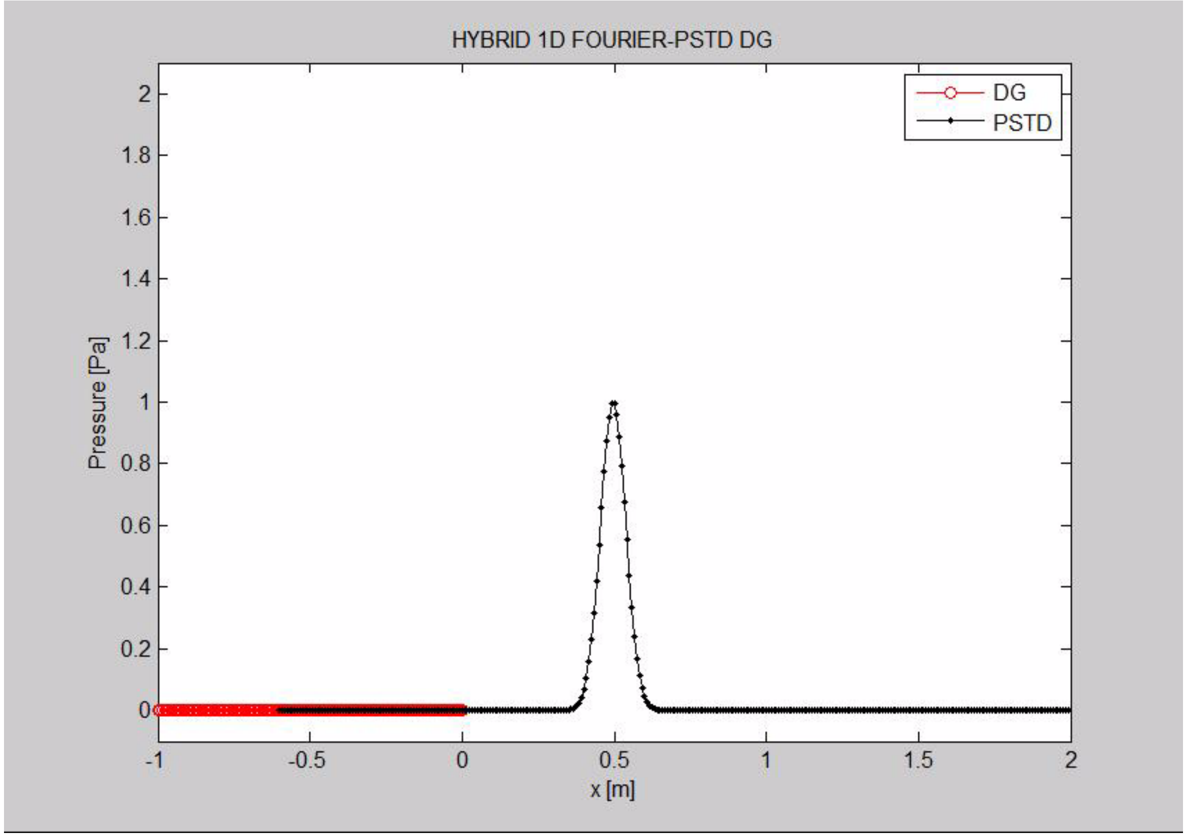
Hybrid method



R. Pagan, M. Hornikx, A hybrid PSTD/DG method to solve the linearized Euler equations, Euronoise 2015.

Hybrid method

1D hybrid Fourier-PSTD and Discontinuous Galerkin implementation

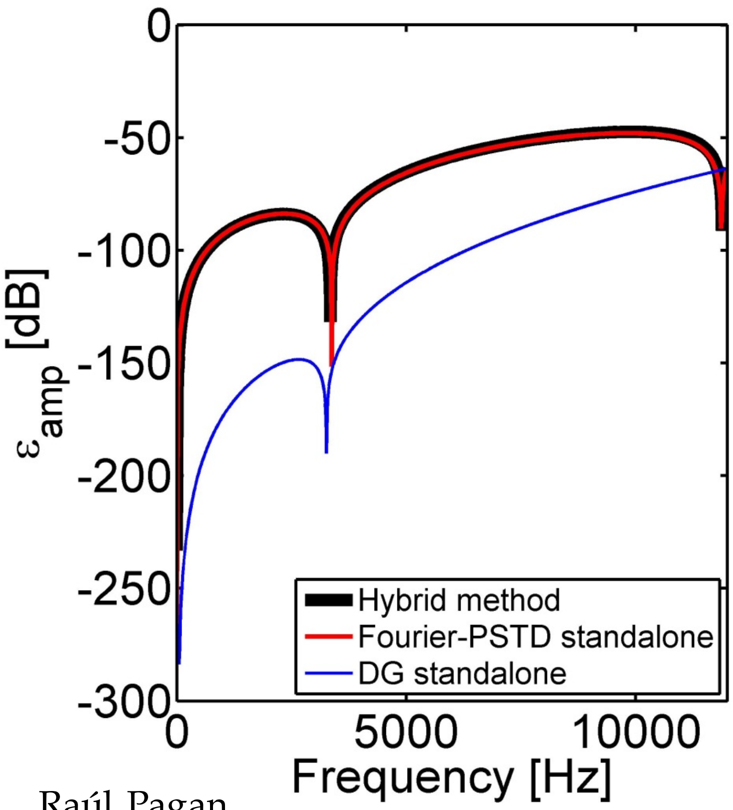


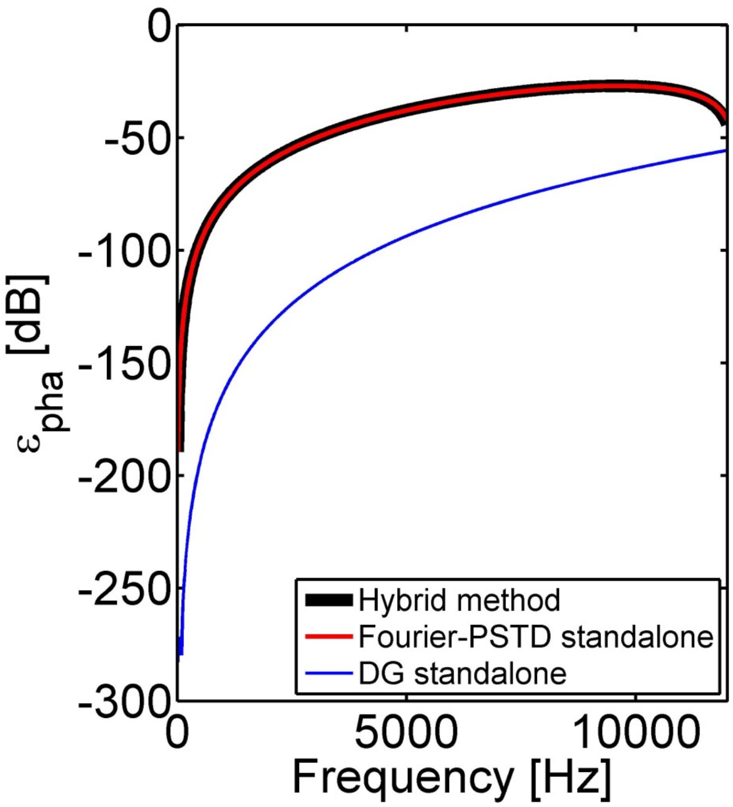
