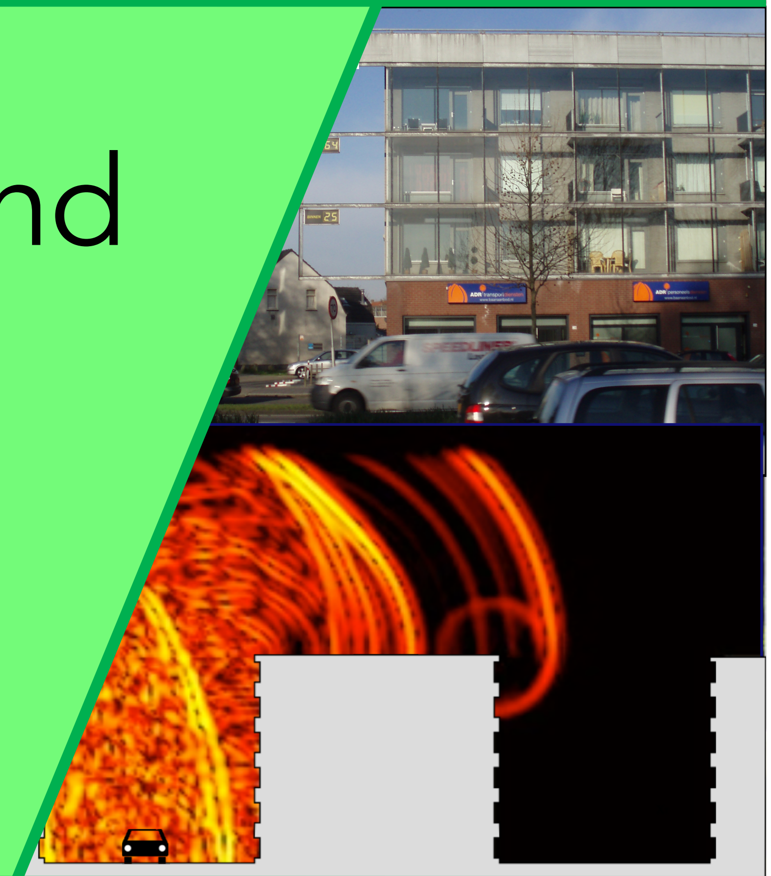
The Science of Sound

Environmental Acoustics



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UNIVERSITY OF
TECHNOLOGY

www.tue.nl/buildingacoustics
www.building-acoustics.net

Contents

Recorded Lecture

- Course material and introduction
- Ground effect
- Meteorological effects
- Screening
- Urban effects

Q&A on lectures (Monday)

Q&A on exercises (Thursday)

Test (quiz) on Environmental Acoustics (Monday)

Course Material

Course material

Ground effect:	SoS 30.3 , CAA Ch. 3,
Meteorological effects:	SoS 30.3, CAA Ch. 4.1-4.4,
Screening:	SoS 32.6, POS Chapter 9.4, 9.5, 9.8,
Urban effects:	SoS 32.5, Paper Picaut et al.

SoS: Science of Sound, course book
CAA: Computational Atmospheric Acoustics, Erik Salomons
POS: Predicting outdoor sound, Attenborough et al.

Environmental Acoustics

Sources
Natural sounds (birds, rustling leaves)
Traffic noise (road, rail, airplane)
Construction sites

http://www.vartgoteborg.se/prod/sk/vargotnu.nsf/1/trafik,rekordokning_f
or_kollektivresandet

http://vanassendelft.jouwweb.nl/afwerken-20-april-2011

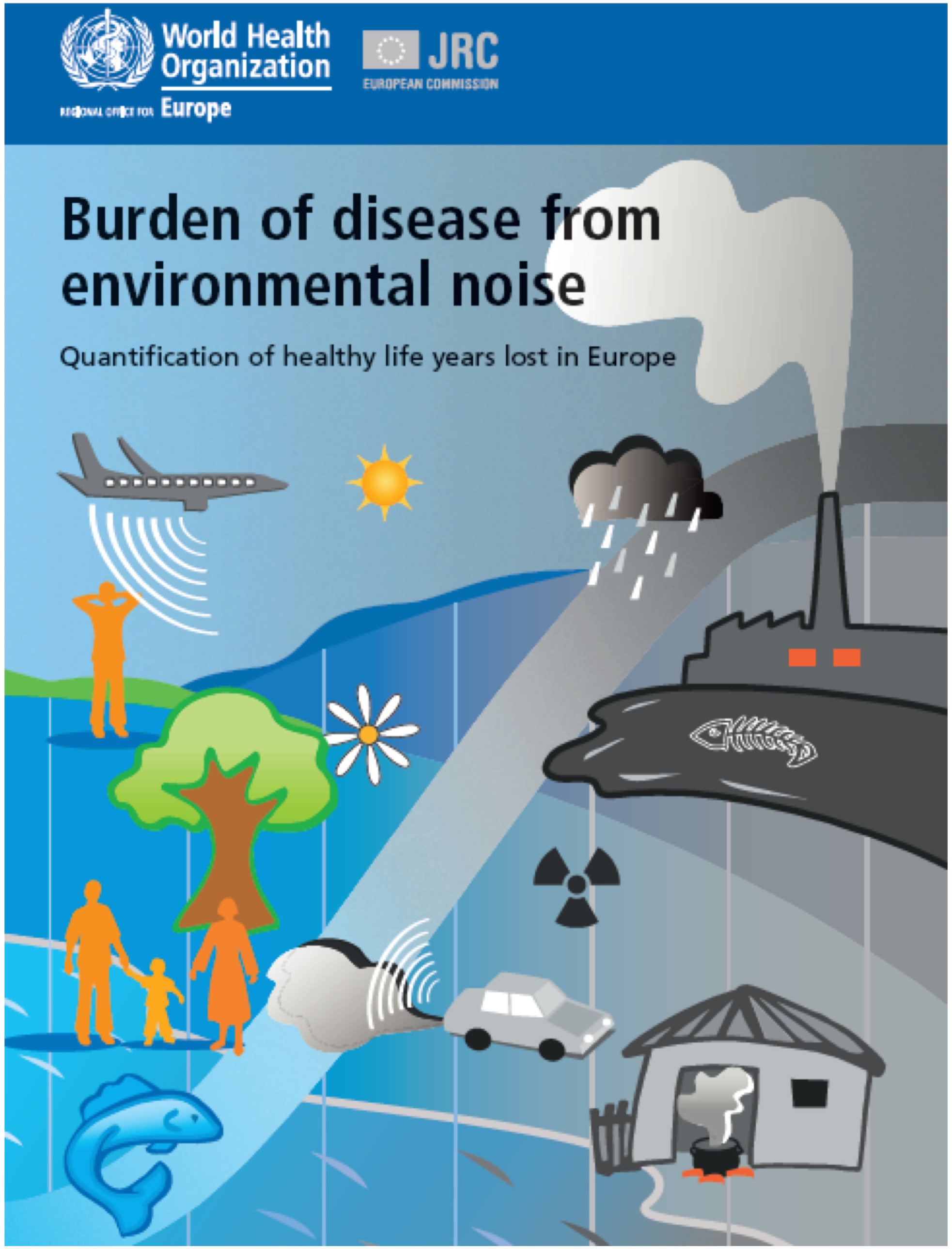
Acoustics of the environment

Receiver
Human response to sound related to activity





Adverse health effects



Health effects due to environmental noise

DALYs are the sum of the potential years of life lost due to premature death and the equivalent years of 'healthy' life lost by virtue of being in states of poor health or disability (WHO2011)

DALYs due to environmental noise

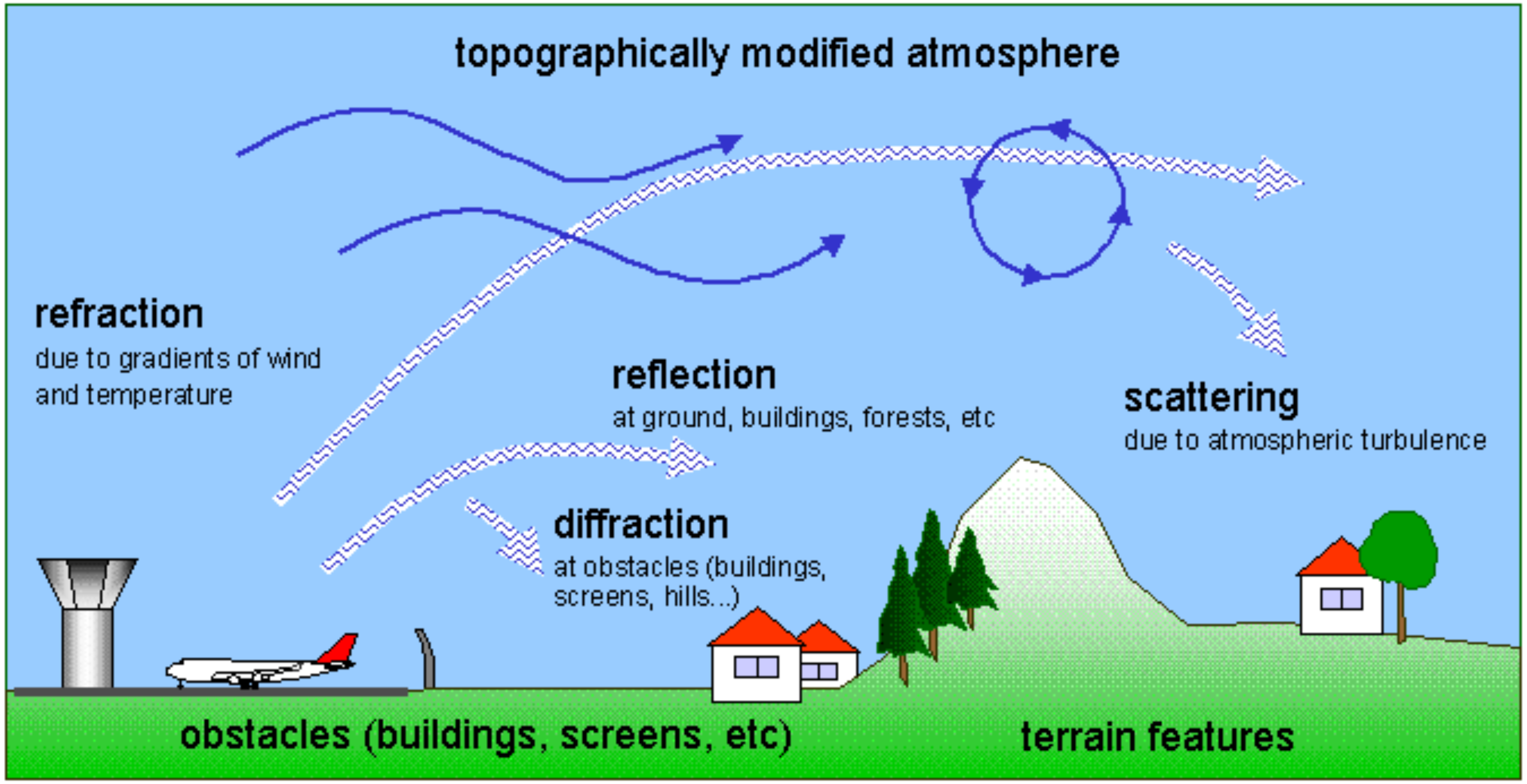
Results for European Union

Adverse health effect	DALYs
Cardiovascular diseases	61 000
Cognitive impairment in children	45 000
Sleep disturbance	903 000
Tinnitus	22 000
Annoyance	587 000

WHO 2011

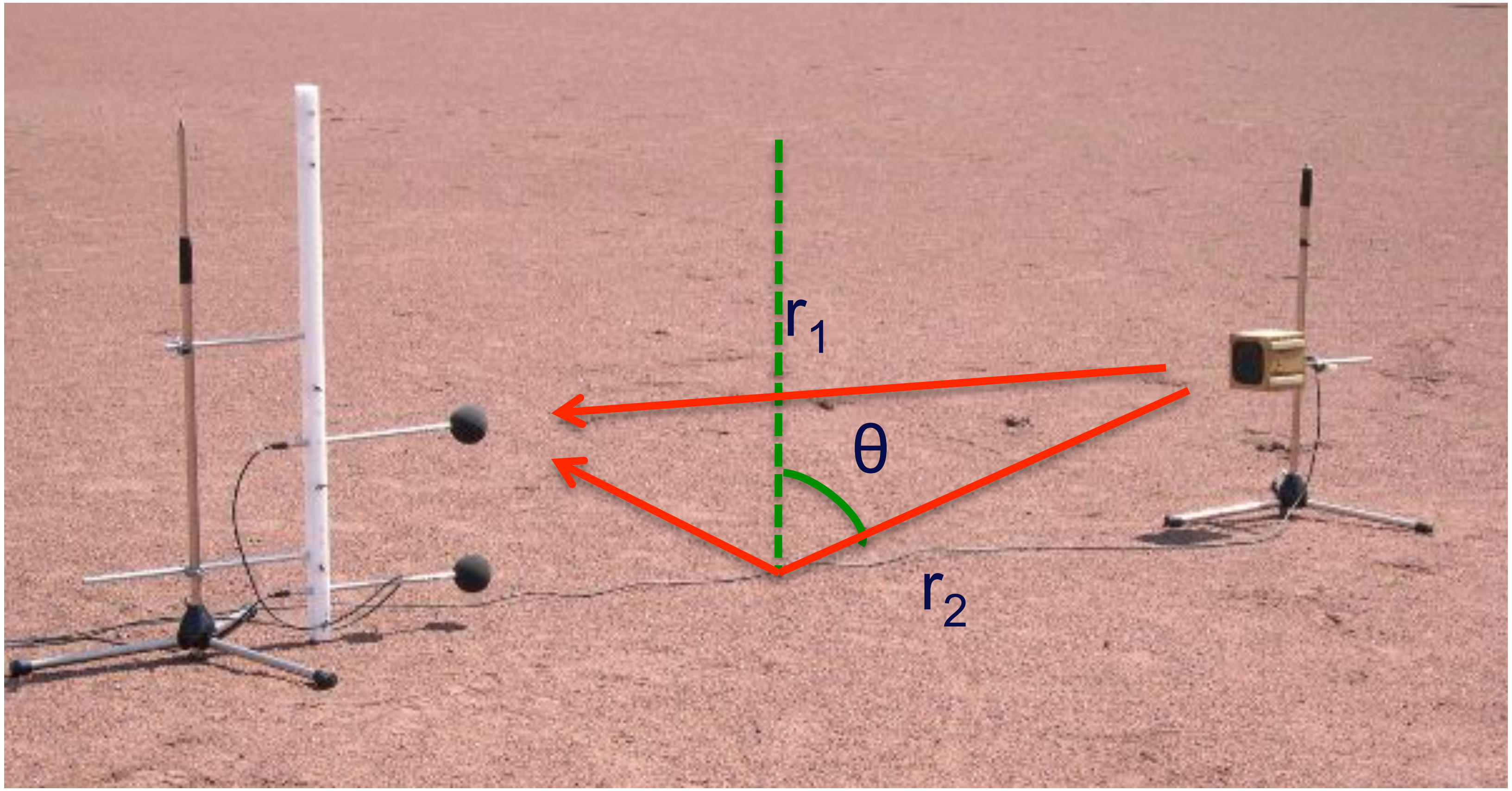
Physical effects influencing urban sound propagation

- Ground effect
- Meteorological effects
- Screening
- Urban effects



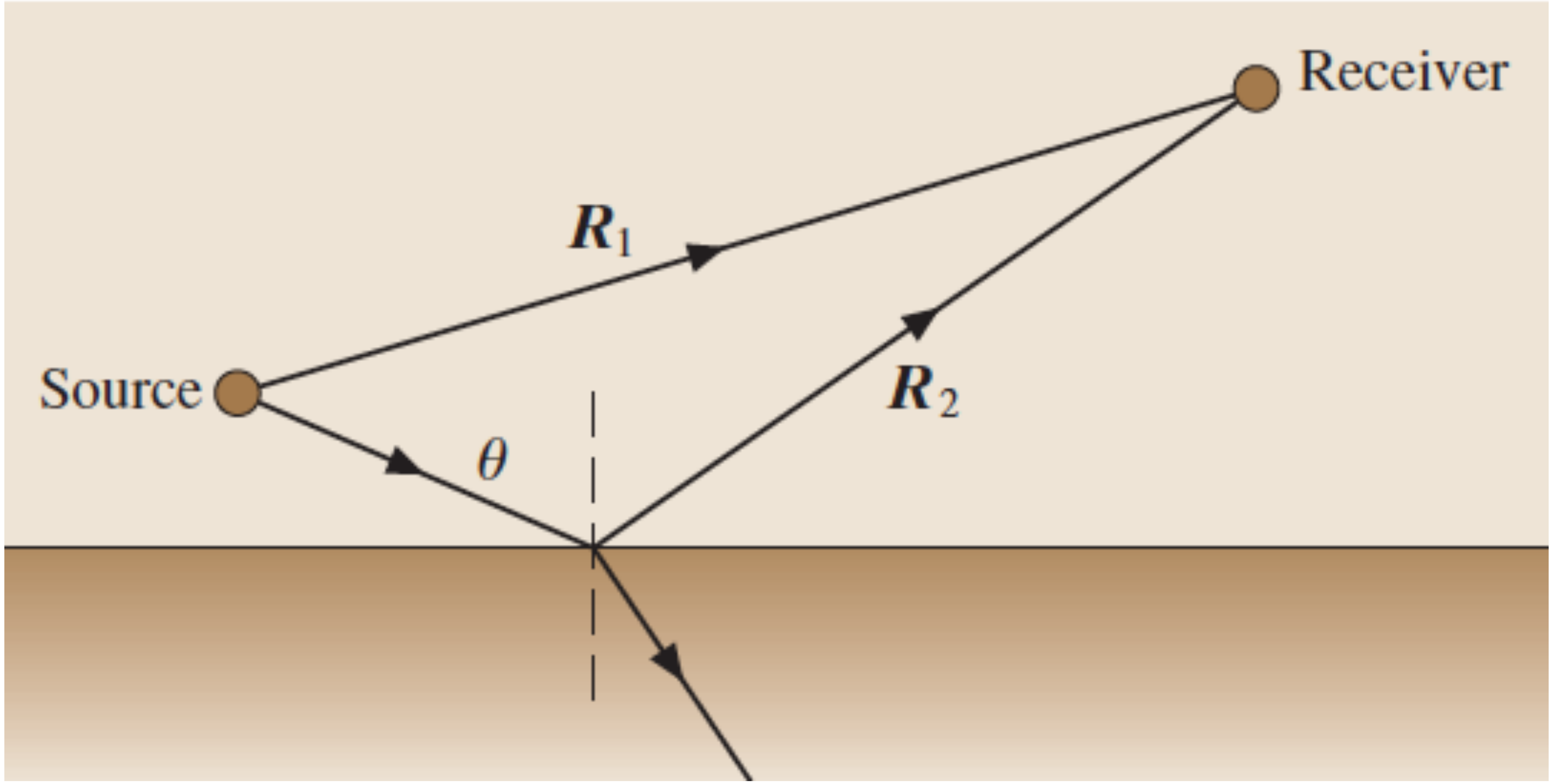
http://www.pa.op.dlr.de/acoustics/index.html

Ground Effect



http://www.akustik.uni-oldenburg.de

Ground Effect



Handbook of Acoustics, Sound propagation in the atmosphere

$$p_{free} = S\frac{e^{jkR_1}}{R_1}$$

$$p_{tot} = S\frac{e^{jkR_1}}{R_1} + QS\frac{e^{jkR_2}}{R_2}$$

Ground Effect

- Spherical wave reflection coefficient Q depends on
  - Frequency
  - Distance
  - Angle of incident sound wave to surface
  - Normalized surface impedance Z_n
- Surface impedance Z_n: a measure of opposition to motion of a medium subjected to acoustic pressure (force).

