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Acoustics
Noise
Vibration

Modelling Sound in the Atmosphere

Presented by:

Nicholas Sylvestre-Williams
Aercoustics Engineering Ltd.

October 21, 2013

AIR & WASTE MANAGEMENT ASSOCIATION
ONTARIO SECTION

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Introduction

The Air & Waste Management Association (A&WMA) is a non-profit, nonpartisan professional organization that enhances knowledge and expertise by providing a neutral forum for technology exchange, professional development, networking opportunities, public education, and outreach to more than 9000 environmental professionals in 65 countries.

Aercoustics Engineering Limited has dedicated itself to providing high quality consulting services in the science and engineering of acoustics, noise and vibration control since 1971.

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Introduction

Rules

- Please turn off cell phones
    - Do not take calls; do not check email
- Ask questions any time
- Group discussion encouraged
    - Only 1 person talking at a time
- There is no foolish question
    - Unless you ask to go to the bathroom

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Objectives

Your presenter:

- Specializes in Environmental noise & vibration
- Provided expert testimony in environmental noise cases
- Principal at Aercoustics
- All-around nice guy

Introduction

The audience

- Who are you?
- Who do you work for?
- What is your experience?
- What do you hope to get today?

Objectives

1. To understand the mechanisms affecting outdoor sound propagation.
2. To understand the current ray tracing models used today.
3. To understand the modern numerical models.

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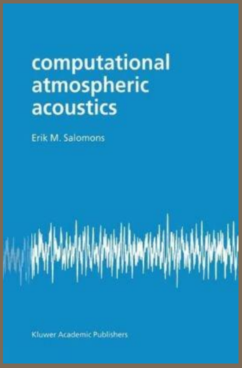
References



- Author: E.M. Salomons.
- ISBN: 0792371615

- Author: Attenborough & Li
- ISBN: 0419235108

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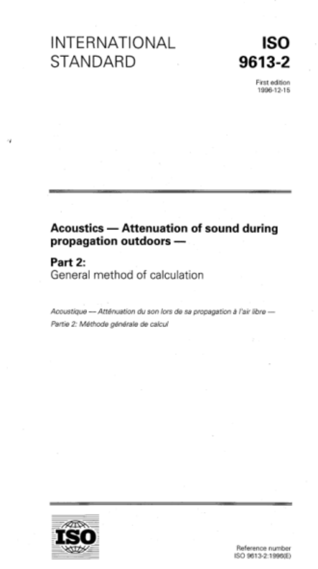
References



INTERNATIONAL
STANDARD

ISO
9613-2

First edition
1996-12-15

Acoustics — Attenuation of sound during propagation outdoors —

Part 2:
General method of calculation

Acoustique — Atténuation du son lors de sa propagation à l'air libre —
Partie 2: Méthode générale de calcul

ISO

Reference number
ISO 9613-2:1996(E)

ISO 9613-2

- Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculations

What do you need to know?

You should have a fundamental understanding of acoustics!

You should know:

- That sound is a wave
- A bit of wave theory (e.g. Fresnel number, complex number)
- The difference between sound power and sound pressure
- A passing familiarity with ISO 9613-2

What do you need to know?

Sound Propagation

Outdoor sound is attenuated by

- distance,
- interaction with the ground,
- atmospheric effects
- and Topography/barriers,

Sound Propagation

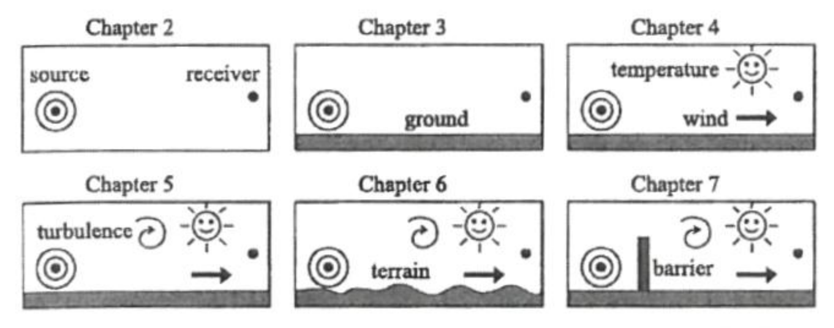


*Figure 1.2 from E. Salomons, pg. 3.