Raúl Pagan

R. Pagan, M. Hornikx, A hybrid PSTD/DG method to solve the linearized Euler equations, Euronoise 2015.

Hybrid method

Errors analysis hybrid PSTD-DG method





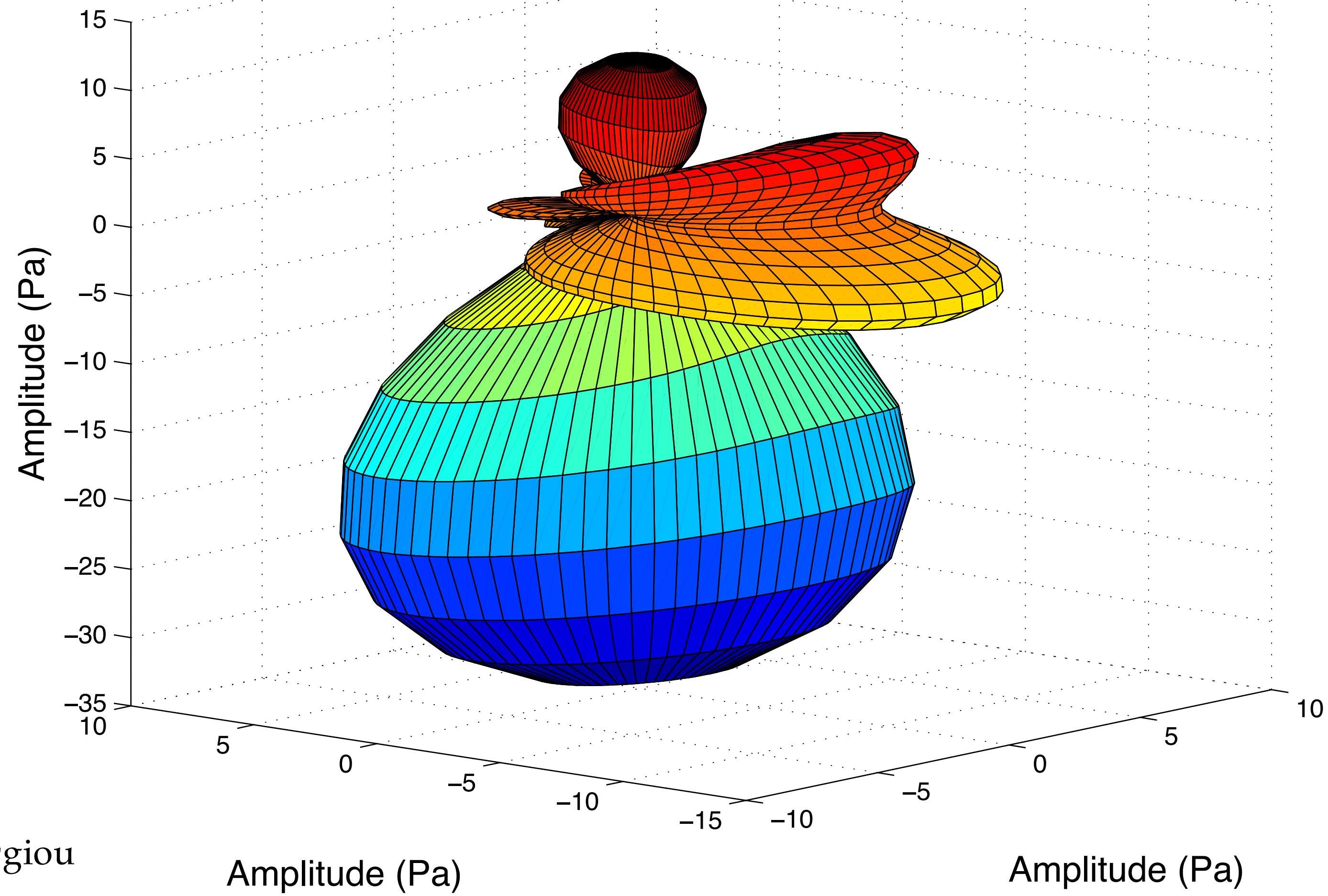
Raúl Pagan

R. Pagan, M. Hornikx, A hybrid PSTD/DG method to solve the linearized Euler equations, Euronoise 2015.