- High frequency approximation: plane wave reflection factor *R*

$$R(f,\theta)=\frac{Z(f)\cos(\theta)-1}{Z(f)\cos(\theta)+1}$$

- Absorption coefficient

$$\alpha(f,\theta)=1-\left|R(f,\theta)\right|^2$$

Ground Effect

Relative sound pressure level

$$p_{free} = S\frac{e^{jkR_1}}{R_1}$$

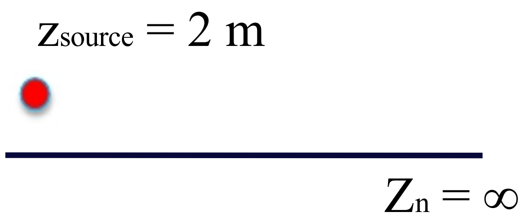
$$p_{tot} = S\frac{e^{jkR_1}}{R_1} + QS\frac{e^{jkR_2}}{R_2}$$

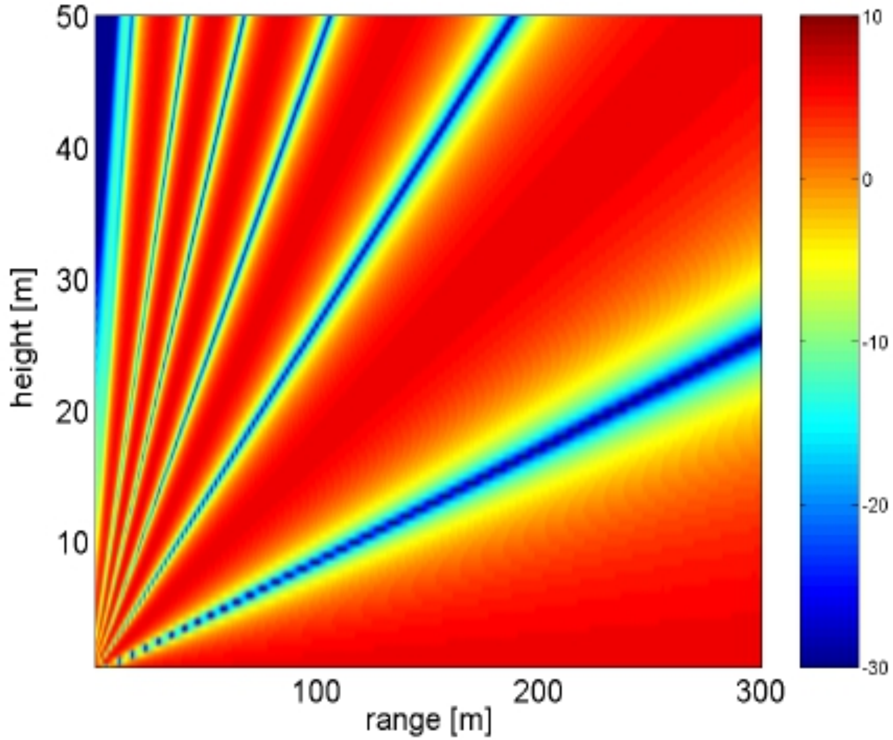
$$\Delta L = 10\log_{10}\left(\frac{|p_{\mathrm{tot}}|^2}{|p_{\mathrm{free}}|^2}\right)$$

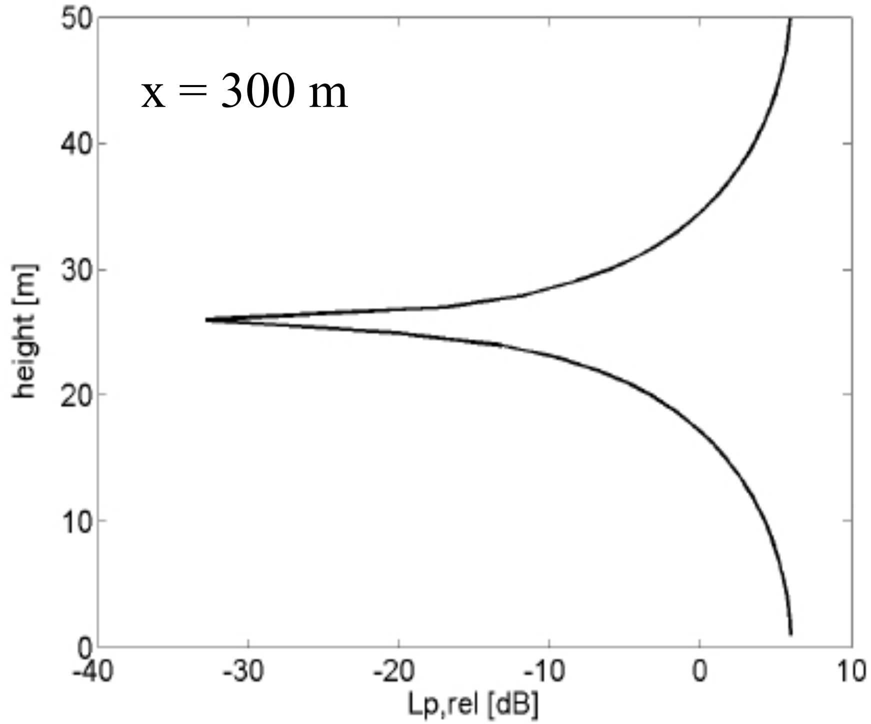
$$\Delta L = 20\log_{10}\left(\left|1 + Q\frac{R_1}{R_2}e^{j(kR_2 - kR_1)}\right|\right)$$

Ground Effect

$f = 500$ Hz







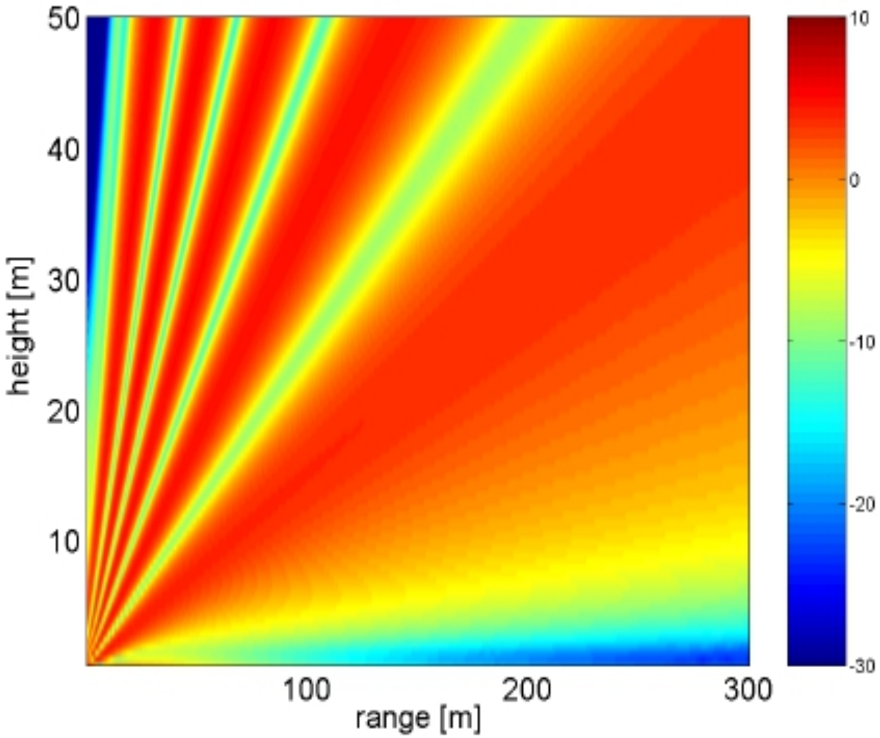
Hornikx, M. Modelling urban sound propagation in a moving medium. (2004). Master's *Thesis report 04.16.A, Acoustics Laboratory, Eindhoven University of Technology, The Netherlands.*

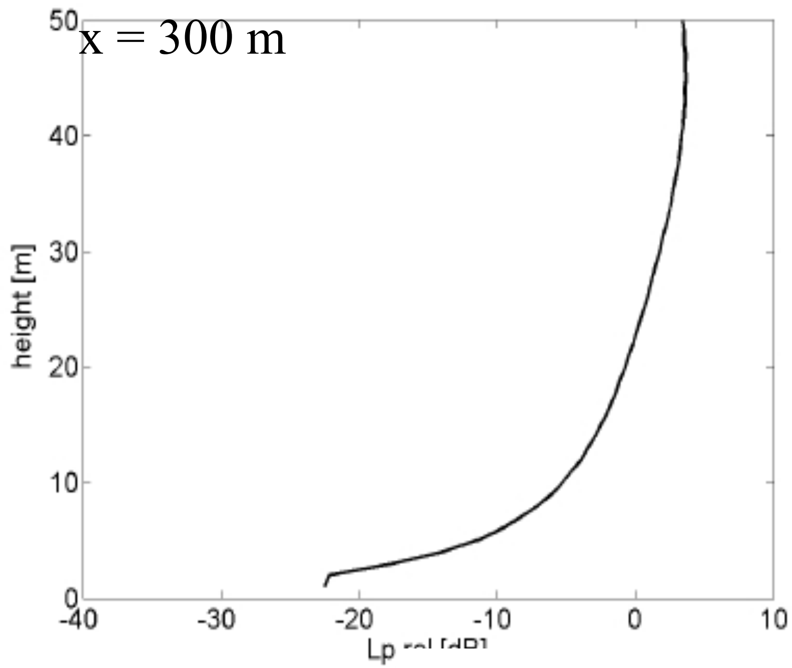
Ground Effect

$f = 500$ Hz

$z_{source} = 2$ m

grass: $Z_n = 300$ kPa.s/m^2





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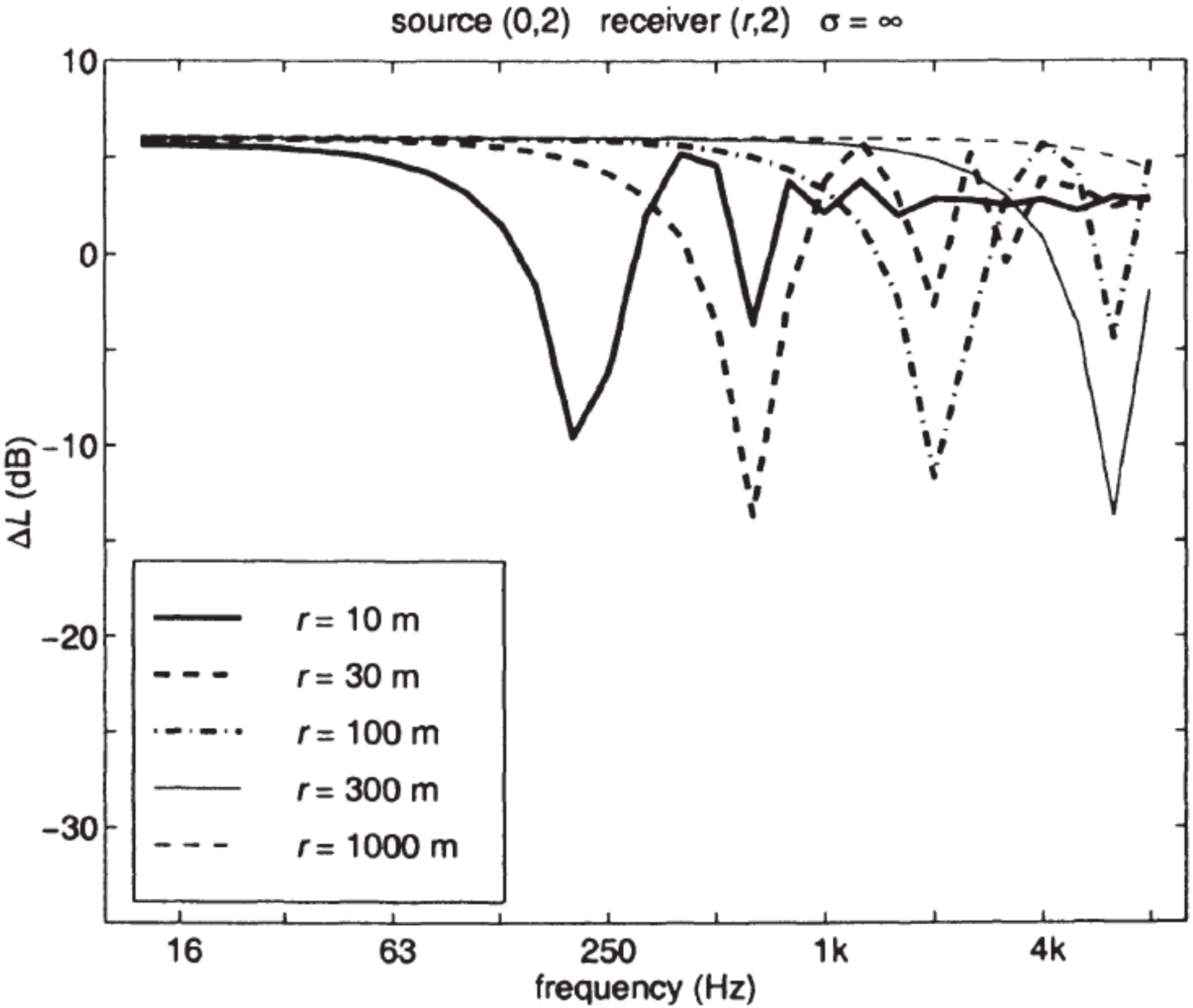
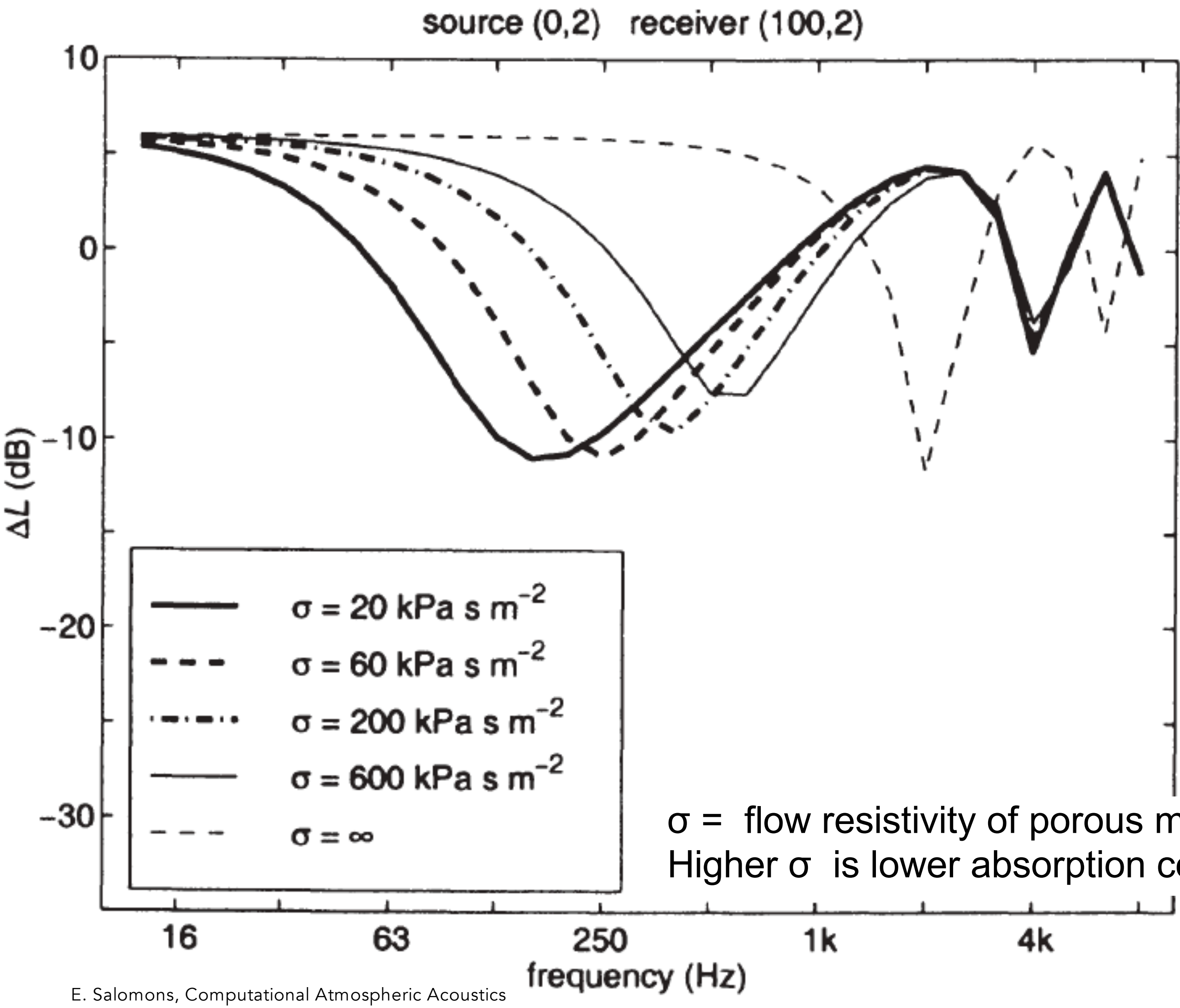
Ground Effect