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Sound Propagation

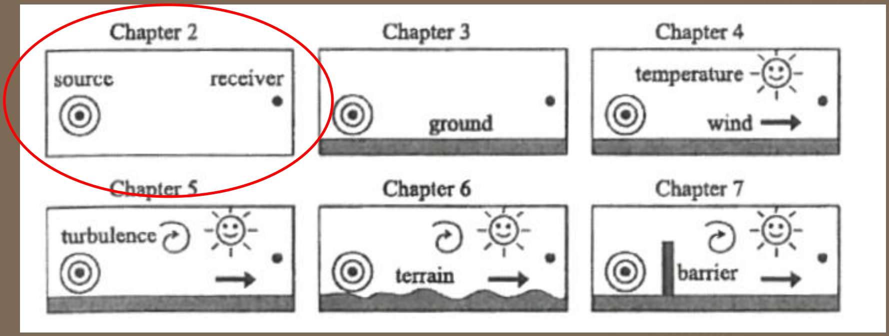

*Figure 1.2 from E. Salomons, pg. 3.

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Waves

Wave Equation:

$$\nabla^2 p + \frac{1}{c^2}\frac{\delta^2 p}{\delta t^2} = 0$$

We cannot solve a differential equation without boundary equations and initial conditions

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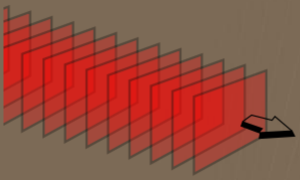
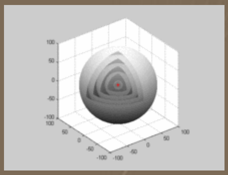
Type Of Waves

- Plane Wave



- Spherical Wave



Wave Equation

Wave Equation:

$$\nabla^2 p + \frac{1}{c^2}\frac{\delta^2 p}{\delta t^2} = 0$$

Solution to Wave travelling in x-direction:

$$p(x,t) = A\cos(kx - \omega t)$$

Or

$$p(x,t) = Re\left[A\,(x)\,e^{ikx}e^{-i\omega t}\right]$$

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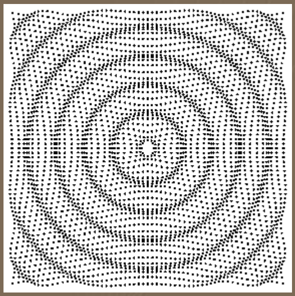
Point Source

Wave Equation:

$$\nabla^2 p + \frac{1}{c^2}\frac{\delta^2 p}{\delta t^2} = 0$$

Solution for Spherical Wave

$$p = \frac{A}{r}e^{ikr}$$



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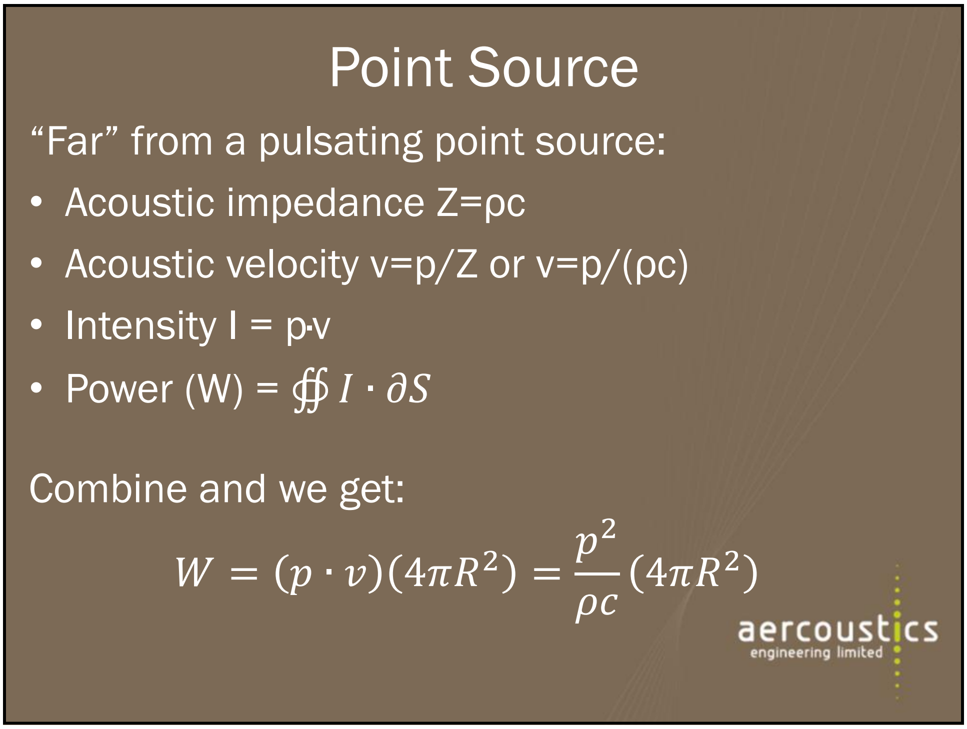


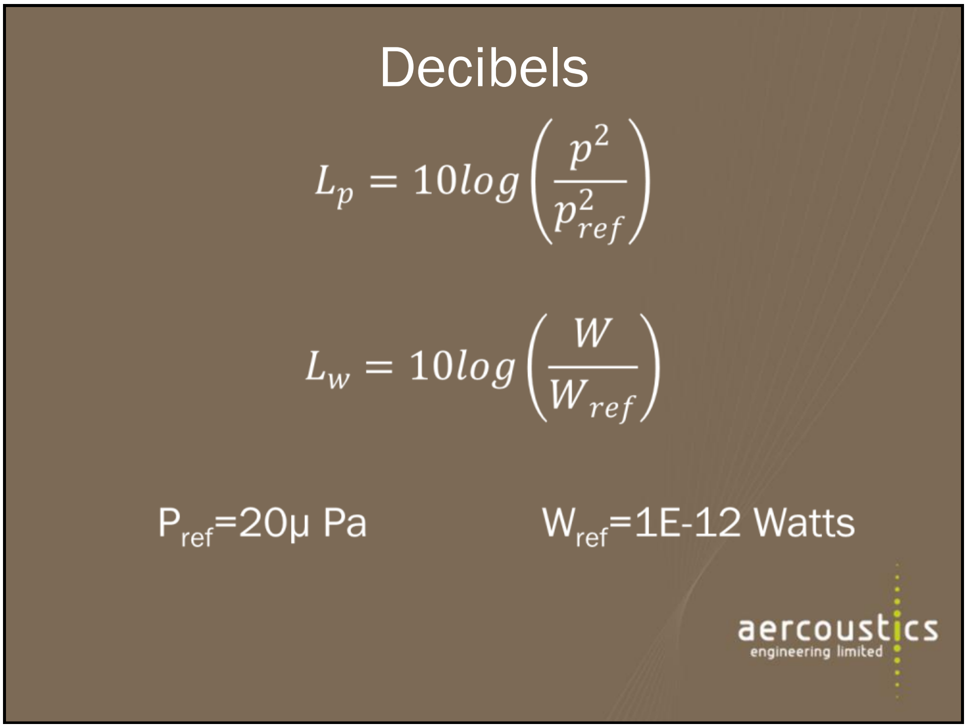
Point Source

"Far" from a pulsating point source:

- Acoustic impedance Z=ρc
- Acoustic velocity v=p/Z or v=p/(ρc)
- Intensity I = p·v
- Power (W) = $\oiint I \cdot \partial S$