Developments

Source directivity method

63 Hz octave band

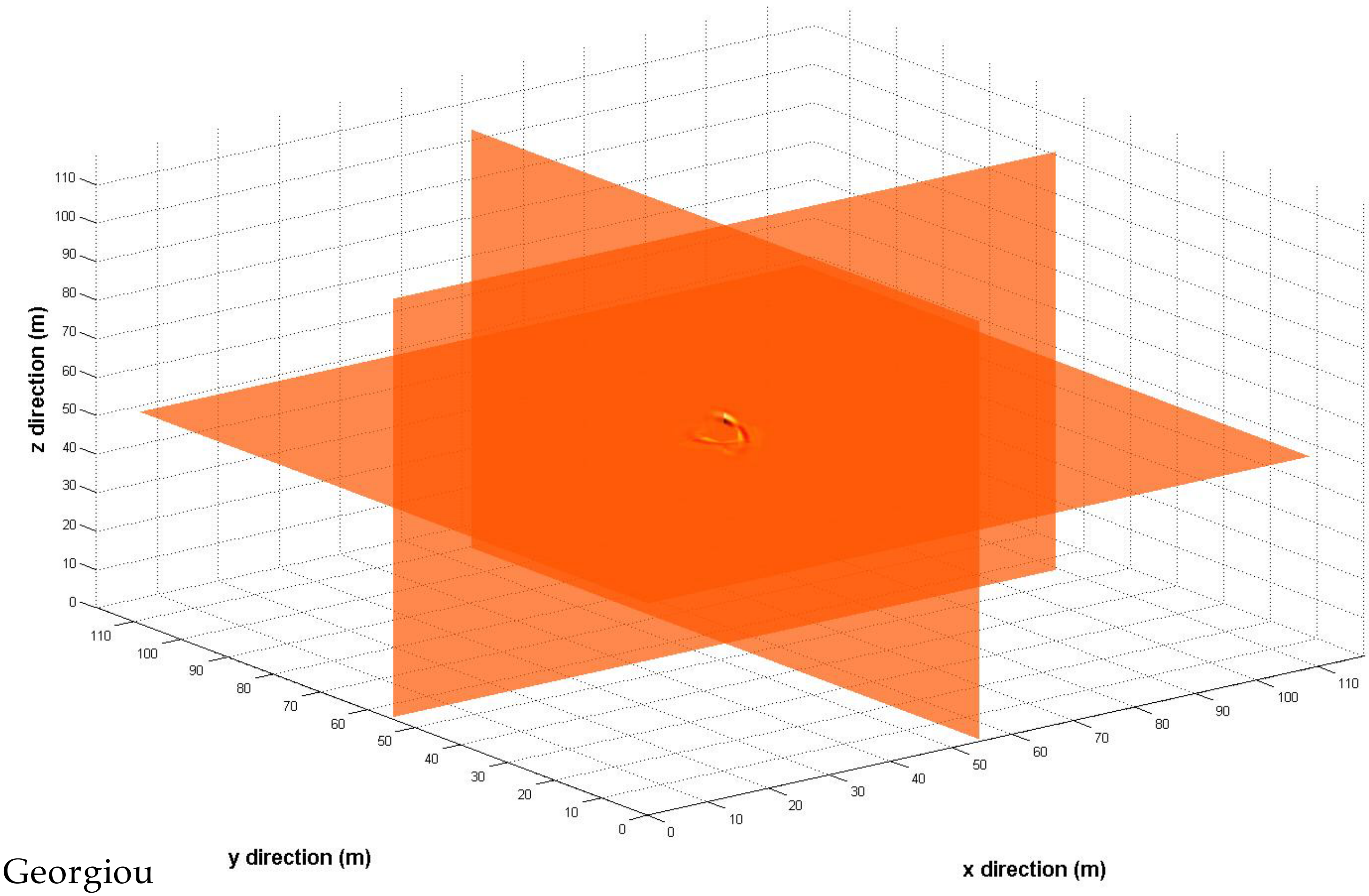


Fotis Georgiou

Georgiou, F., Hornikx, M. (2014). Incorporating source directivity in the Pseudospectral time-domain method by using spherical harmonics. , J. Acoust. Soc. Am., Manuscript in preparation for submission.