E. Salomons, Computational Atmospheric Acoustics

Ground Effect



σ = flow resistivity of porous material
Higher σ is lower absorption coefficient

E. Salomons, Computational Atmospheric Acoustics

Ground noise reduction measures

Brick lattice along road

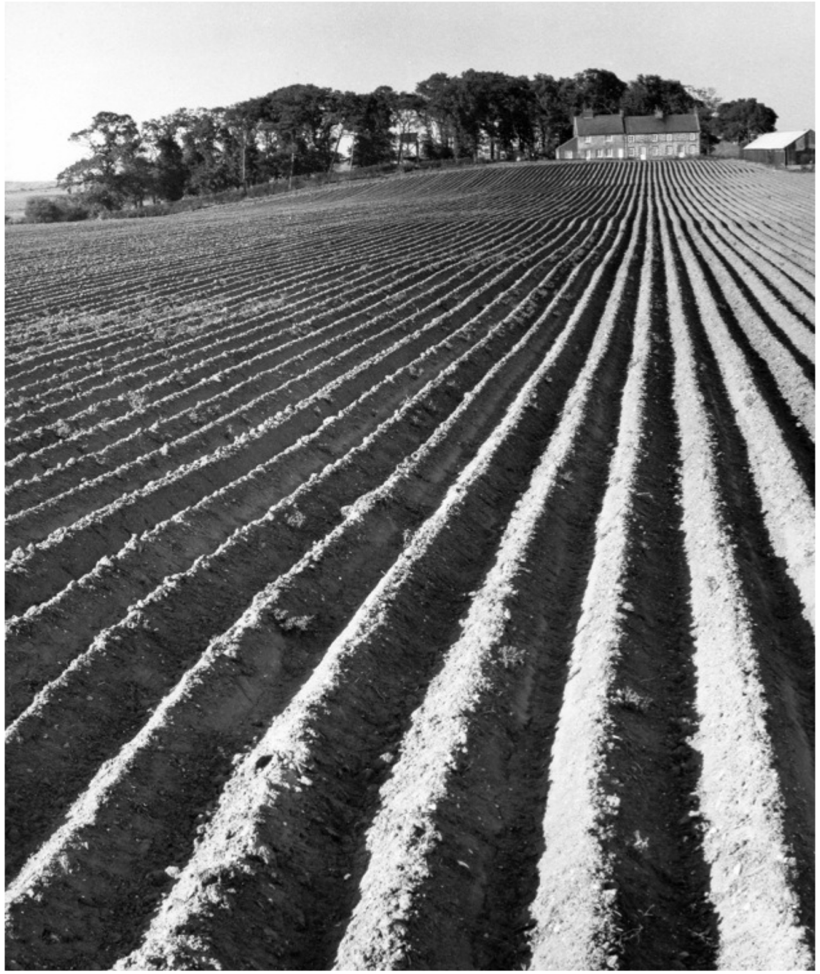
Lattice: 0.3 m high square lattice	Insertion loss (dB) – 2 lane road
1.65 m Wide	6.2
3.05 m Wide	7.2
5.85 m Wide	8.7
12.05 m Wide	10.5

Bashir, I., Hill, T., Taherzadeh, S., Attenborough, K., Hornikx, M. (2014). Reduction of Surface Transport Noise by Ground Roughness. Applied Acoustics, **83**, 1-15.

Ground noise reduction measures

Ploughed ground: up to 10 dB more noise reduction compared to flat soft surface

K. Attenborough, T. Waters-Fuller, K.M. Li, J.A. Lines: Acoustical properties of Farmland, J. Agric. Eng. Res. 76, 183–195 (2000)



http://www.beetlesandhuxley.com/gallery/all-stock/newly-ploughed-field-holkham-norfolk-1970.html

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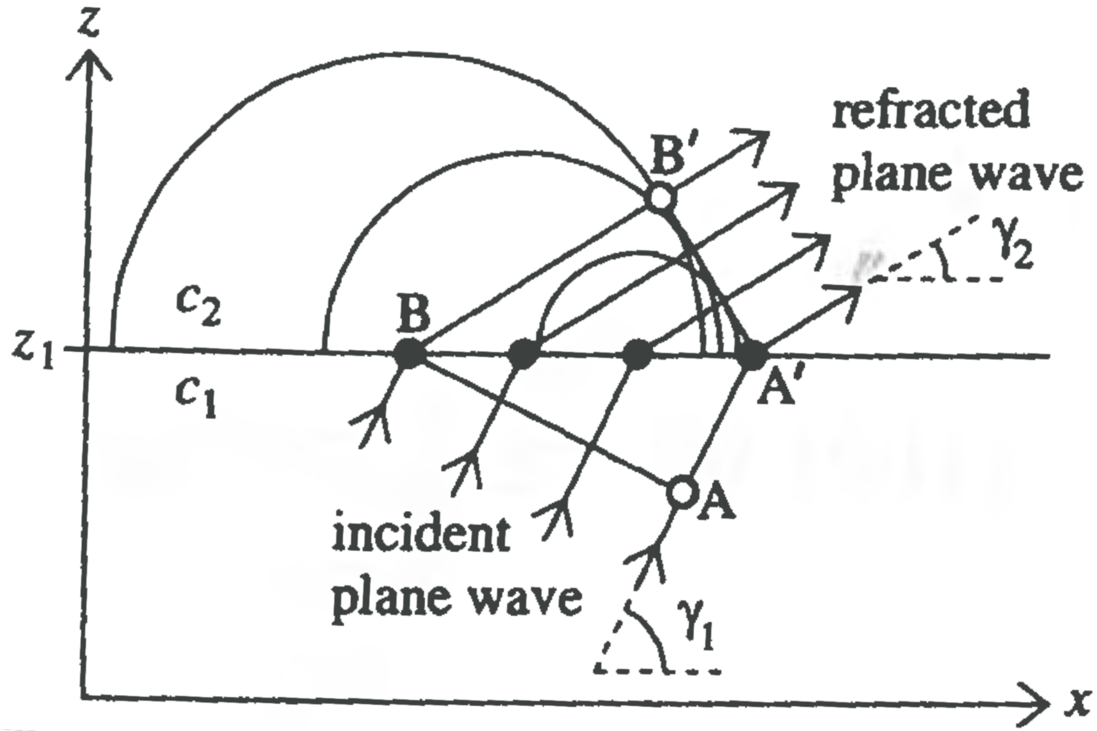
Ground noise reduction measures

Helmholtz resonators in asphalt

3 dB reduction possible

http://acoustics.org/pressroom/httpdocs/165th/2aNSa8_Maennel.html

Meteorological effects



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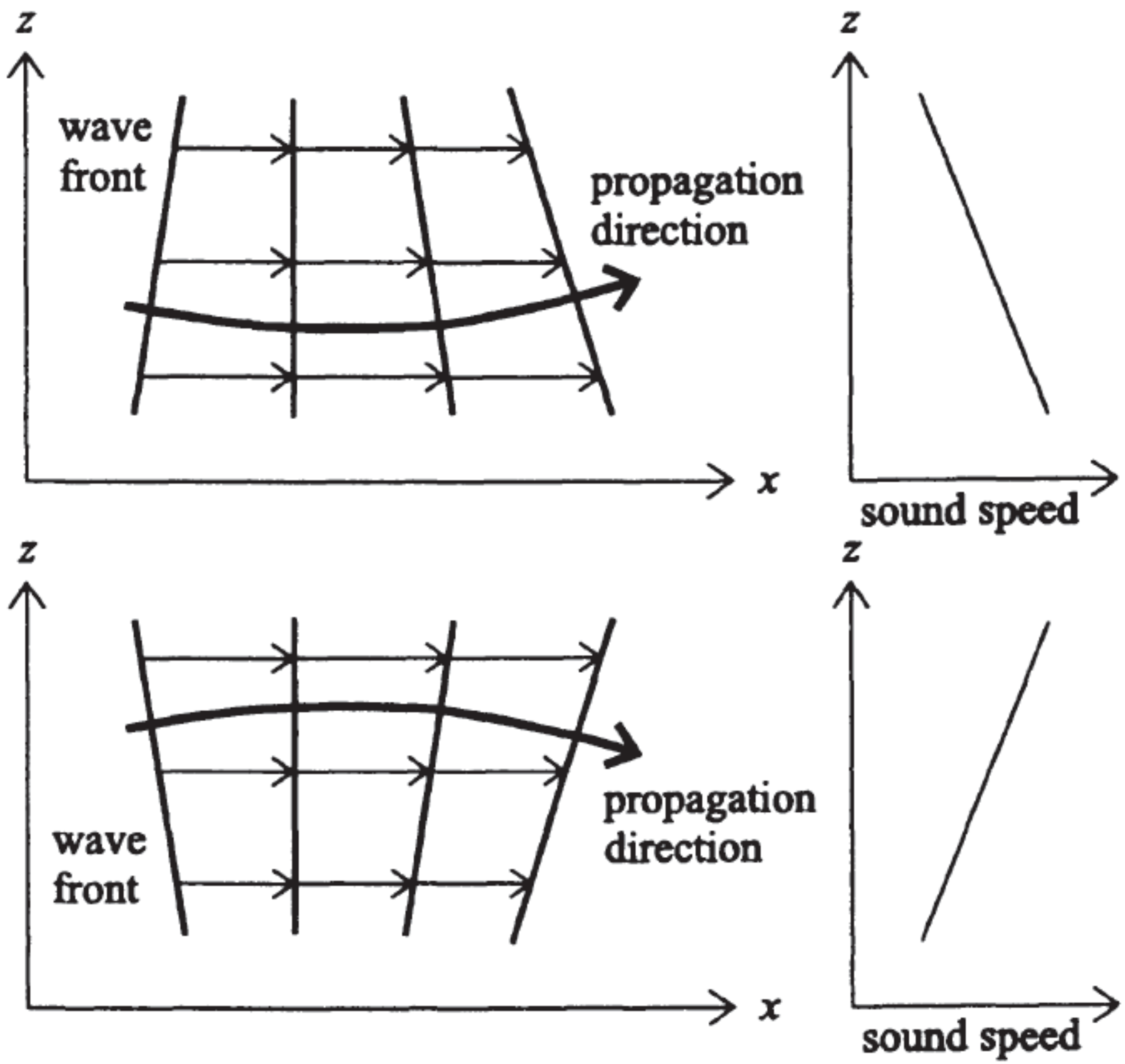
$$\frac{\cos\gamma_1}{c_1} = \frac{\cos\gamma_2}{c_2}$$

Meteorological effects

Sound speed is higher for

- Higher wind velocity
- Higher temperature



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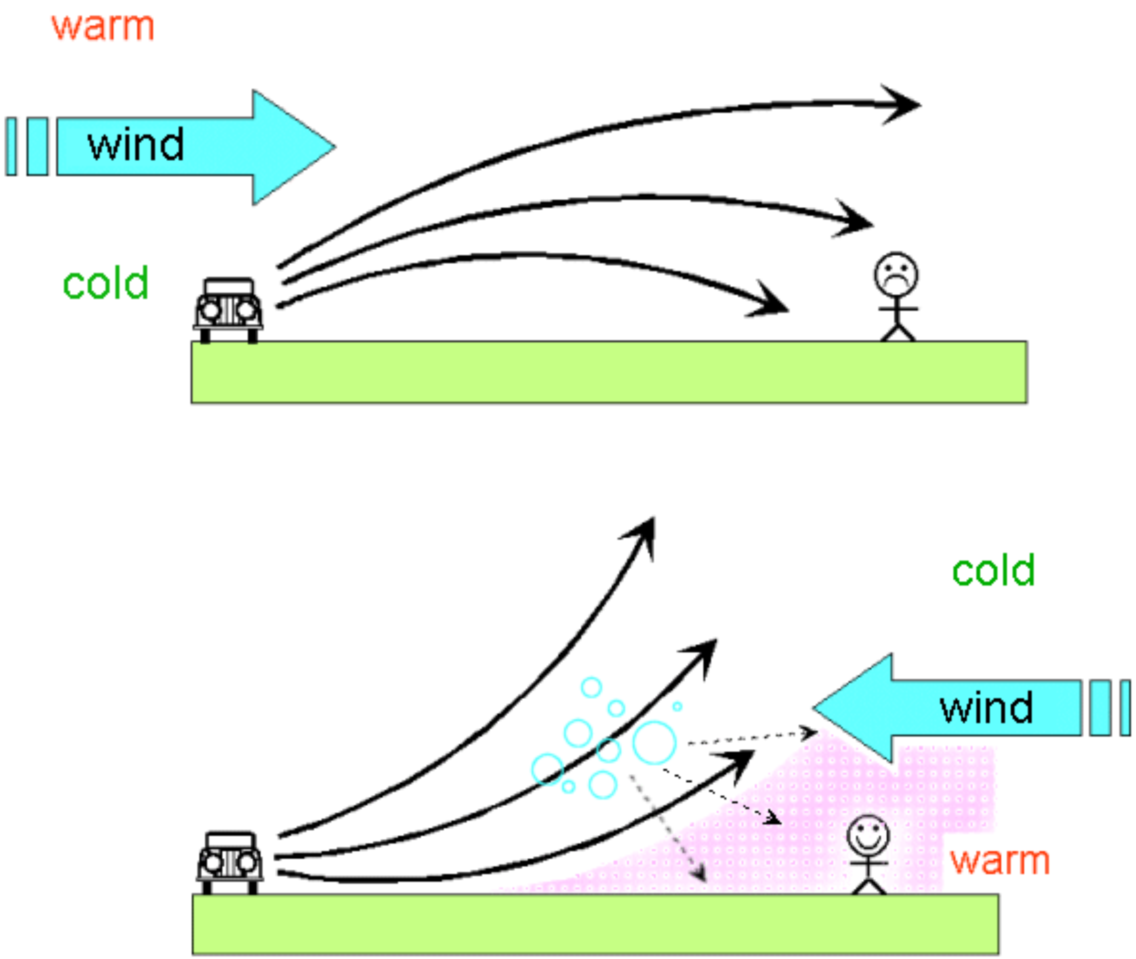
Meteorological effects



Heimann, D., (2003). Influence of meteorological parameters on outdoor noise propagation, EuroNoise Conference Naples 19-21 May 2003.