Combine and we get:

$$W = (p \cdot v)(4\pi R^2) = \frac{p^2}{\rho c}(4\pi R^2)$$

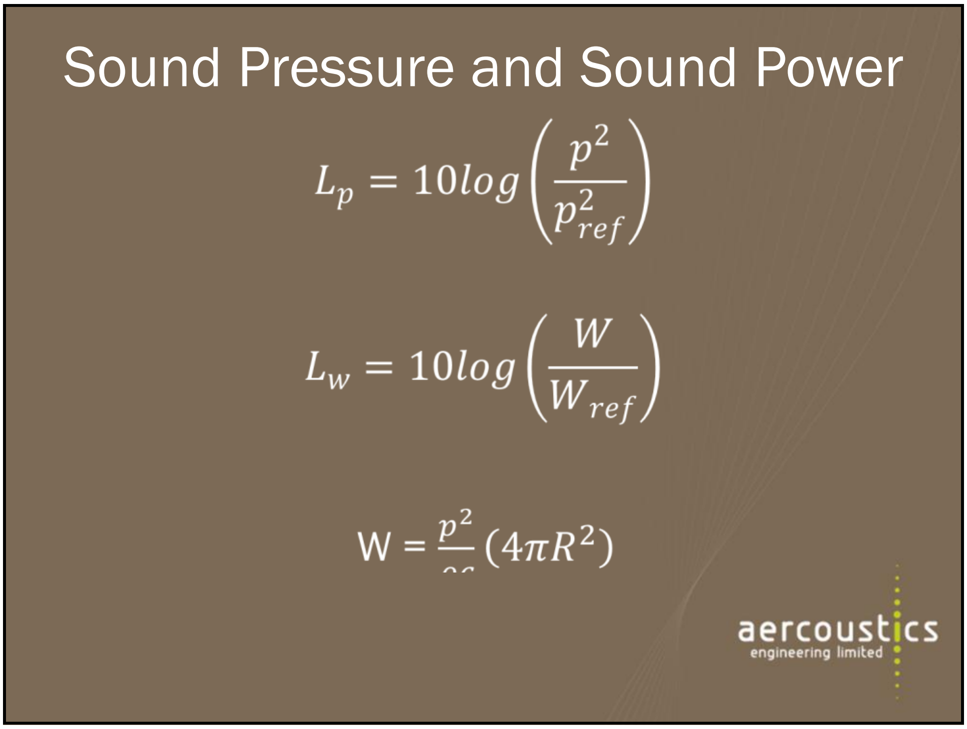


Decibels

$$L_p = 10log\left(\frac{p^2}{p_{ref}^2}\right)$$

$$L_w = 10log\left(\frac{W}{W_{ref}}\right)$$

P_{ref}=20μ Pa W_{ref}=1E-12 Watts



Sound Pressure and Sound Power

$$L_p = 10log\left(\frac{p^2}{p_{ref}^2}\right)$$

$$L_w = 10log\left(\frac{W}{W_{ref}}\right)$$

$$\mathrm{W} = \frac{p^2}{\rho c}(4\pi R^2)$$

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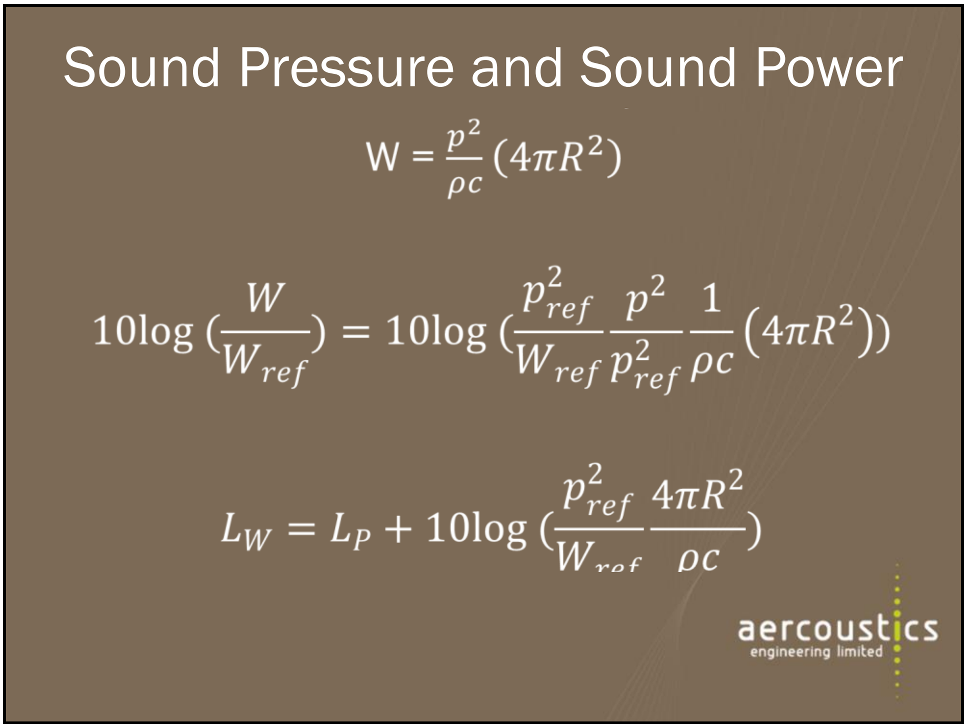