Developments

Source directivity method



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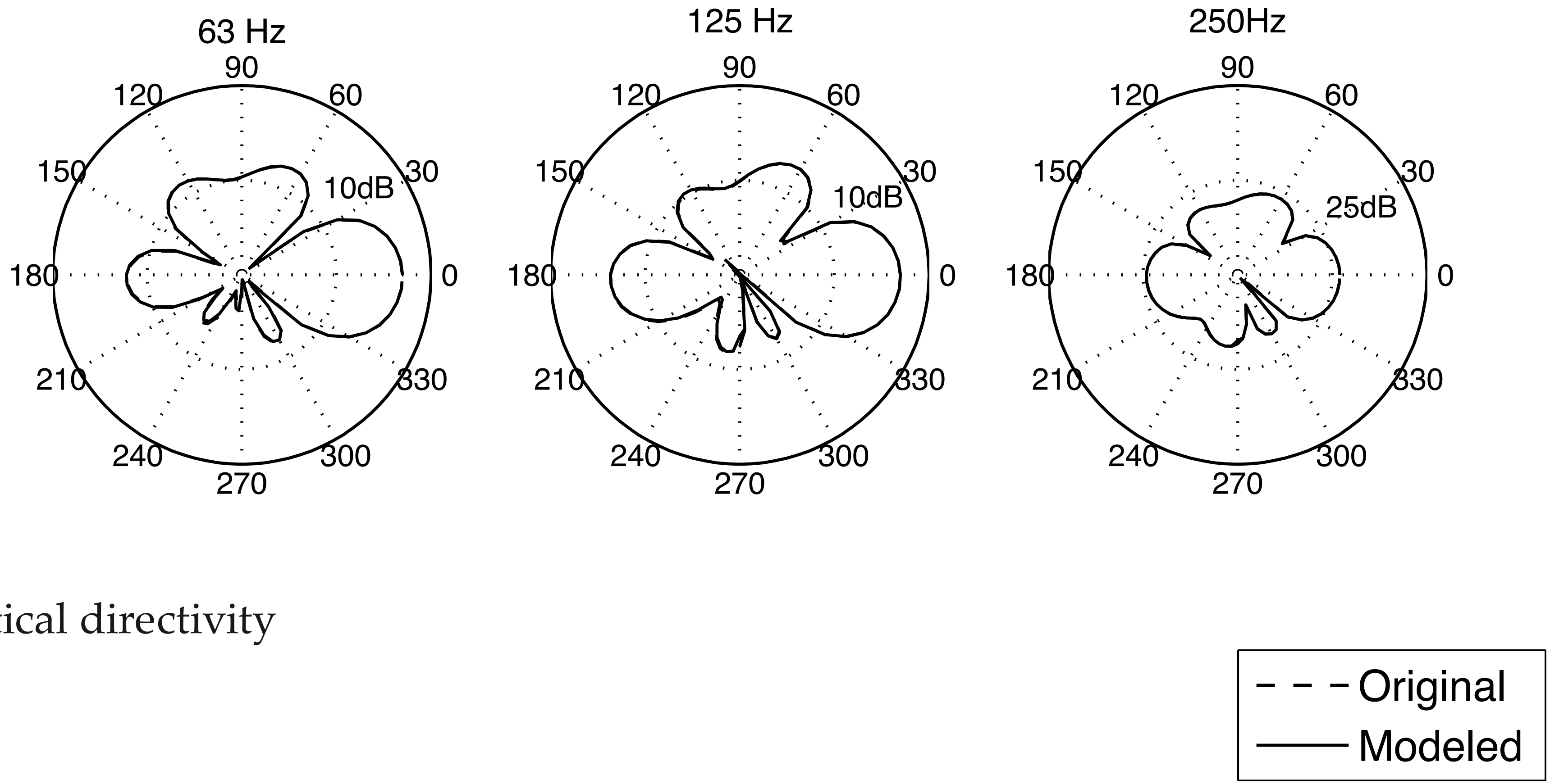
Developments

Source directivity method



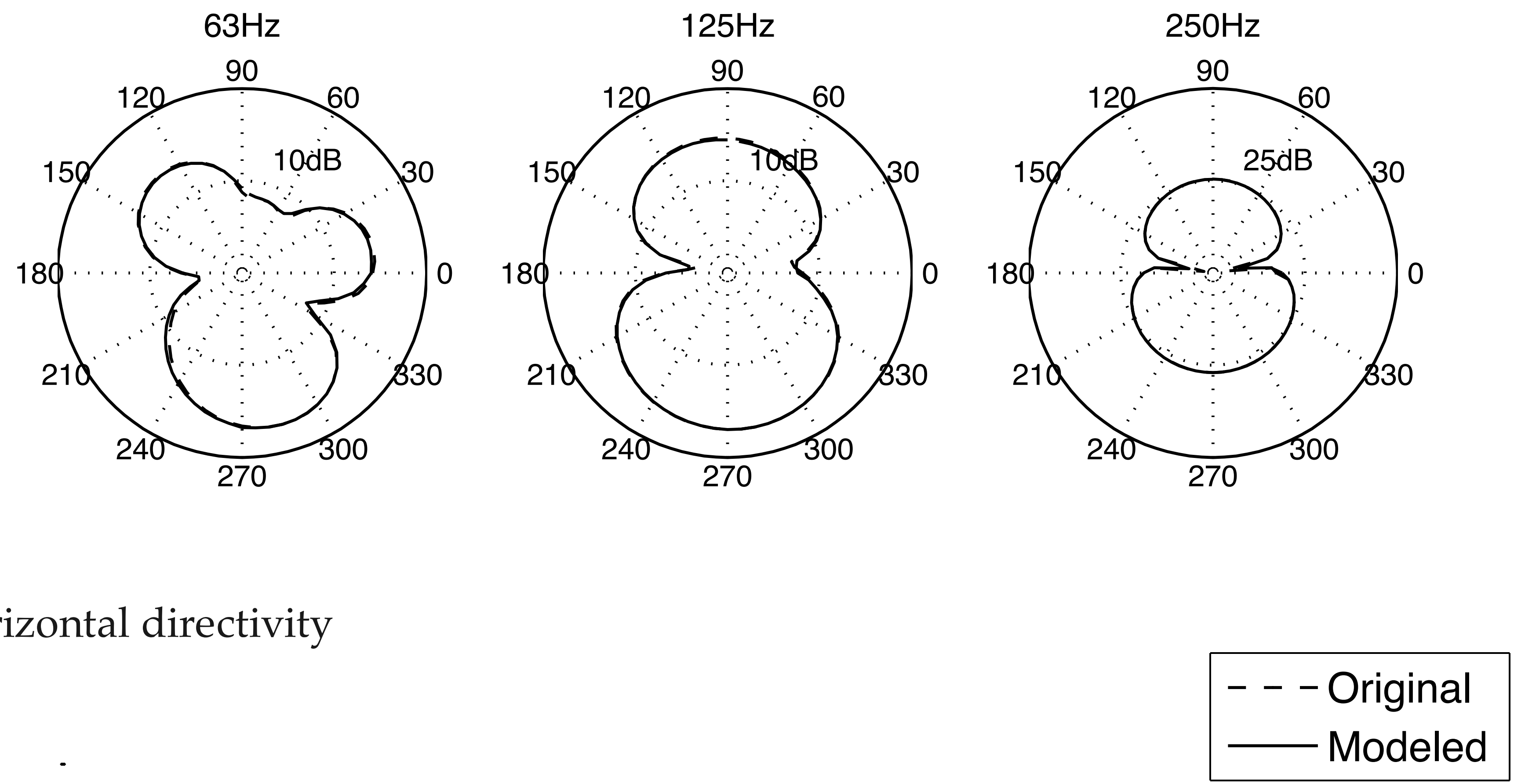
Vertical directivity

Fotis Georgiou

Georgiou, F., Hornikx, M. (2014). Incorporating source directivity in the Pseudospectral time-domain method by using spherical harmonics. , J. Acoust. Soc. Am., Manuscript in preparation for submission.