Meteorological effects

$$c_{\text{eff}}(z) = c_0 + b \ln\left(\frac{z}{z_0} + 1\right)$$

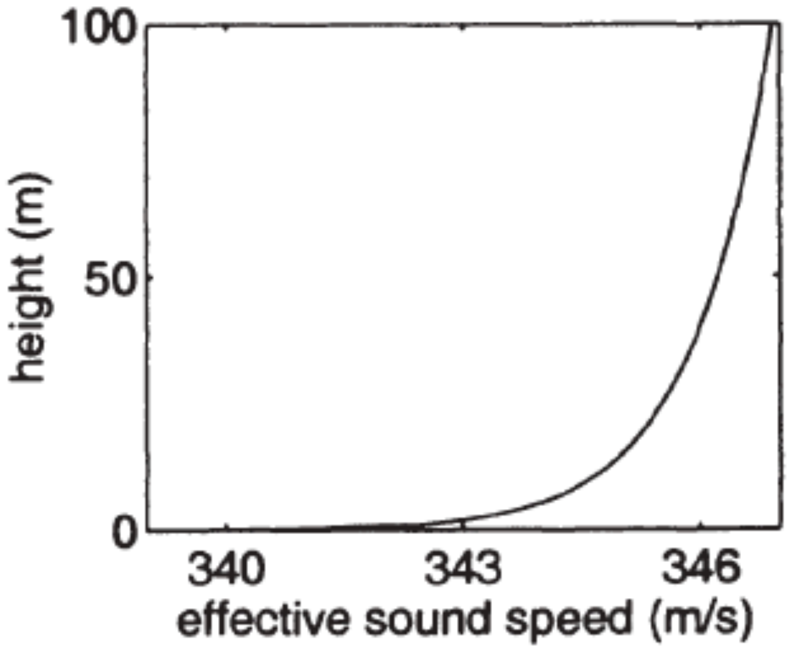
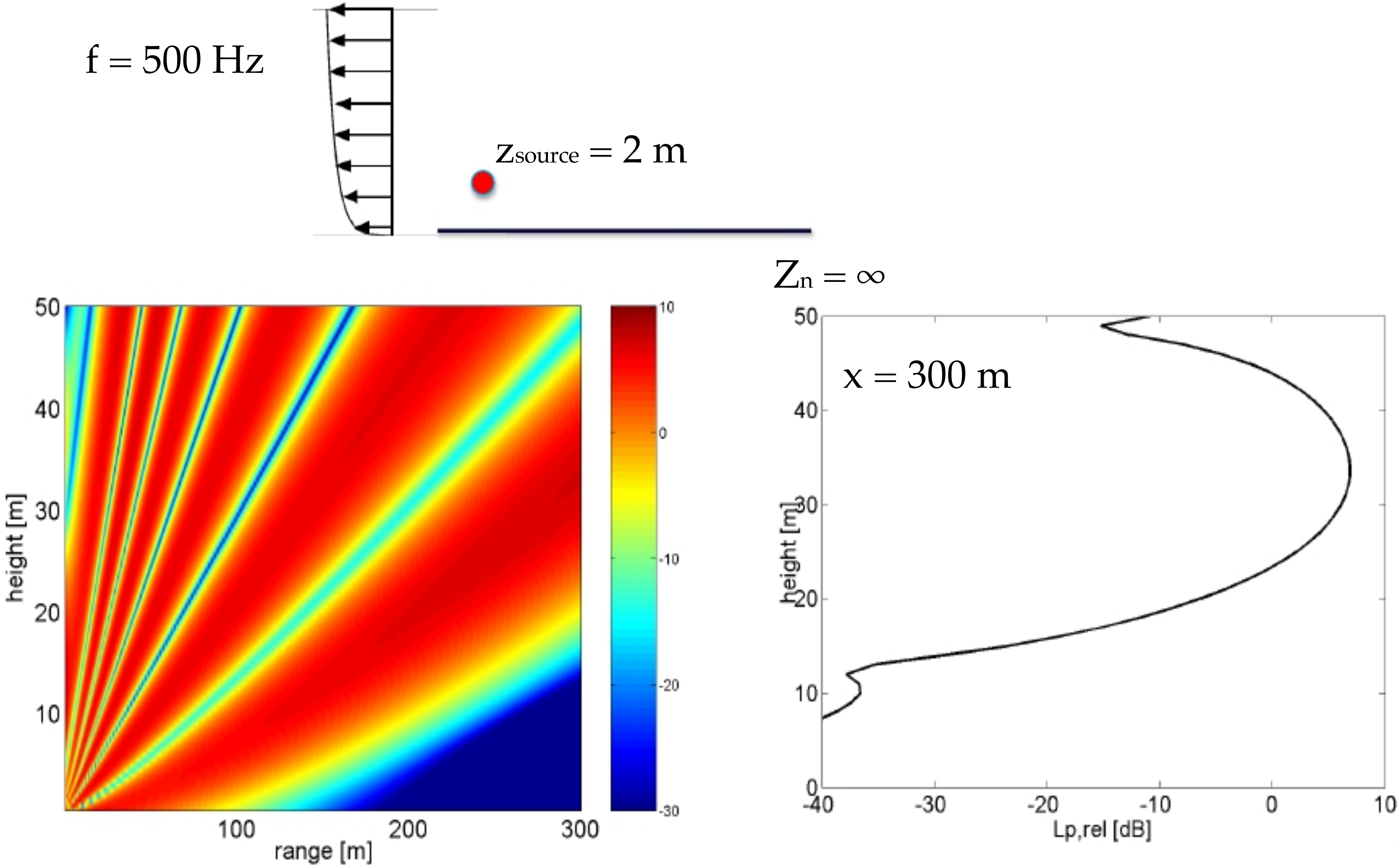


Figure 4.3. Logarithmic profile (4.5) of the effective sound speed, for $c_0 = 340$ m/s, $z_0 = 0.1$ m, and $b = 1$ m/s.

Meteorological effects



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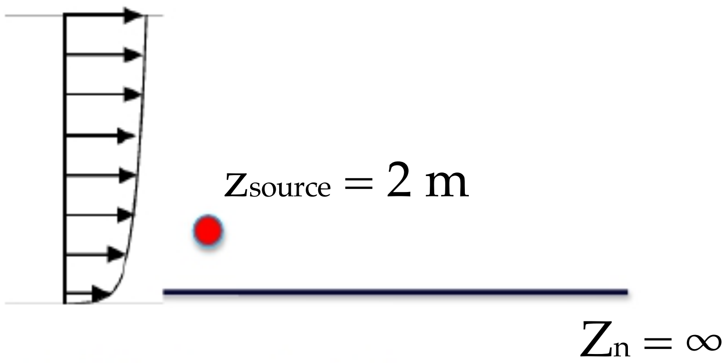
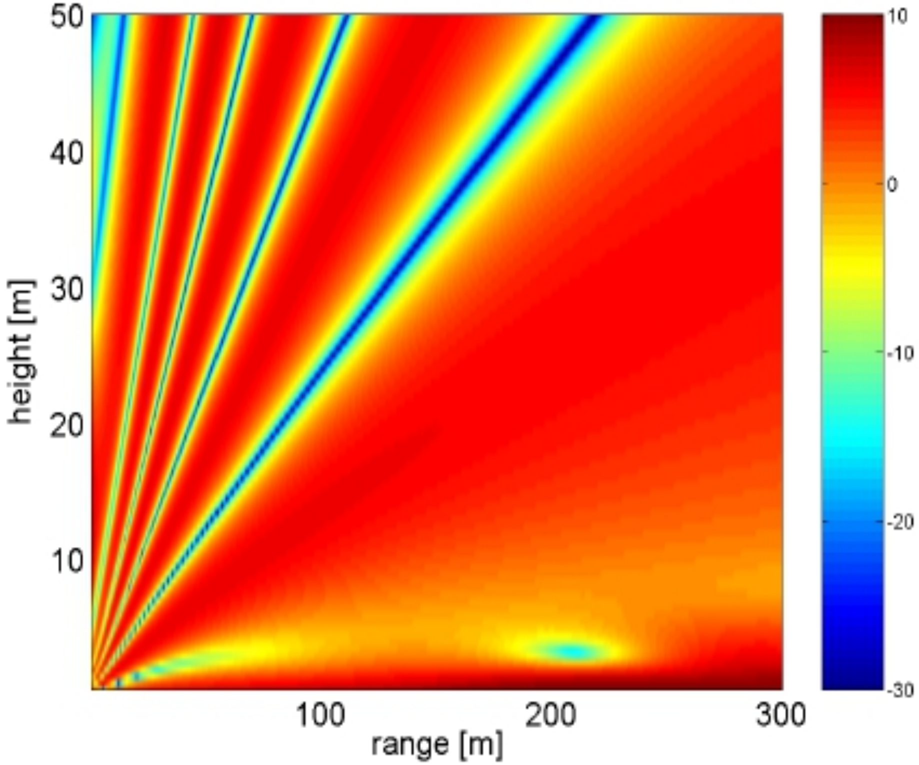
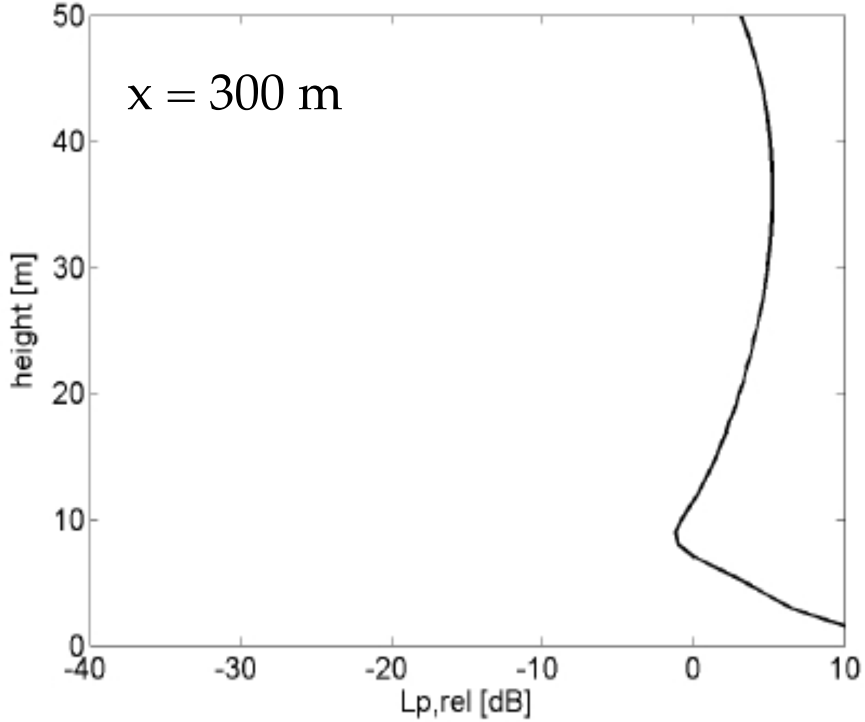
Meteorological effects

f = 500 Hz







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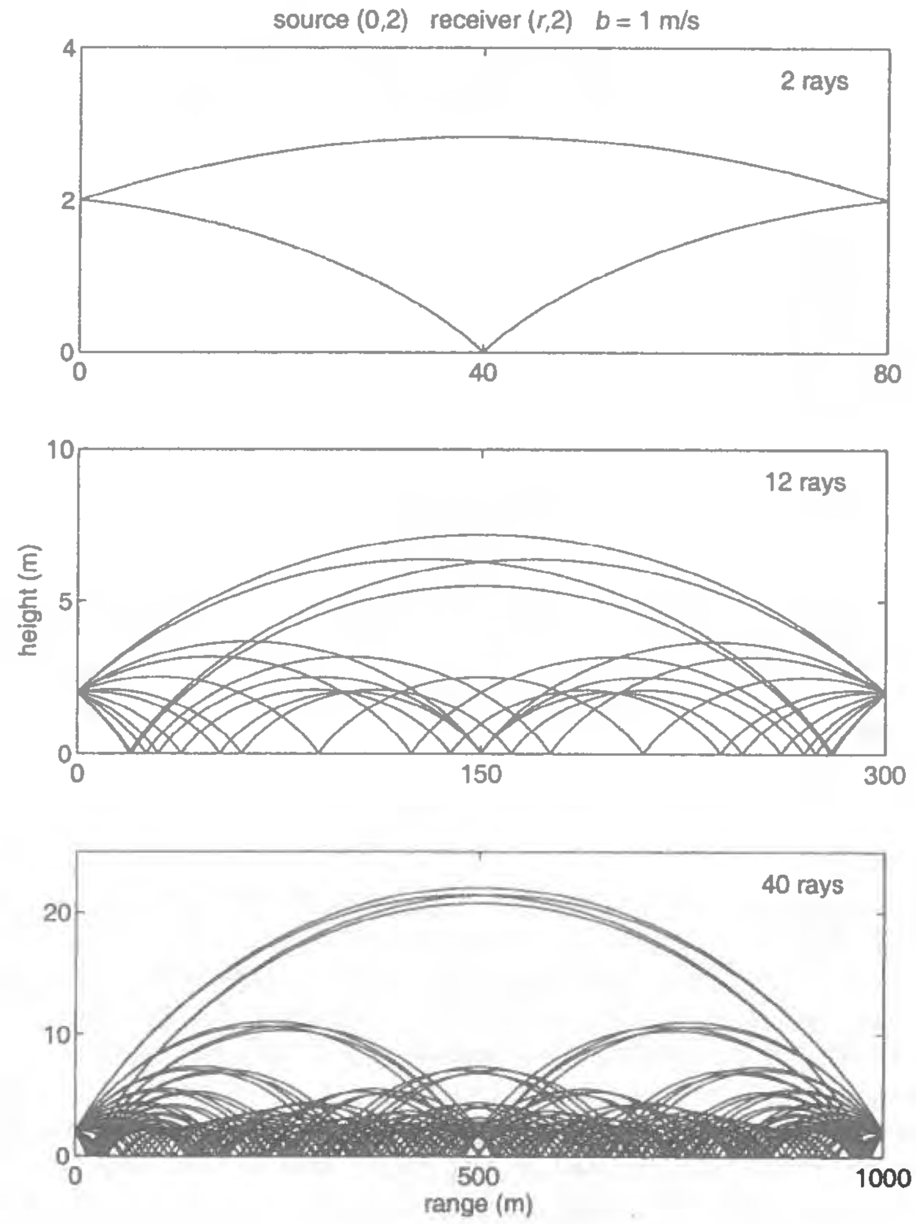
Meteorological effects

Ray approach



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Meteorological effects

Ray approach
Problems: caustics and shadow zones

$$p_c = \sum_{m=1}^{N_{rays}} A_m e^{j\phi_m}$$

$$A_m = f_m C_m^{N_m} \frac{S}{R_1}$$

C_m = reflection coefficient
D = ray tube diameter
D_{free} = D in free field in homogeneous medium at rest

$$f_m = \sqrt{\frac{D_{free}}{D}}$$

Meteorological effects

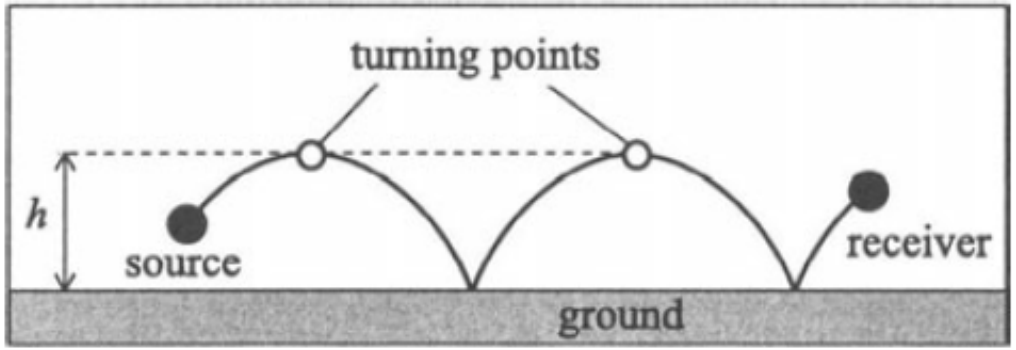

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Figure 4.9. Example of a sound ray with two turning points ($n = 2$). The maximum height of the ray, denoted as h, is indicated.

$$h_n \approx \frac{r}{n}\sqrt{\frac{b}{2\pi c_0}}$$

h_n = height of ray with n turning points
r = horizontal source-receiver distance

Meteorological effects

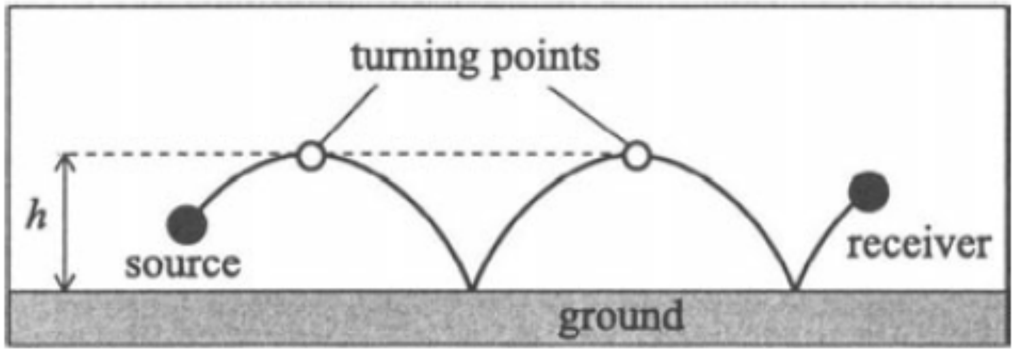

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Figure 4.9. Example of a sound ray with two turning points ($n = 2$). The maximum height of the ray, denoted as h, is indicated.

$$N_{\mathbf{rays}} \approx 4h_1/z_{\mathbf{sr}}$$

$$\Delta L \approx 10\lg N_{\mathbf{rays}}$$

z_{sr} = Average height source and receiver

ΔL = Low frequency increase of sound pressure level due to downwind

Meteorological effects

Atmospheric turbulence
Small scale refraction leading to phase and amplitude changes of sound waves

http://skullsinthestars.files.wordpress.com/2009/08/shimmer2.jpg

Meteorological effects

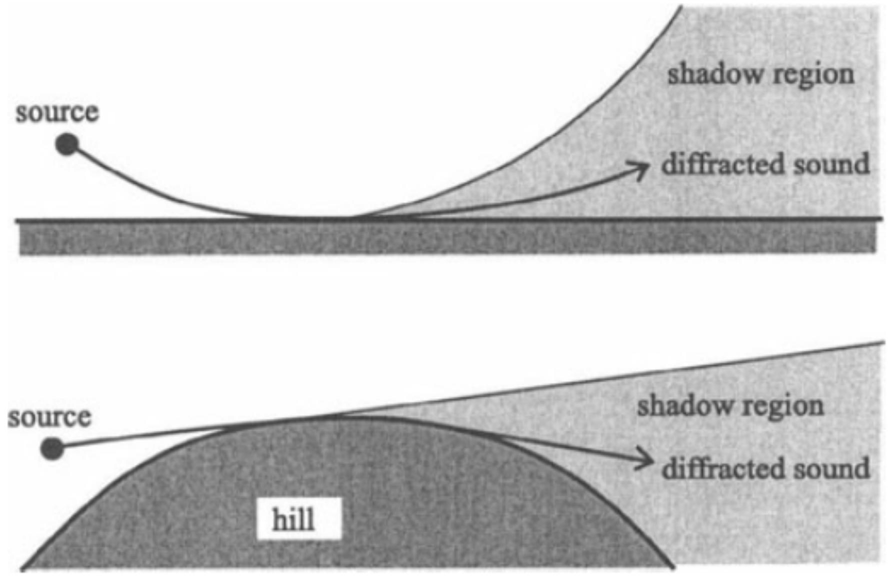


Figure 5.1. Diffraction of sound into a refractive shadow region is analogous to diffraction of sound into a shadow region behind a hill.