Sound Pressure and Sound Power

$$\mathrm{W} = \frac{p^2}{\rho c}(4\pi R^2)$$

$$10\log\left(\frac{W}{W_{ref}}\right) = 10\log\left(\frac{p_{ref}^2}{W_{ref}}\frac{p^2}{p_{ref}^2}\frac{1}{\rho c}(4\pi R^2)\right)$$

$$L_W = L_P + 10\log\left(\frac{p_{ref}^2}{W_{ref}}\frac{4\pi R^2}{\rho c}\right)$$

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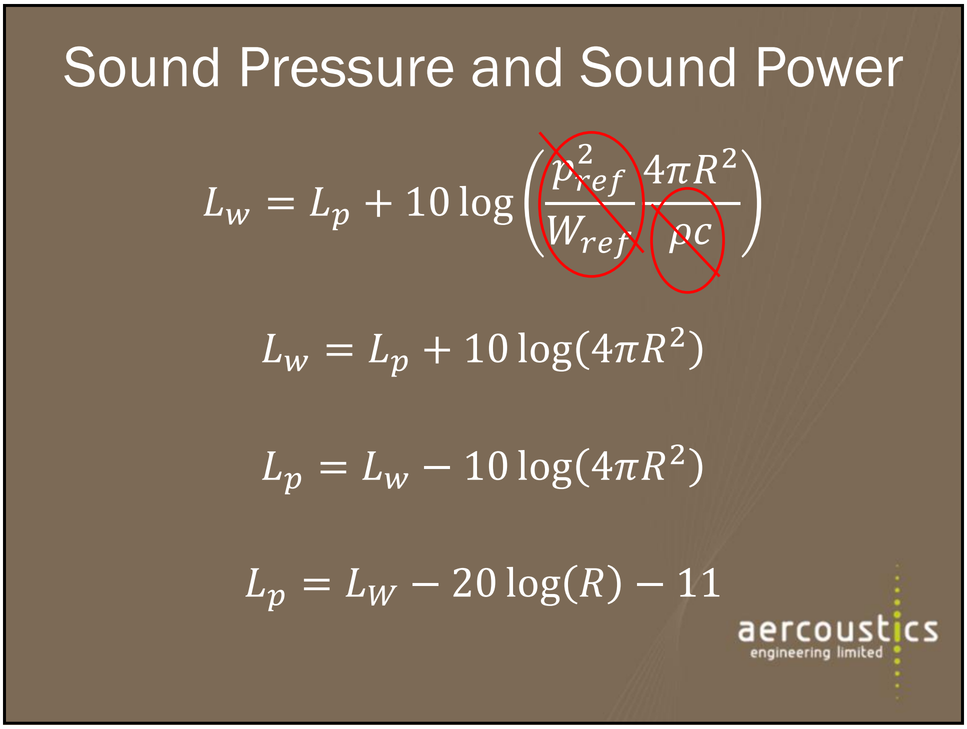