Developments

Source directivity method



Horizontal directivity

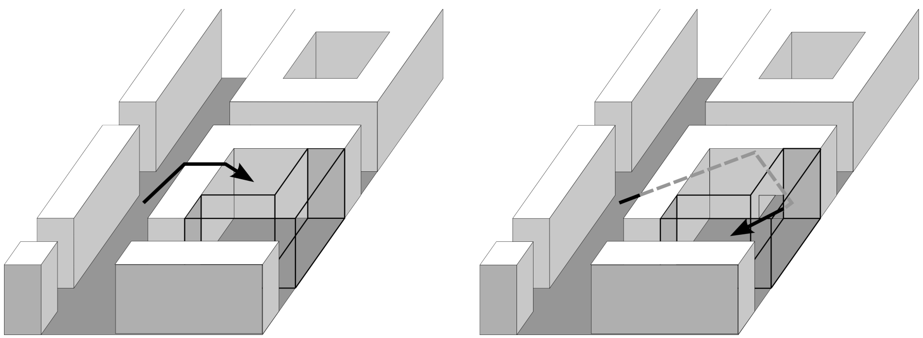
-

Fotis Georgiou

Georgiou, F., Hornikx, M. (2014). Incorporating source directivity in the Pseudospectral time-domain method by using spherical harmonics. , J. Acoust. Soc. Am., Manuscript in preparation for submission.

3D urban environments

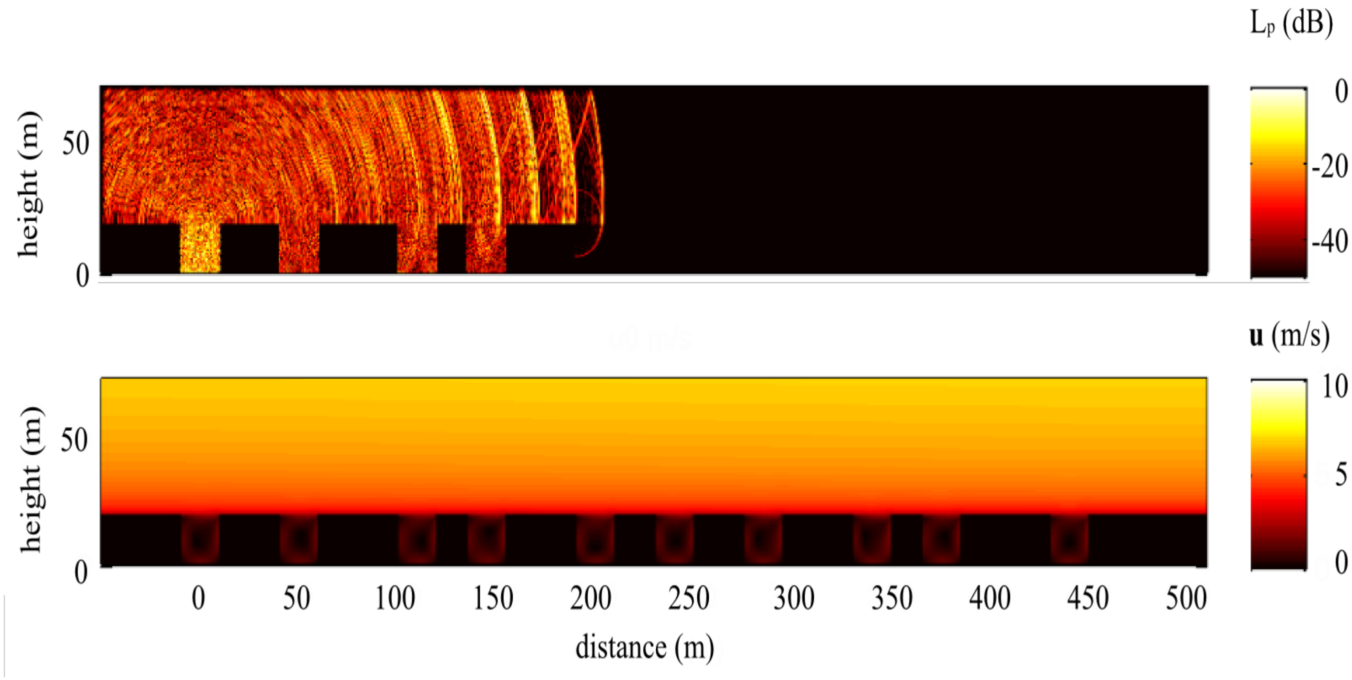
Openings to courtyards



Hornikx, M. Forssen, J. (2011). Modelling of sound propagation to three-dimensional urban courtyards using the extended Fourier PSTD method. Applied Acoustics, 72, 665-676.