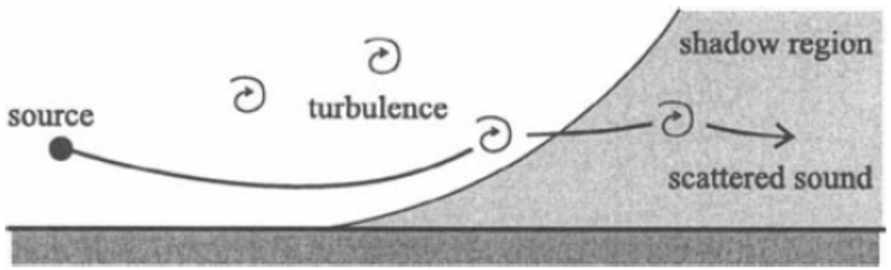


Figure 5.2. Scattering of sound into a refractive shadow region. Four turbulent inhomogeneities (eddies) are shown.

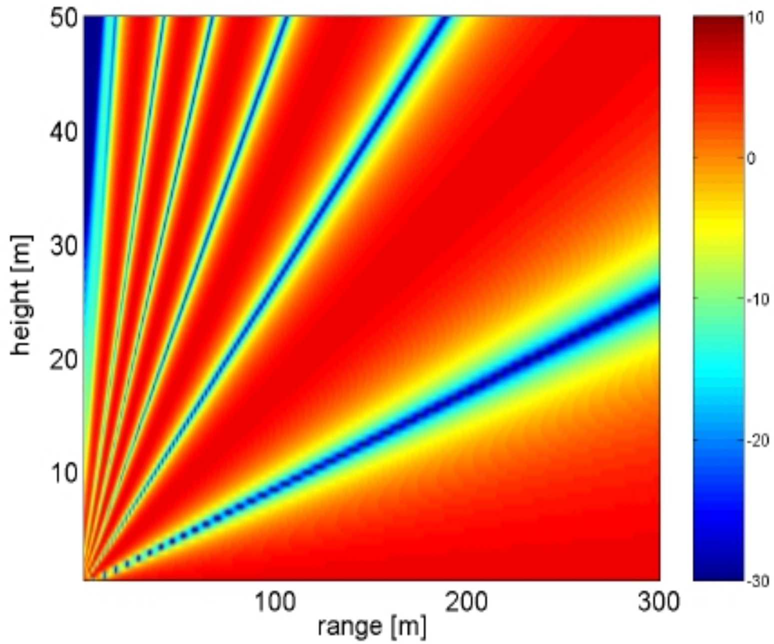
Meteorological effects

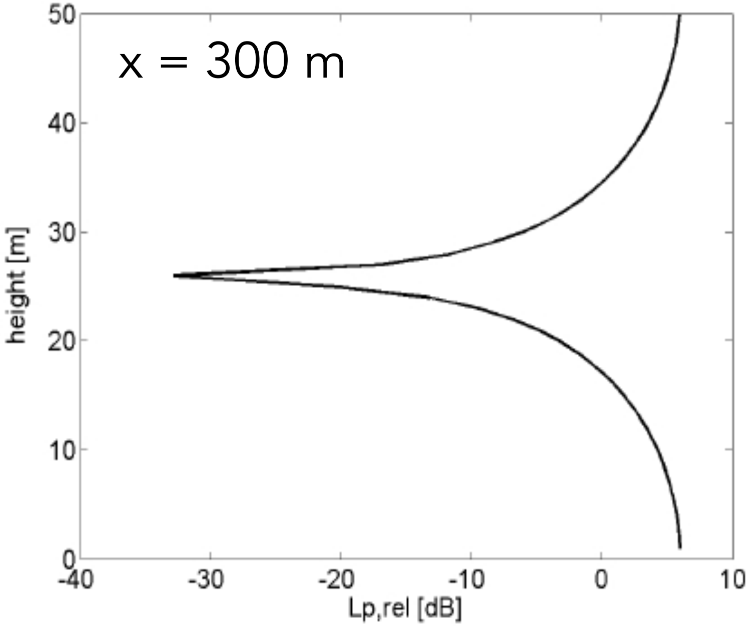
f = 500 Hz

z_{source} = 2 m

$Z_n = \infty$

No turbulence



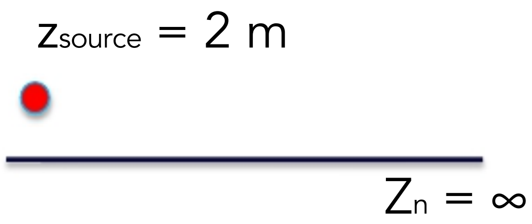


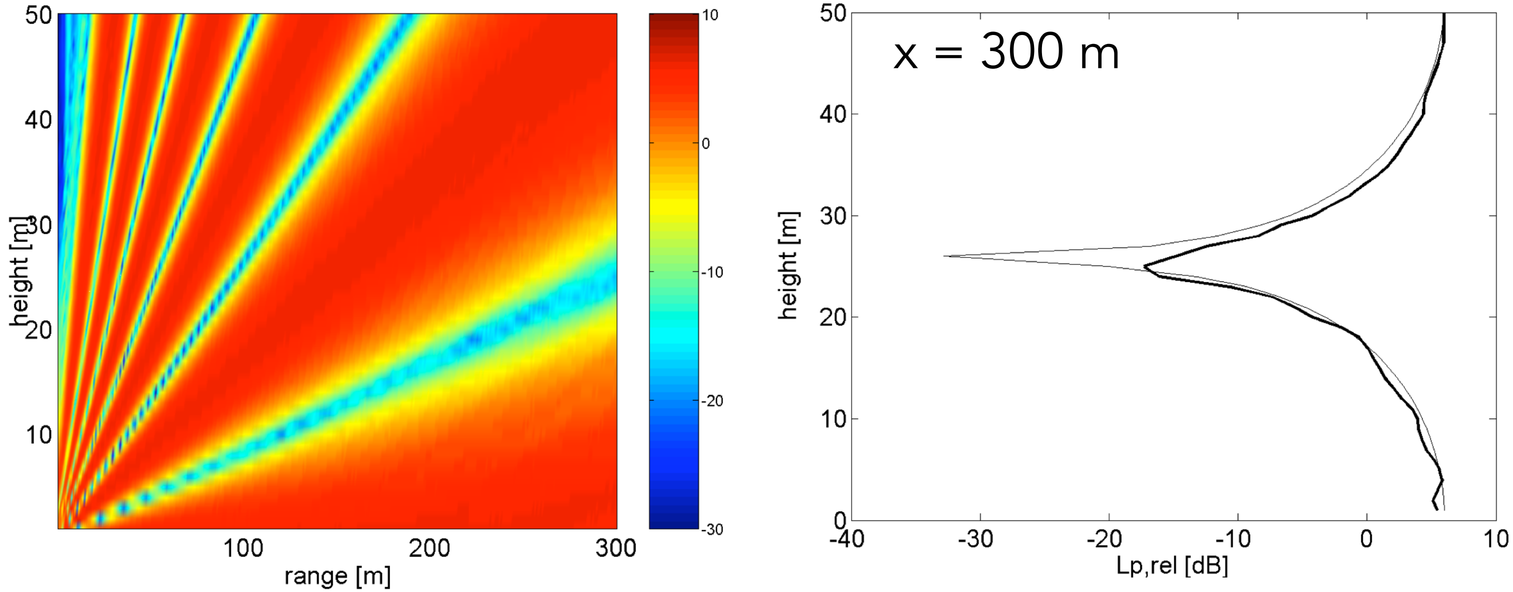
Hornikx, M. Modelling urban sound propagation in a moving medium. (2004). Master's *Thesis report 04.16.A, Acoustics Laboratory, Eindhoven University of Technology, The Netherlands.*

Meteorological effects

+ Turbulence

f = 500 Hz





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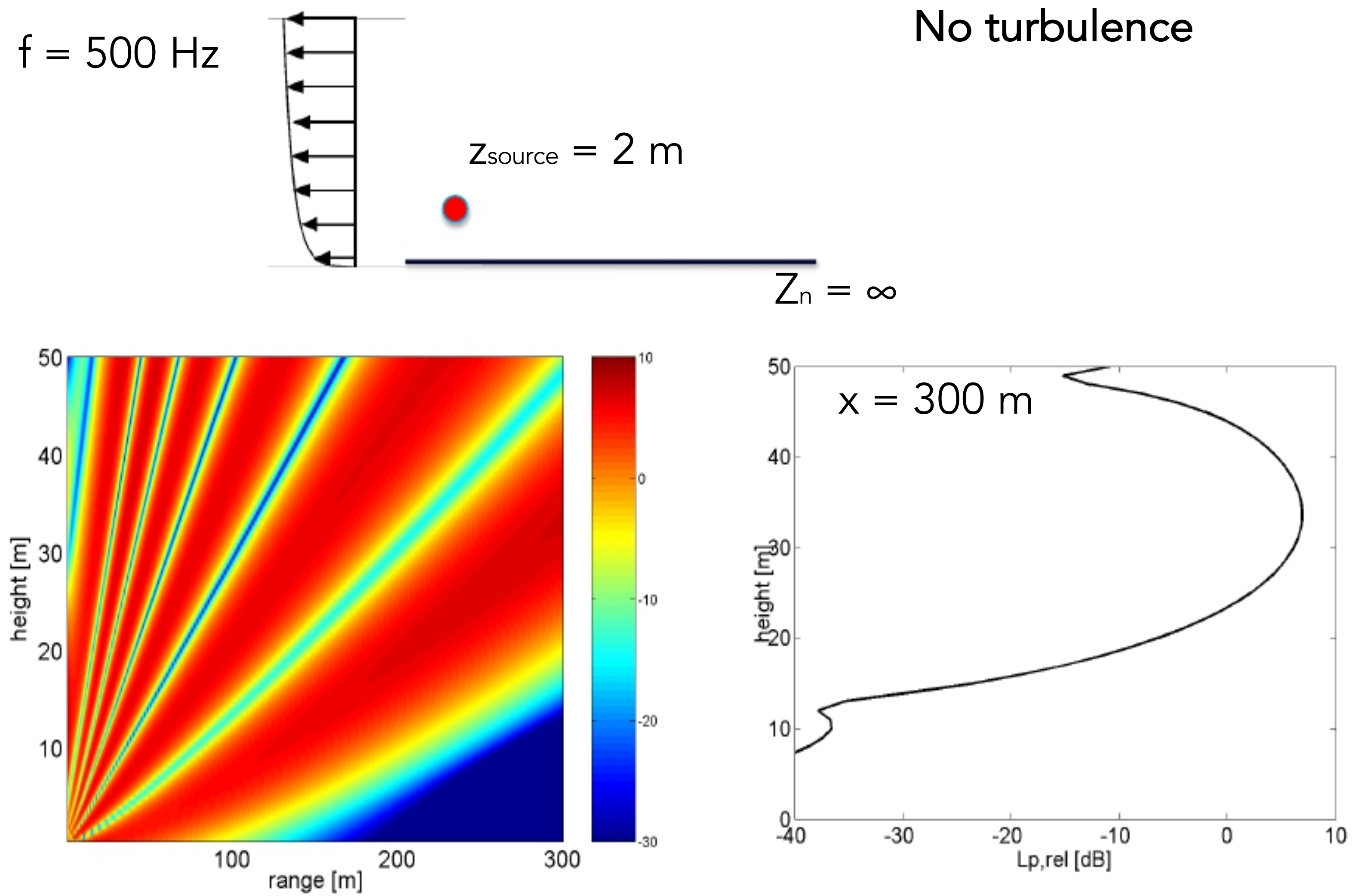
Meteorological effects



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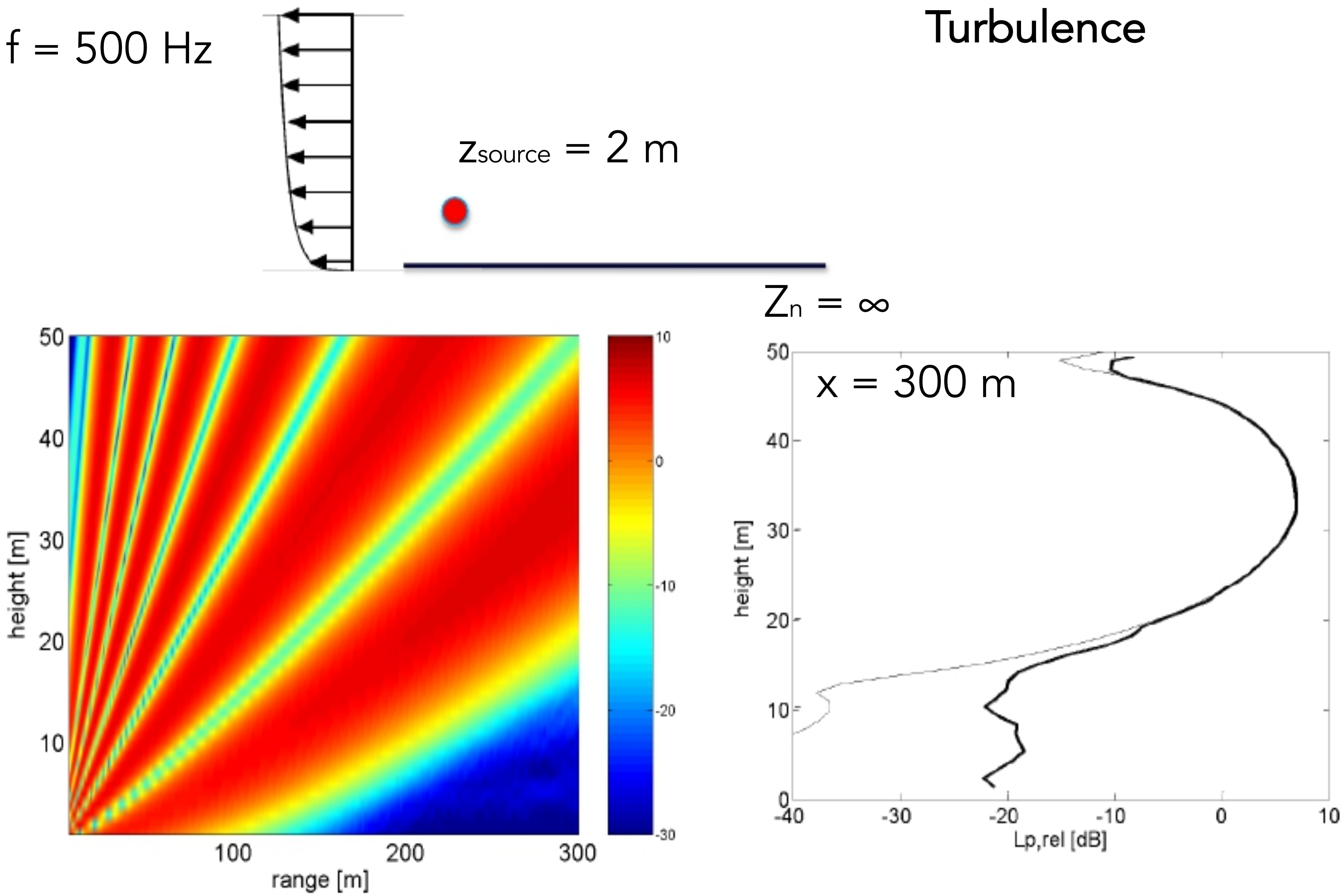
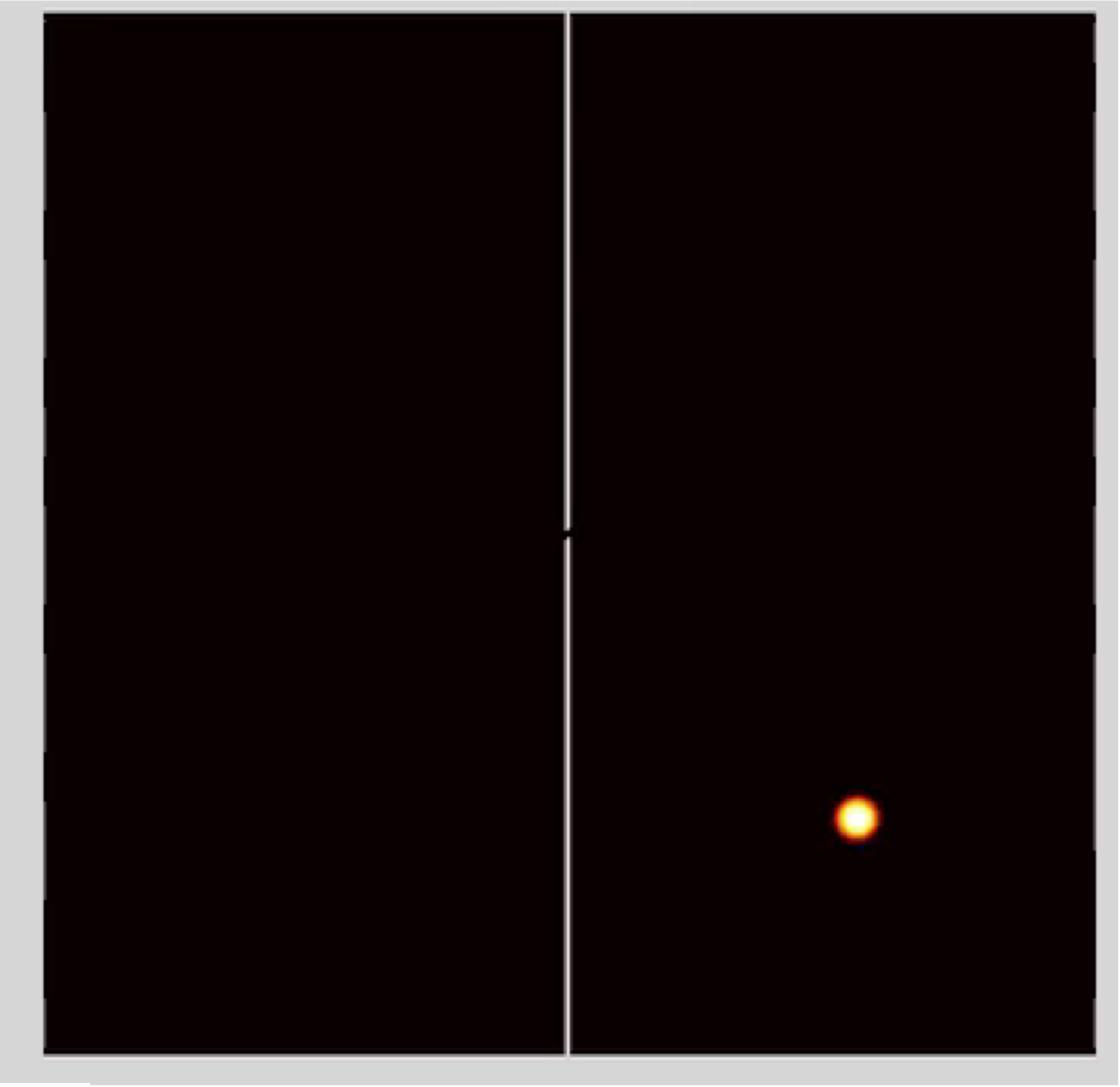
Meteorological effects



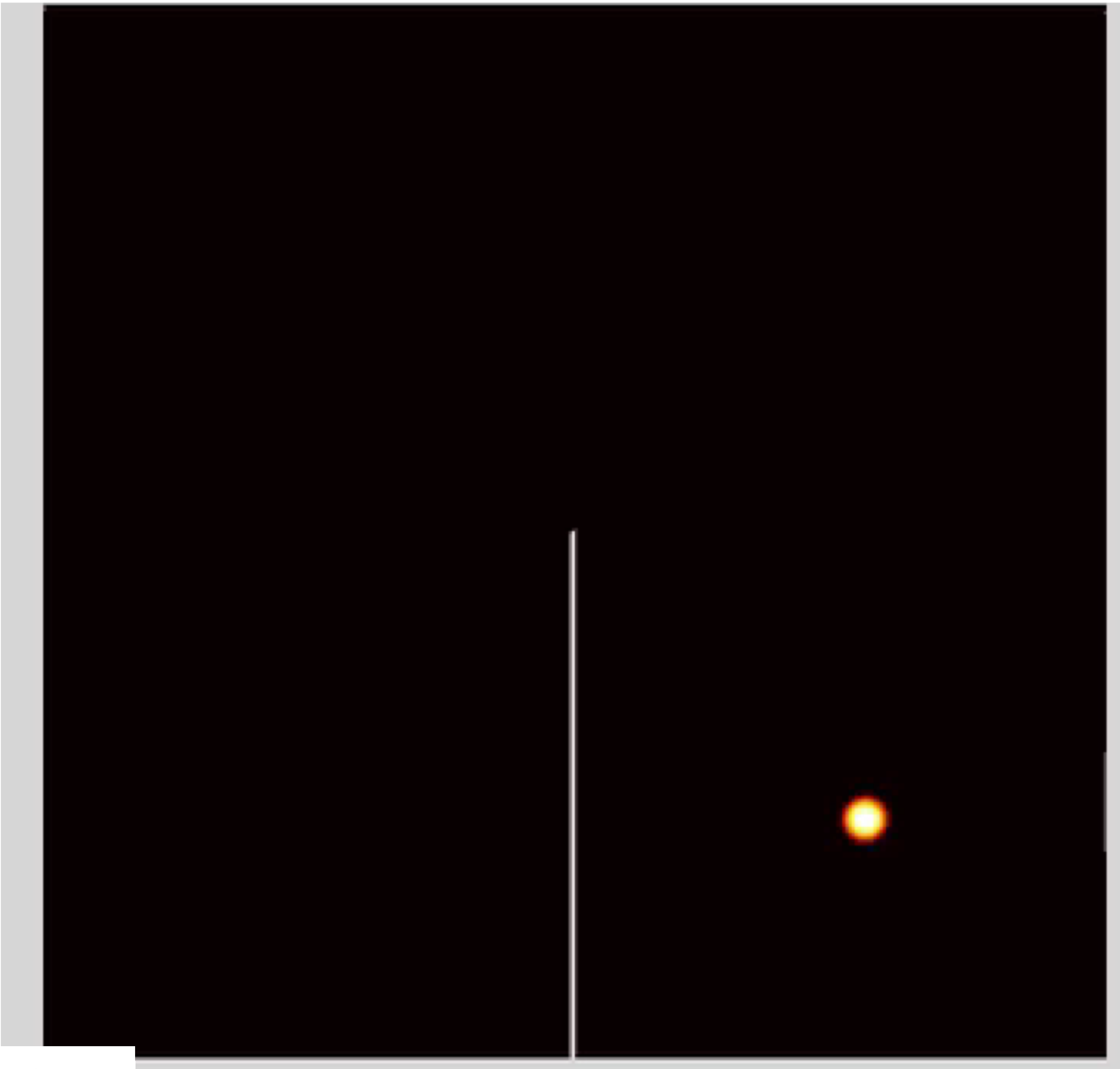
Hornikx, M. Modelling urban sound propagation in a moving medium. (2004). Master's *Thesis report 04.16.A, Acoustics Laboratory, Eindhoven University of Technology, The Netherlands.*

Screening

Screening



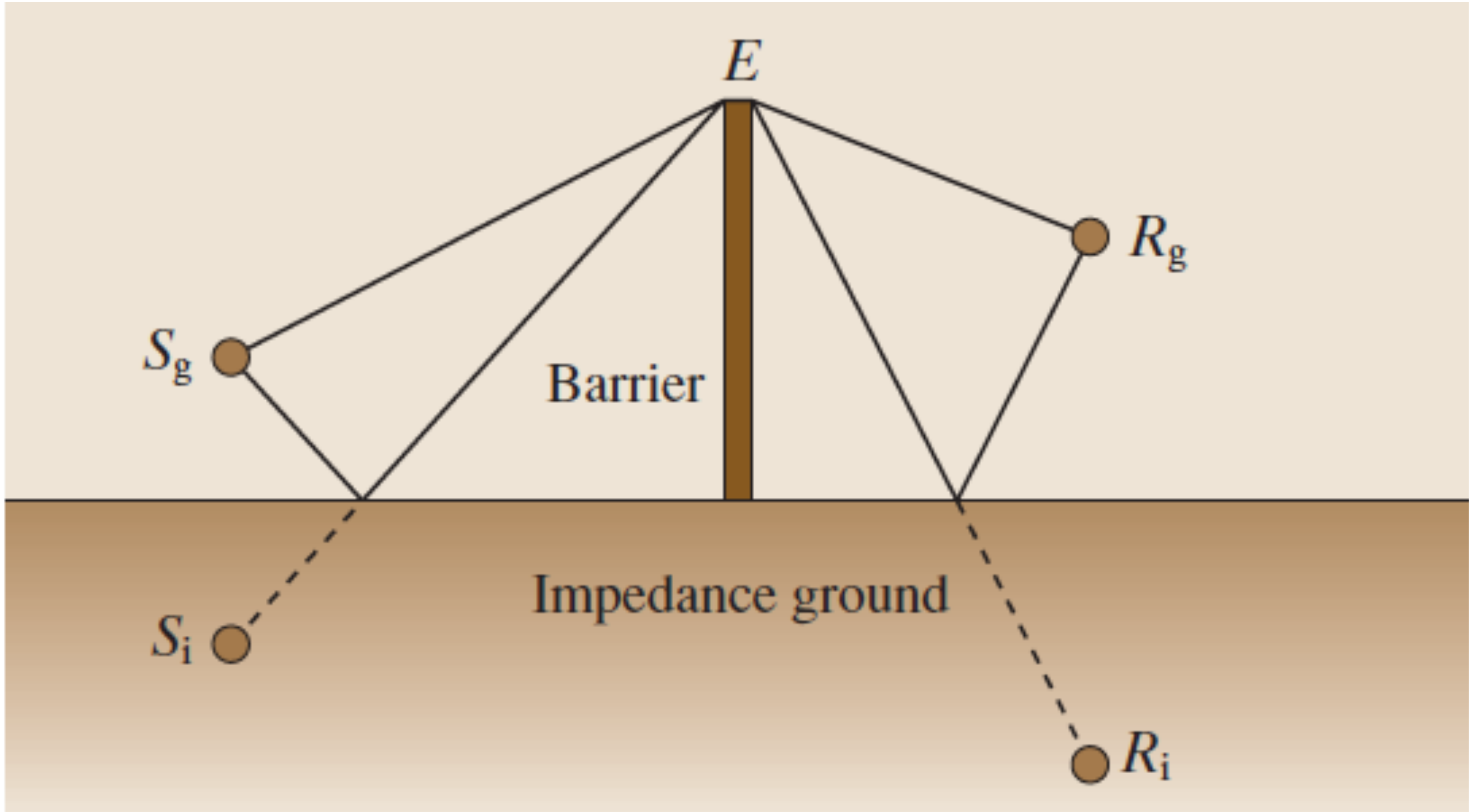
Screening



Screening

Ray approach

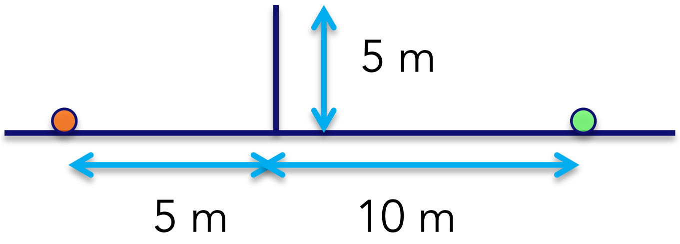
$$P_T = P_1 + Q_s P_2 + Q_R P_3 + Q_s Q_R P_4,$$

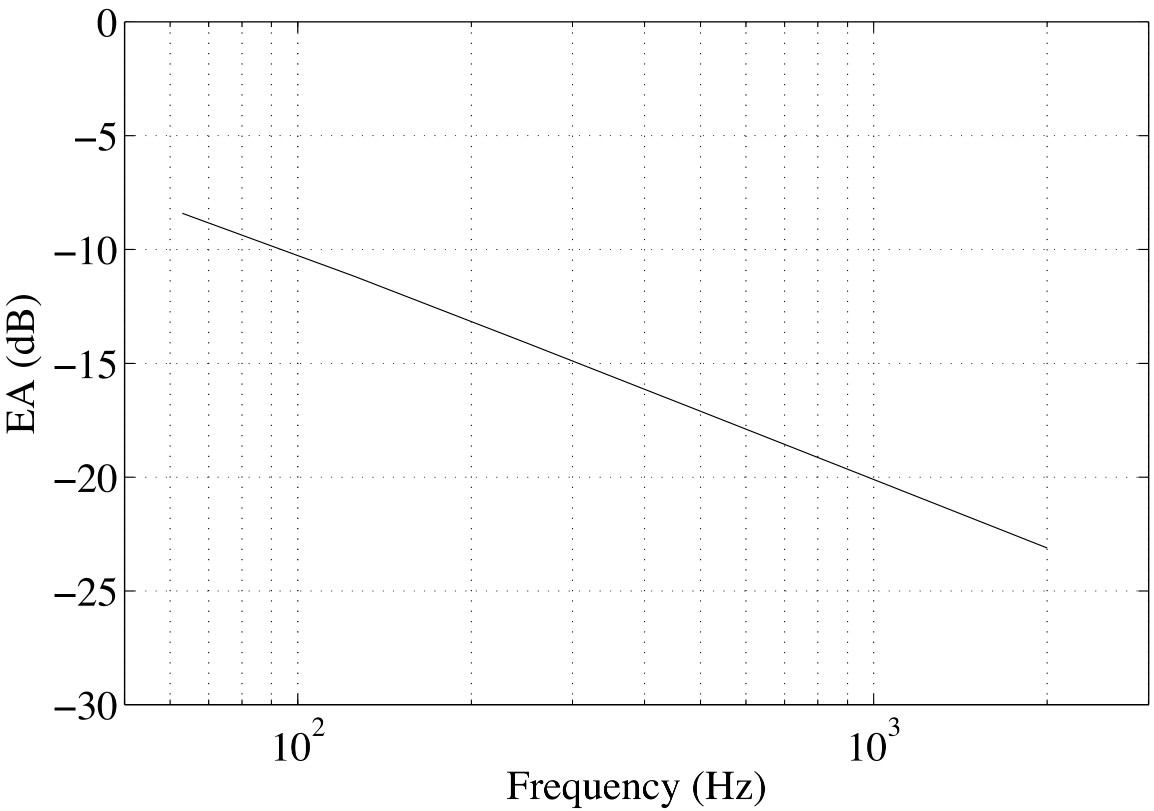


Handbook of Acoustics, Sound propagation in the atmosphere

Screening

Frequency dependency of shielding

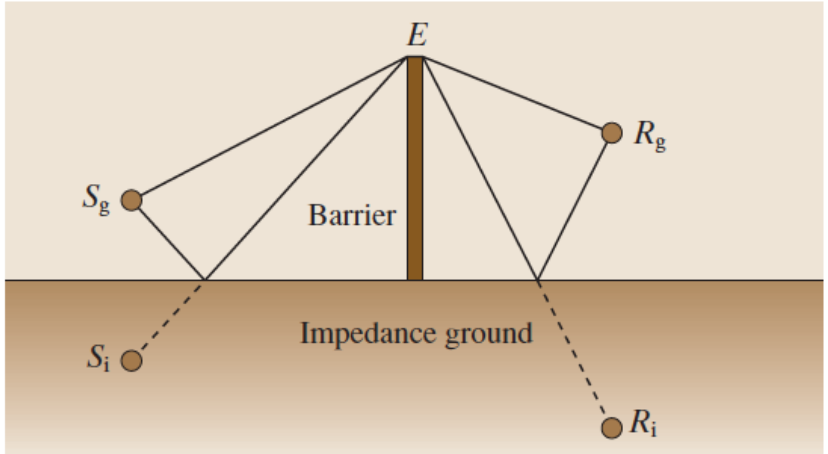




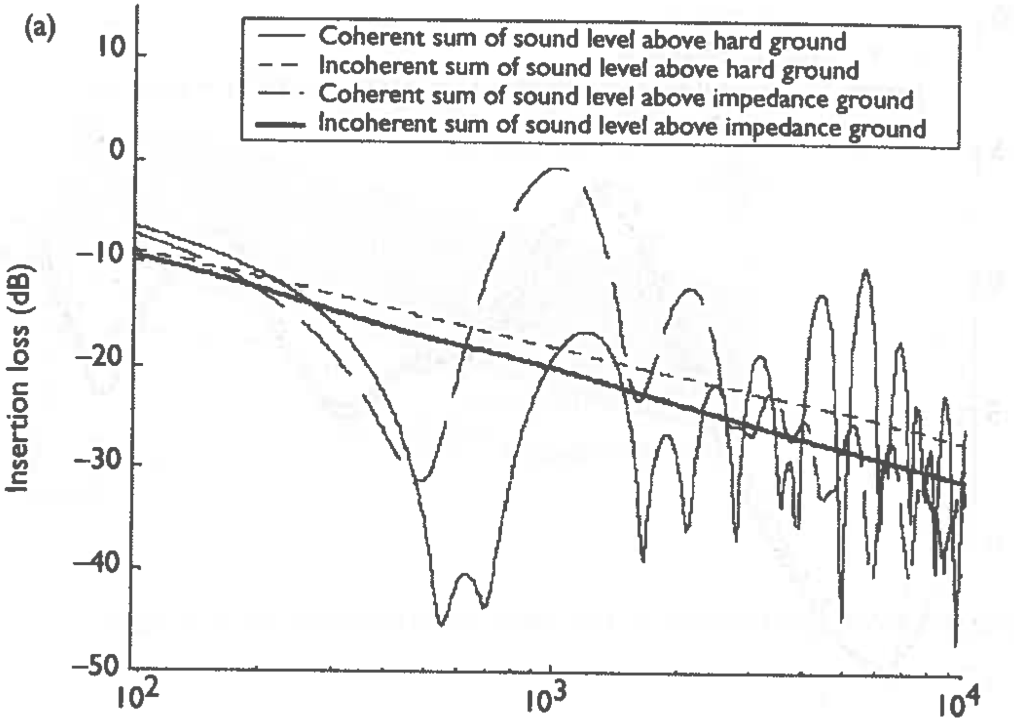
Computed with the diffraction model as presented in: Hadden, J.W. and Pierce, A.D., "Sound diffraction around screens and wedges for arbitrary point source locations," J. Acoust. Soc. Am. 69, 1266-1267, (1981). Erratum; J. Acoust. Soc. Am. 71, 1290, (1982).