Applications

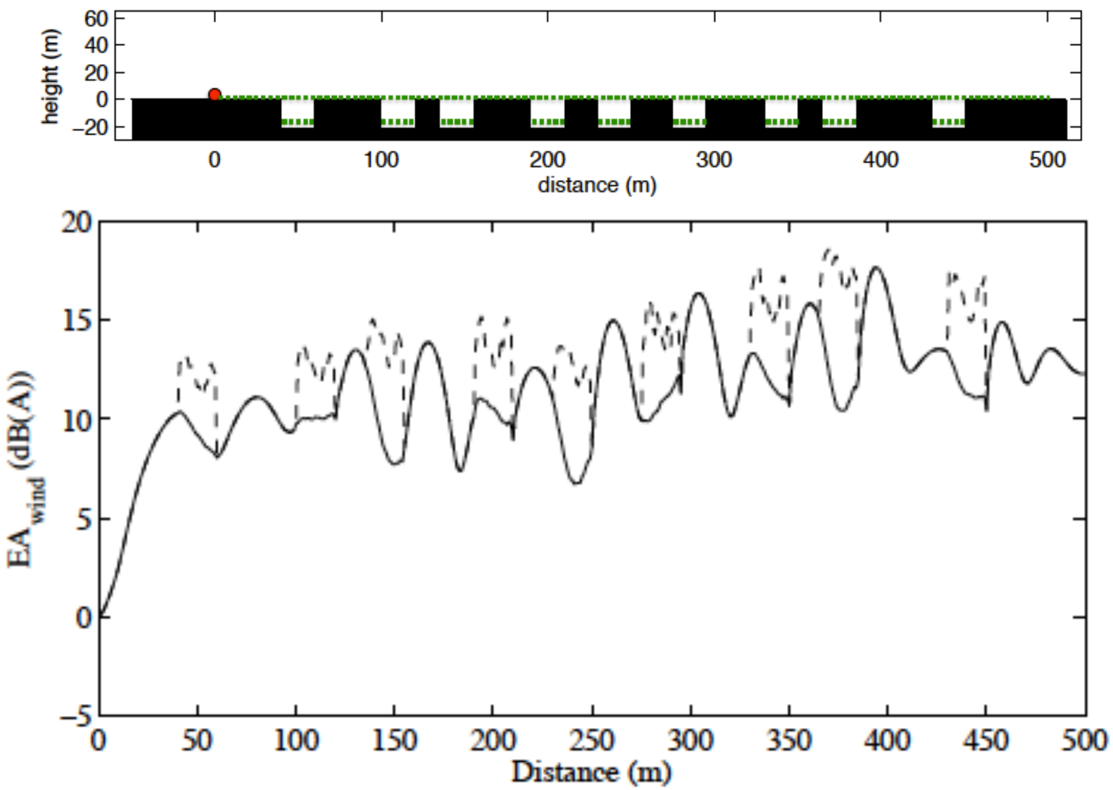
Urban topology and wind



Karin Conen

Hornikx, M., Conen, K., van Hooff, T., Blocken, B., (2013). The influence of the urban flow field modelling approach on computing sound propagation over the urban roof level. AIA-DAGA 2013 Conference on Acoustics, 18-21 March, Merano,

Urban topology and wind



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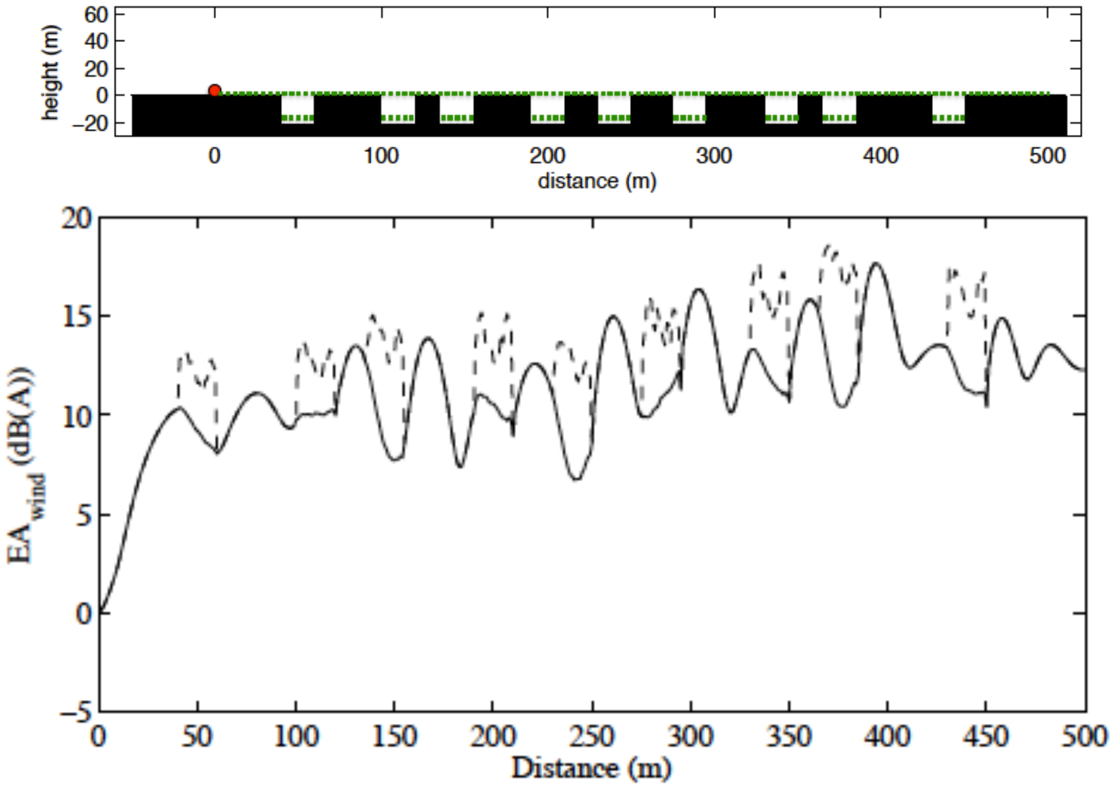