Screening

Frequency dependency of shielding



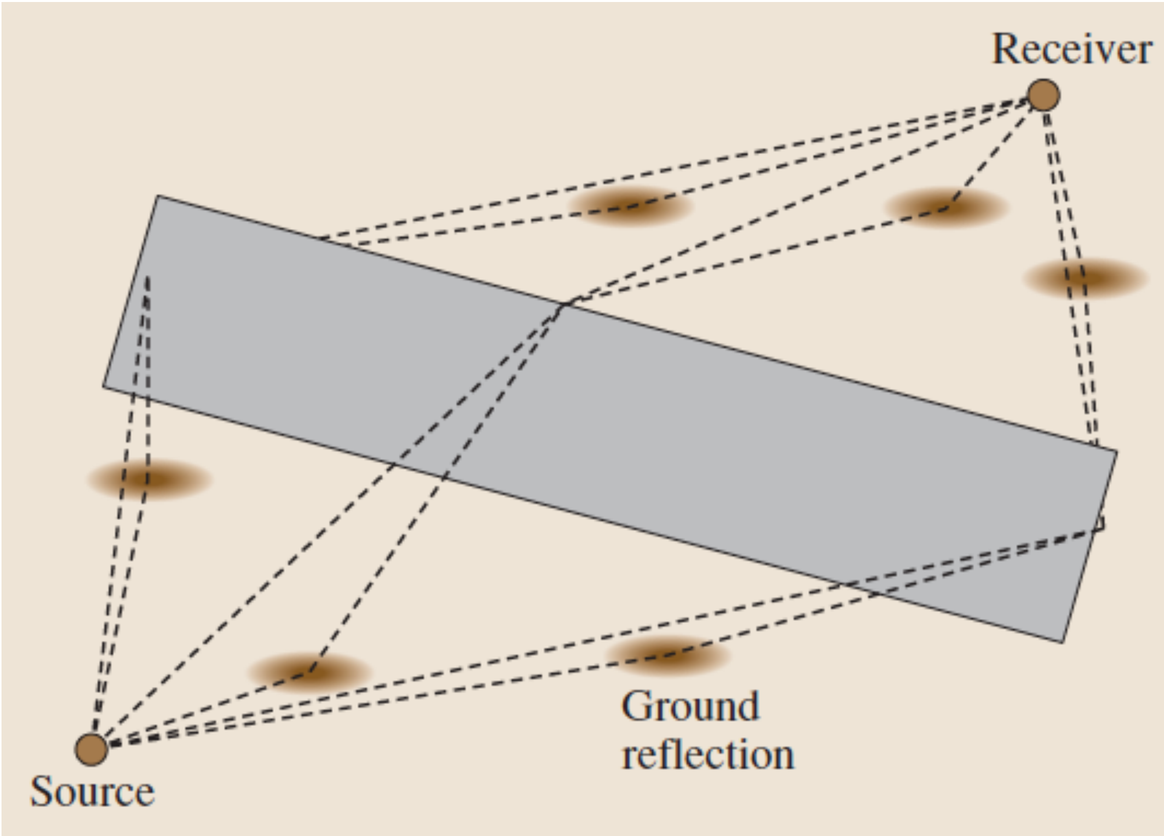
Handbook of Acoustics, Sound propagation in the atmosphere



K. Attenborough et al., Predicting Outdoor Sound

Screening

Finite barrier effect

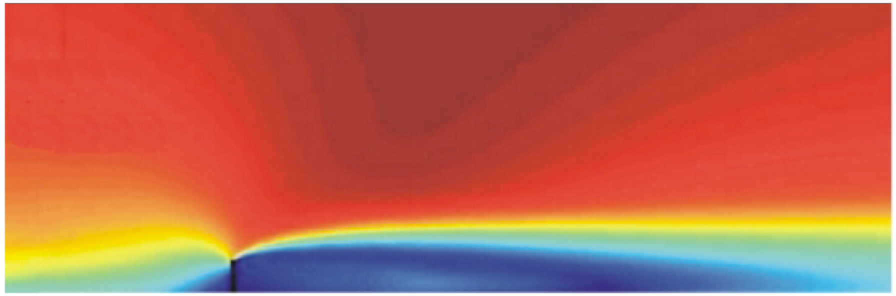


Handbook of Acoustics, Sound propagation in the atmosphere

Screening

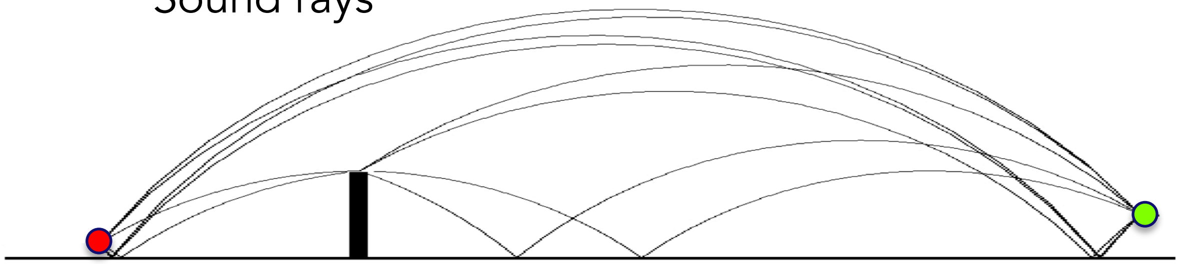
- Unfavourable effects in presence of noise barrier
- Downward refraction due to wind or temperature gradients

Wind field

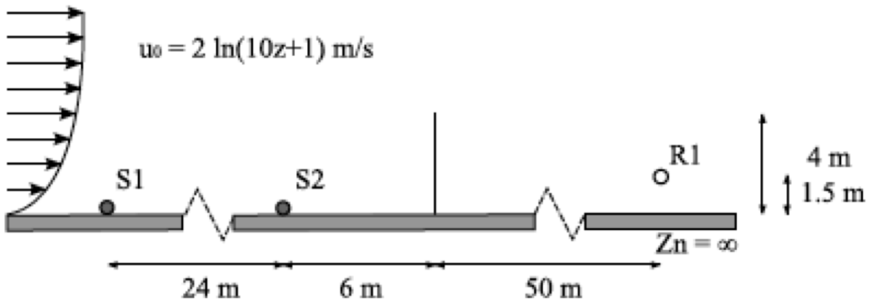


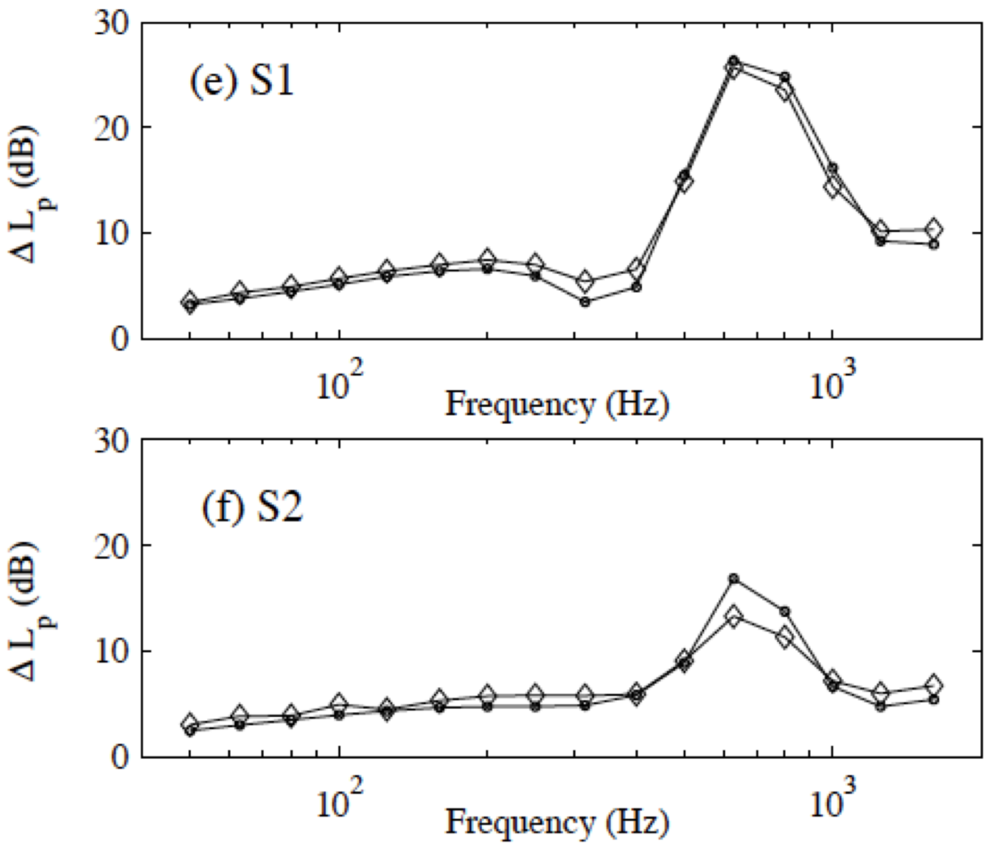
Timothy van Renterghem

Sound rays



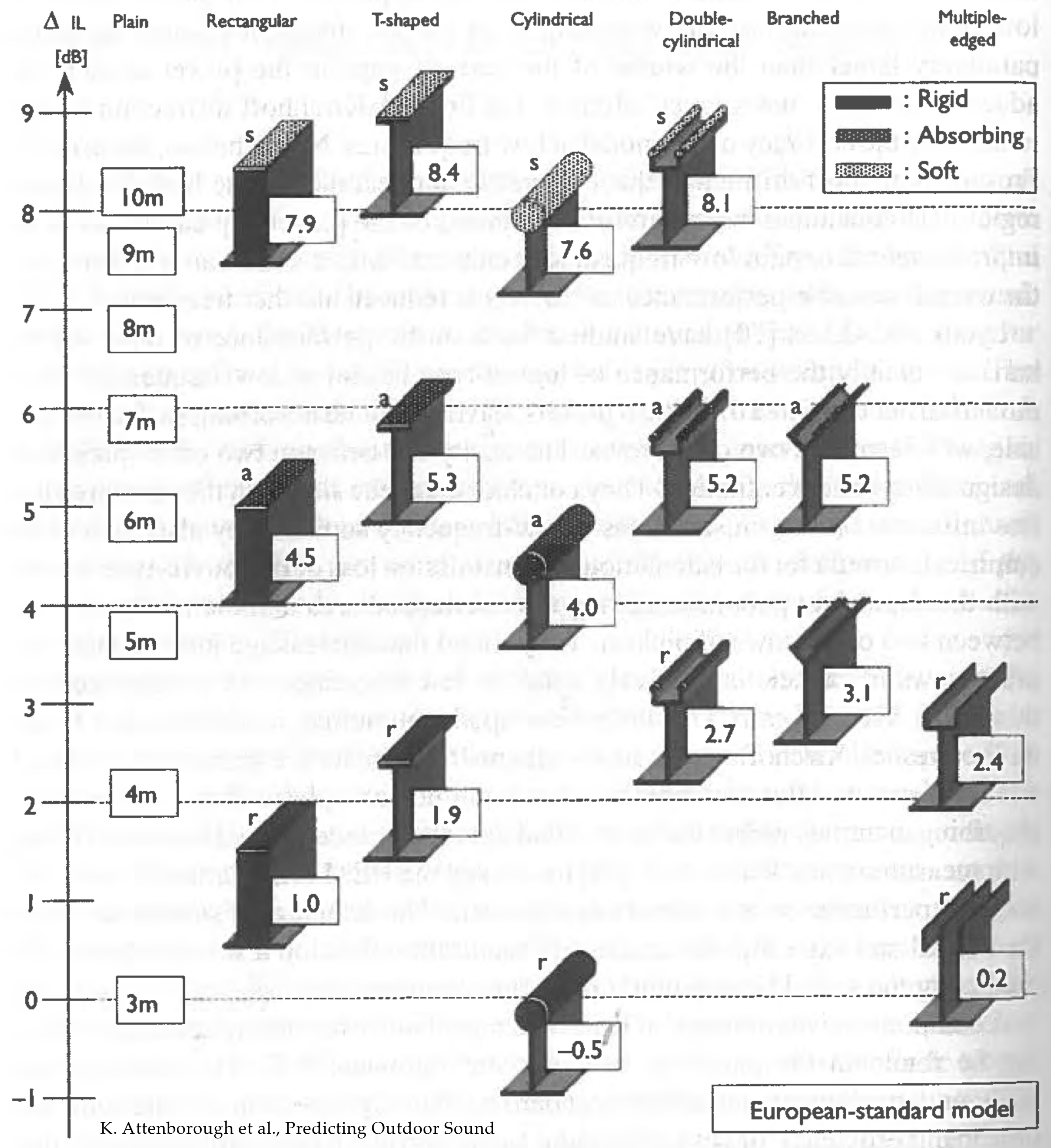
Screening





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.

Screening



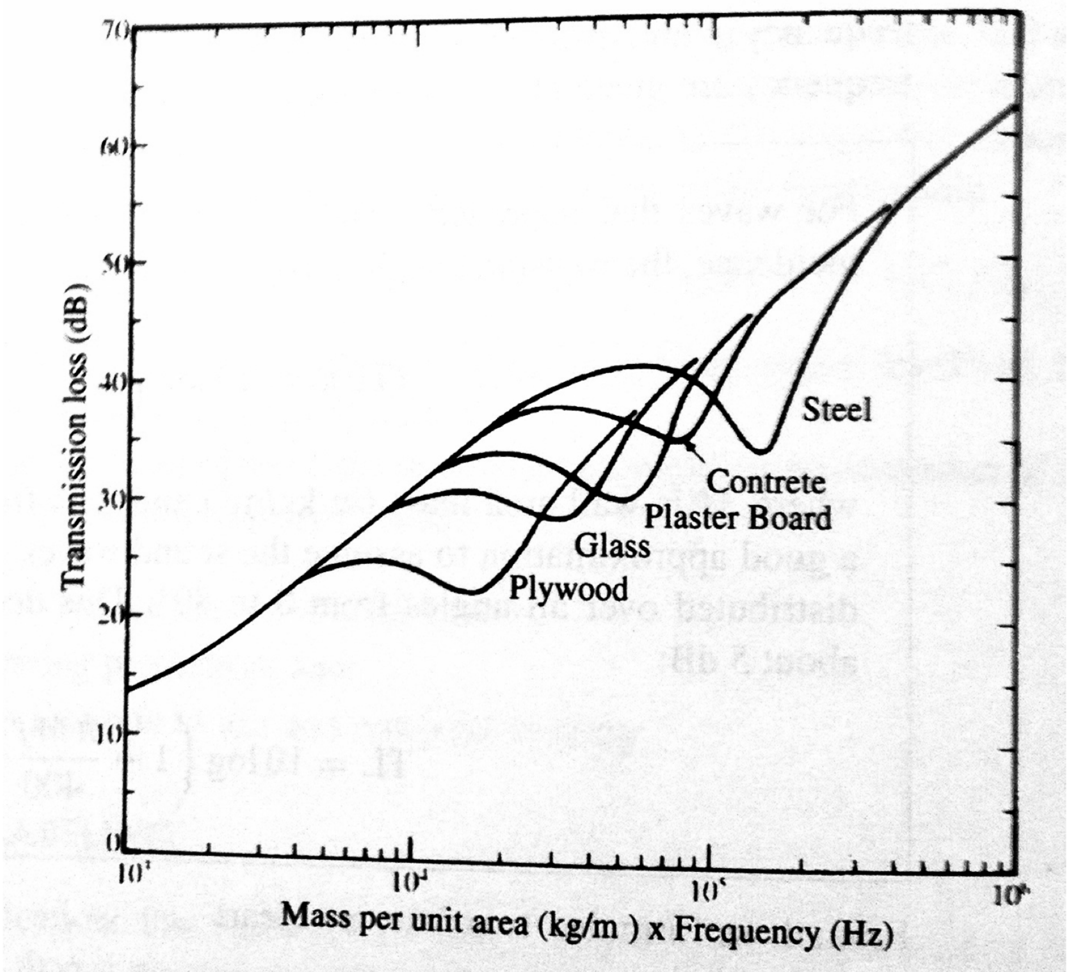
K. Attenborough et al., Predicting Outdoor Sound

The figures indicate the relative change in the mean insertion loss relative to a 3 m plane screen [73]. Reprinted with permission from Elsevier.