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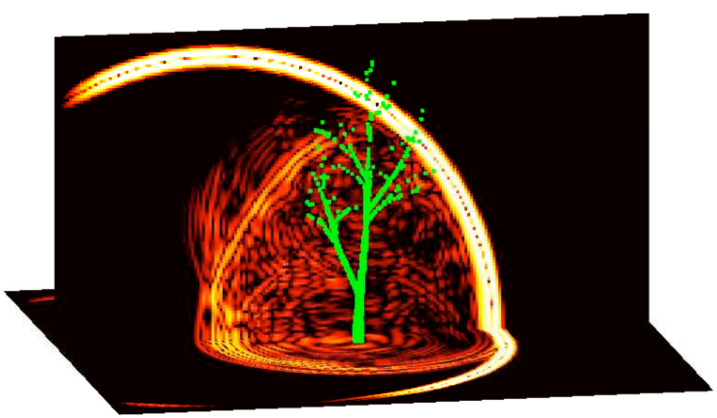
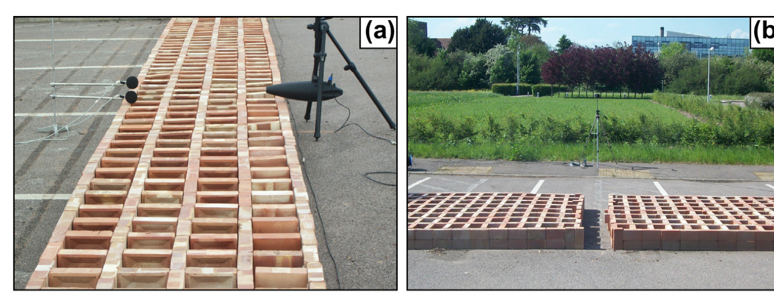
Urban noise mitigation

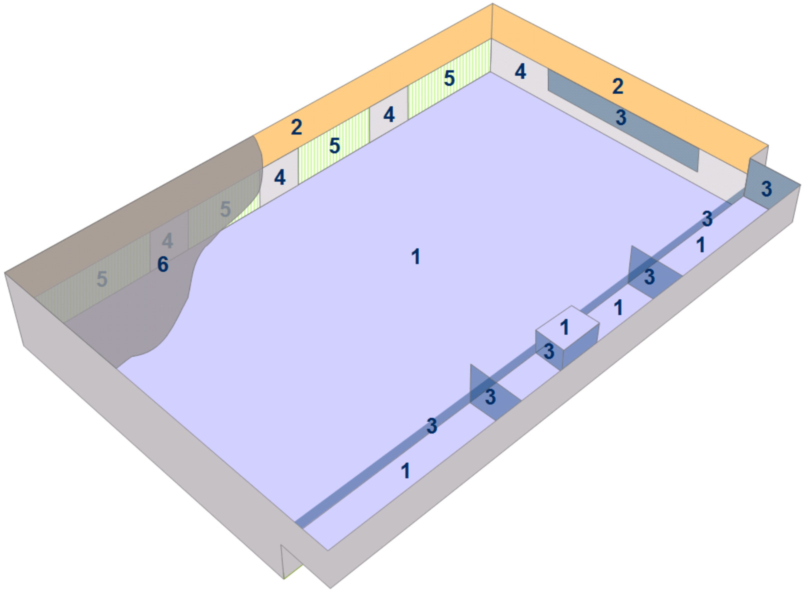
- Green facades
- Green roofs
- Low height green barrier
- Trees
- Ground roughness





References at www.openpstd.org/PSTD%20applications.html

Sports hall



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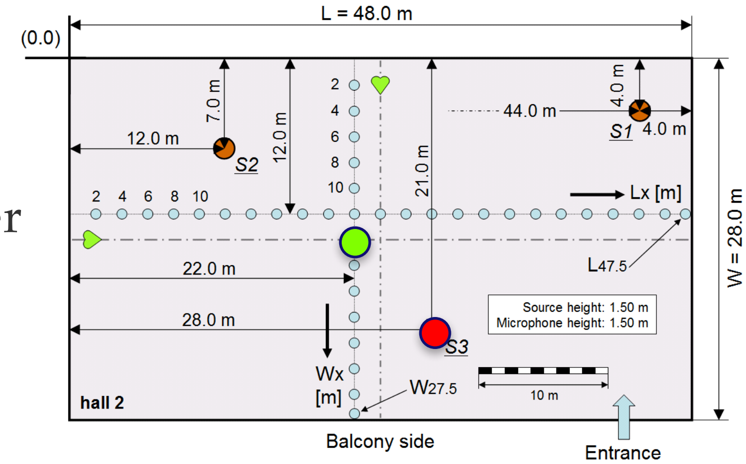
Applications