Urban aspects

Transmission loss into buildings:

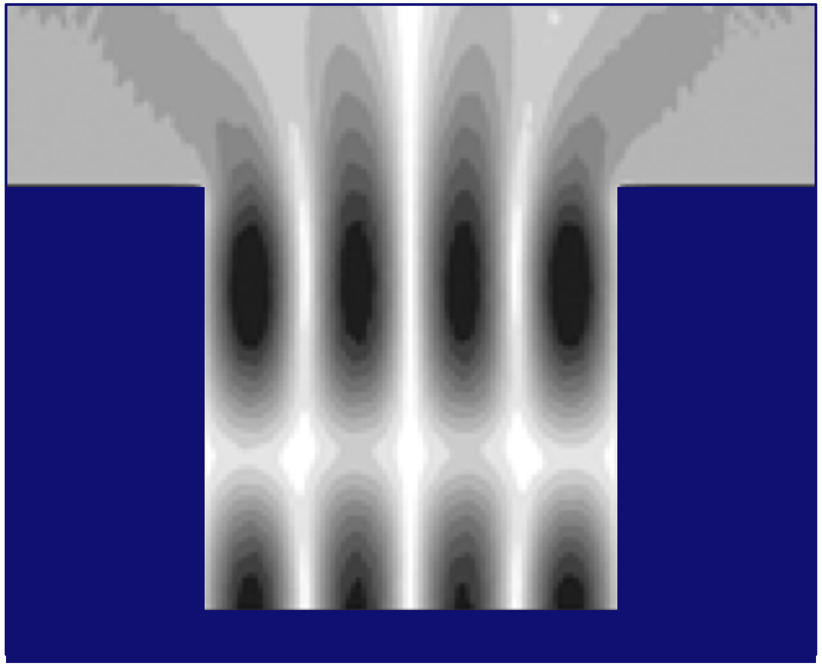
$$\mathrm{TL} = 10\log\left(1 + \frac{\pi M f}{400}\right) - 5.$$



Rossing et al., The science of sound.

Urban aspects

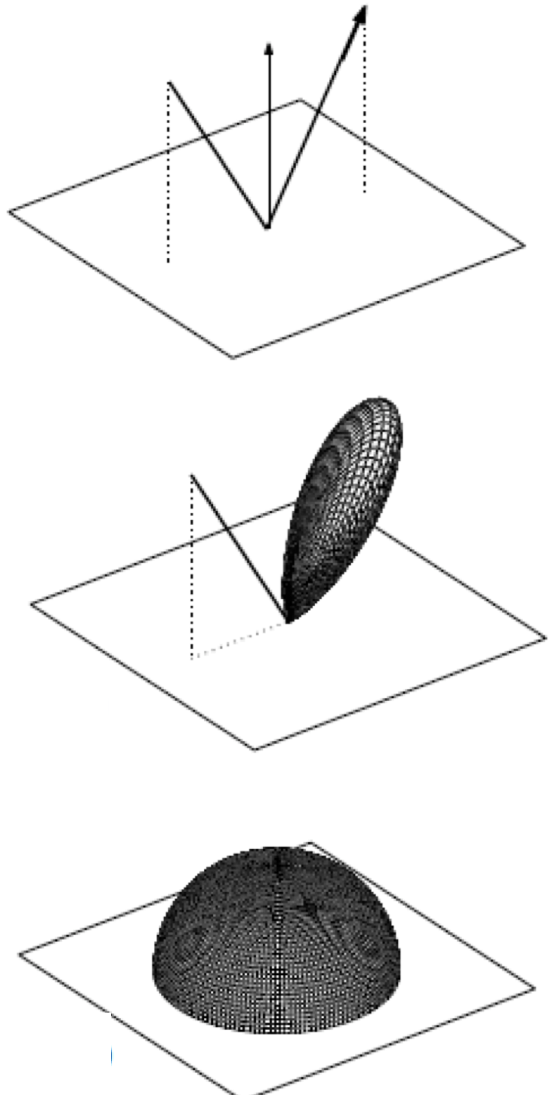
- Inner city configuration comparable with indoor environment
- Interferences may cause high levels locally



Pelat et al., J. Acoust. Soc. Am. 129 (3), 1240–1249

Urban aspects

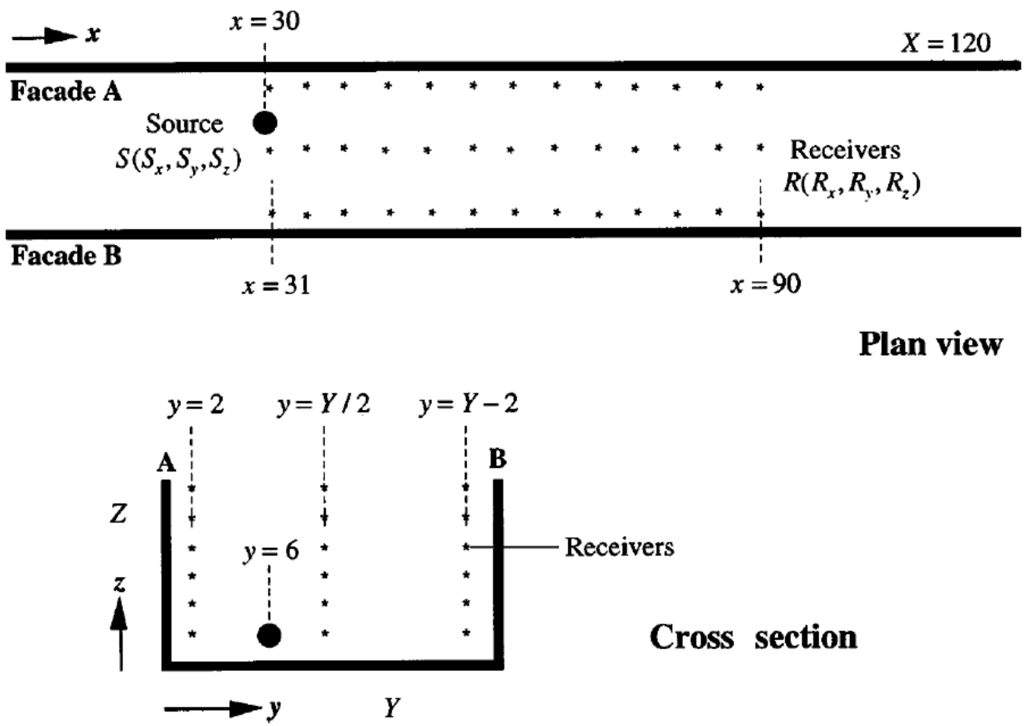
- Reflections from building facades and other surfaces
- Specular versus diffuse reflection

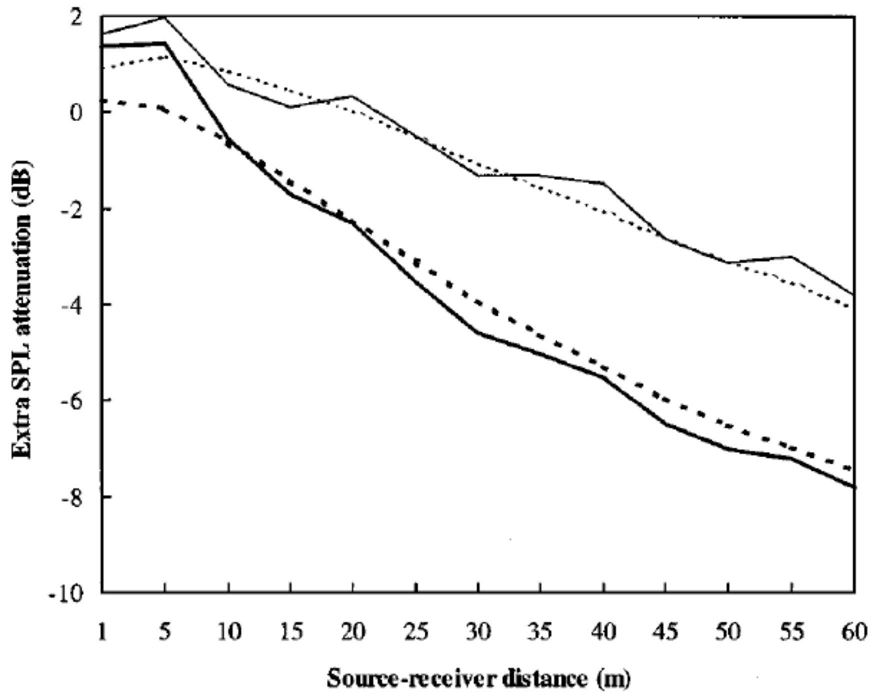


Picaut et al., Acta Acustica united with Acustica 95 (2009), 653-668

Urban aspects

- Attenuation of diffuse façade reflections versus specular reflections

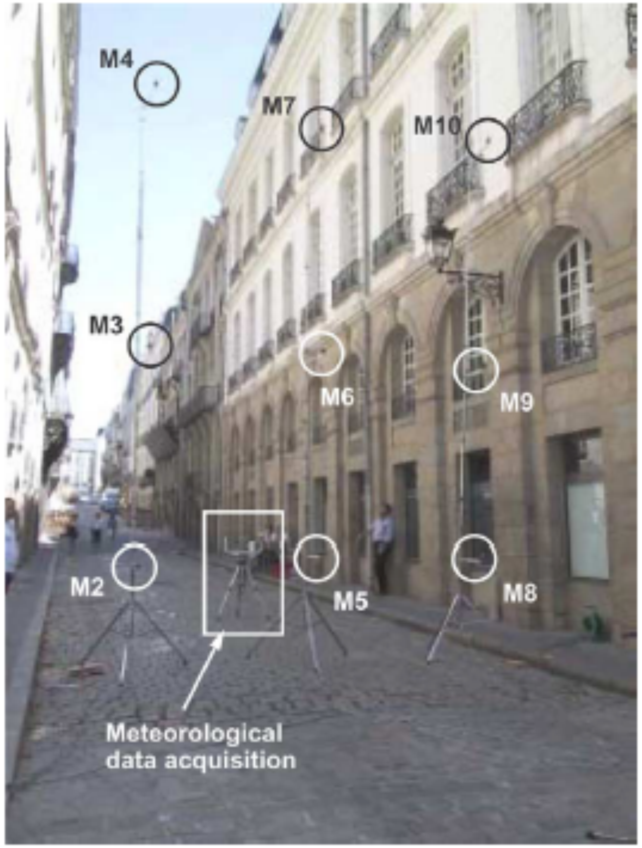


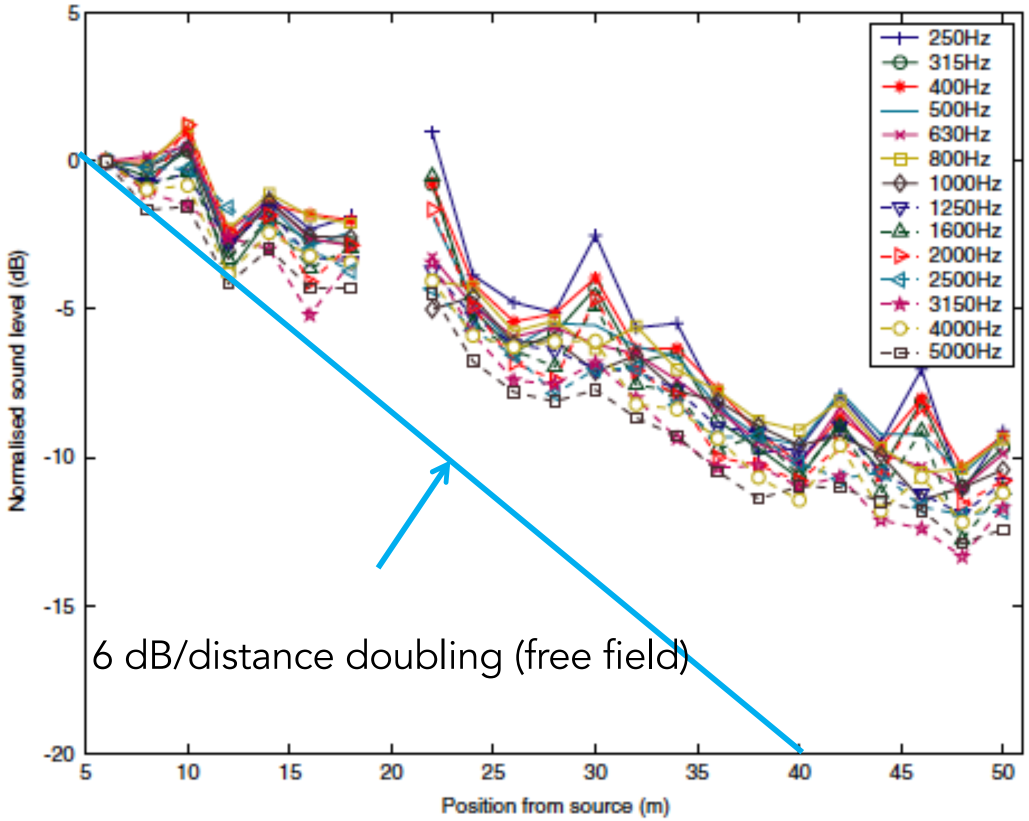


Kang, J., "Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries," J. Acoust. Soc. Am. 107, 1394-1404, (2000).

Urban aspects

Attenuation in street versus free field

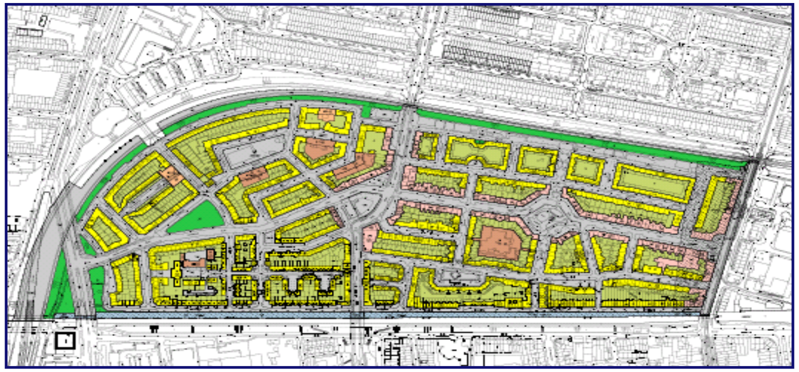




Picaut, J., Le Polles, T., L'Hermite, T., Gary, V. Experimental study of sound propagation in a street. App. Acoust. 66 (2005) 149–173.

Urban aspects

In Amsterdam and other Dutch cities it was common to build with closed housing blocks (courtyards)



http://www.qside.eu

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Low-height barrier: 3–12 dB(A) noise reduction for an urban road

Thomas *et al*. Auralisation of a car pass-by behind a low finite-length vegetated noise barrier, Euronoise 2012, 10-13 June, Prague, Czech Republic.

Urban aspects

Green facades

Noise reduction

- 3 to 4 dB(A) reduction in courtyard*
- 2 to 3 dB(A) in trafficked street

*Van Renterghem, T., Hornikx, M., Forssen, J., Botteldooren, D., (2013), The potential of building envelope greening to achieve quietness. Build. Environ., **61**, 34-44.

Urban aspects

Green roofs

Noise reduction only in courtyard:

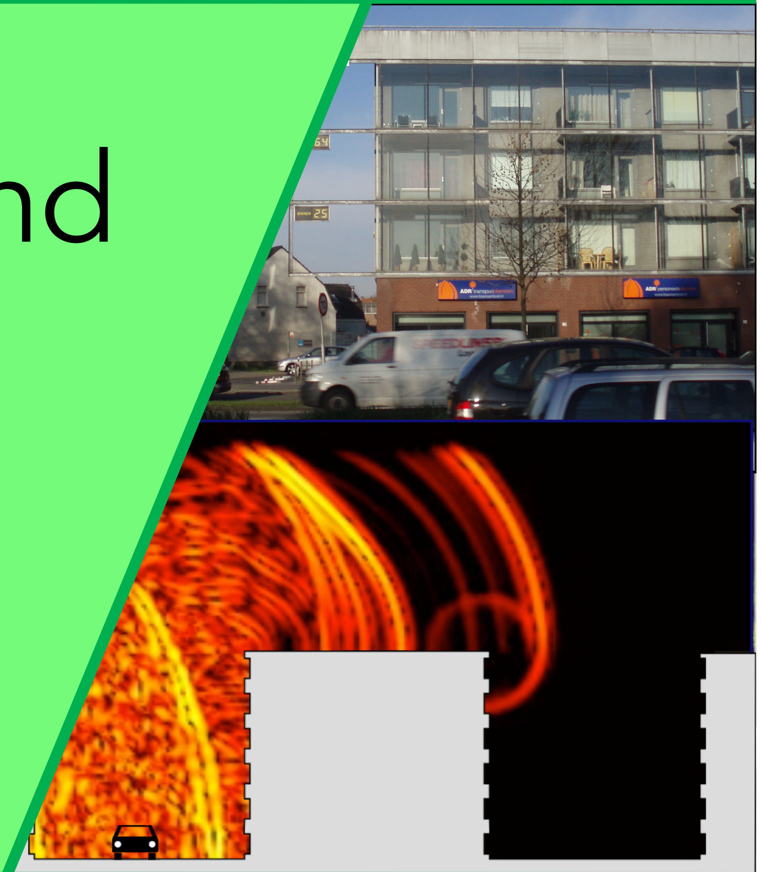
- 2.5 dB(A) for flat roofs and
- 8 dB(A) for angled roofs

*Van Renterghem, T., Hornikx, M., Forssen, J., Botteldooren, D., (2013), The potential of building envelope greening to achieve quietness. Build. Environ., **61**, 34-44.

The Science of Sound

Environmental Acoustics

prof.dr.ir. Maarten Hornikx



www.tue.nl/buildingacoustics
www.building-acoustics.net

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