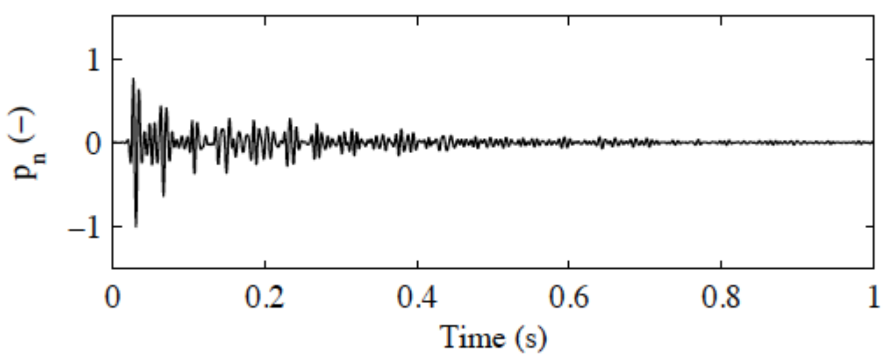
Sports hall

Receiver

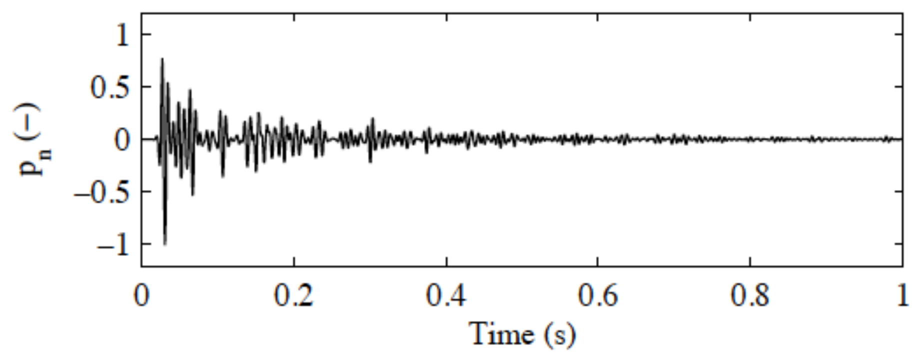
Source



PSTD



Measured



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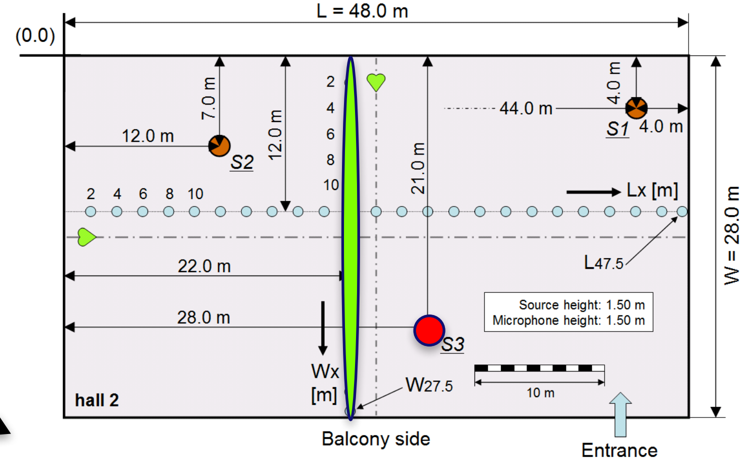
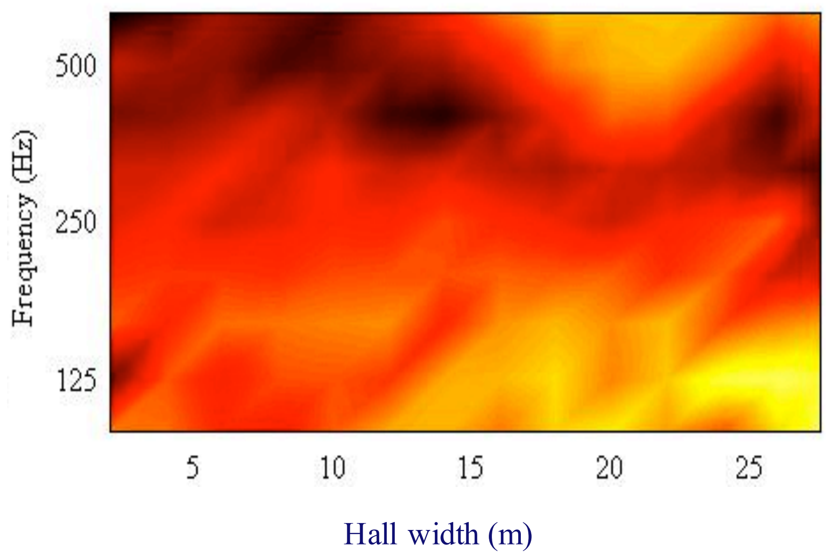
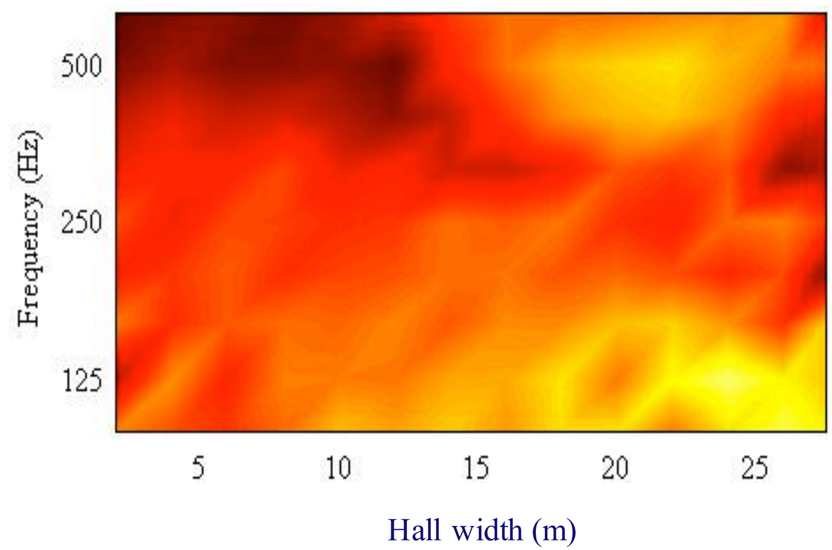
Sports hall

Sports hall

- Measured
- PSTD







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openPSTD

- New User Interface
- Implementation of recent developments
  - 3D implementation
  - Grid refinement
  - Meteorological effects
  - Source directivity
- Code Efficiency
  - Parts of code in C++
  - Including combined CPU/GPU acceleration

Developments and Applications

- Further developments
  - Hybrid PSTD-DG method
  - Broadband impedance boundary conditions
  - Turbulence scattering
  - Include coupling with structural vibrations (building acoustics)

- Applications
  - Indoor and outdoor scenarios that need to be solved by a wave-based method
  - Auralization of environments

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- Eef Brouns

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