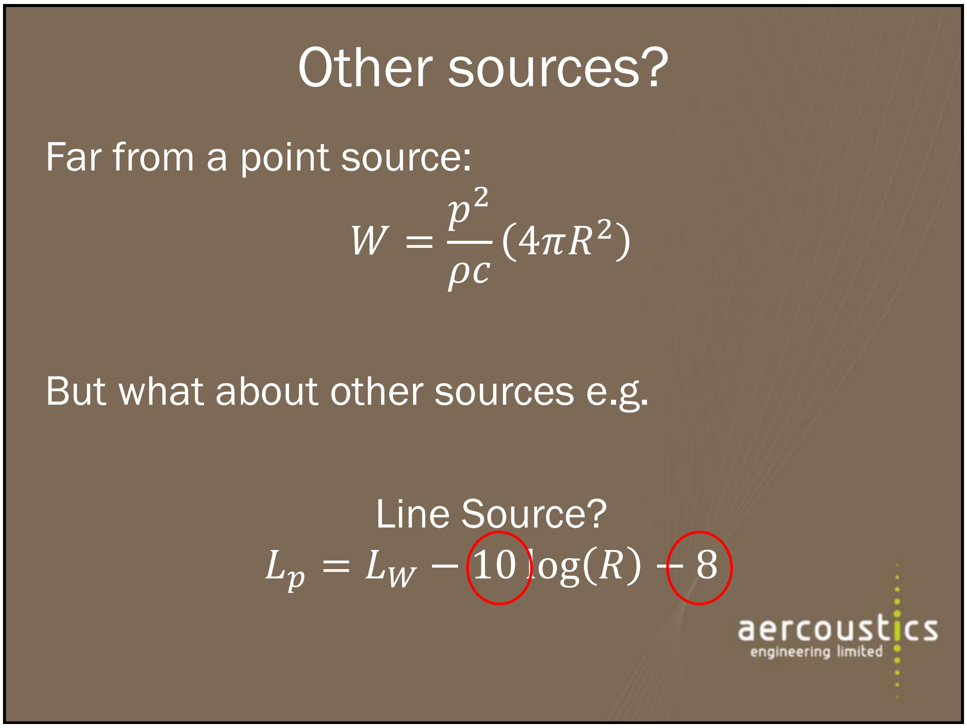
Sound Pressure and Sound Power

$$L_w = L_p + 10\log\left(\cancel{\frac{p_{ref}^2}{W_{ref}}}\,\frac{4\pi R^2}{\cancel{\rho c}}\right)$$

$$L_w = L_p + 10\log(4\pi R^2)$$

$$L_p = L_w - 10\log(4\pi R^2)$$

$$L_p = L_W - 20\log(R) - 11$$



Other sources?

Far from a point source:

$$W = \frac{p^2}{\rho c}(4\pi R^2)$$

But what about other sources e.g.

Line Source?

$$L_p = L_W - \boxed{10}\log(R) \boxed{-8}$$

Sound Propagation

Outdoor sound is attenuated by

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Sound Propagation

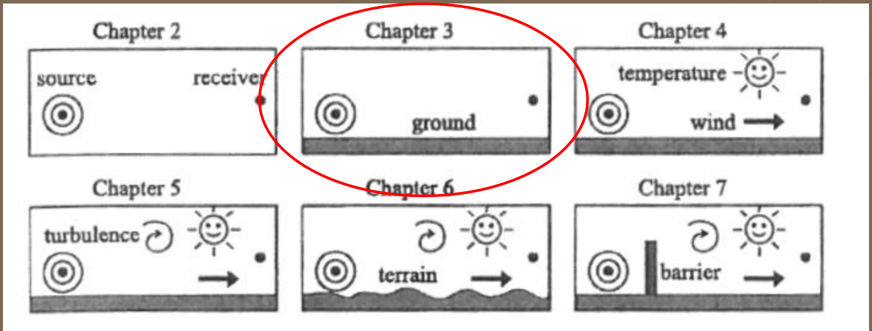

*Figure 1.2 from E. Salomons, pg. 3.

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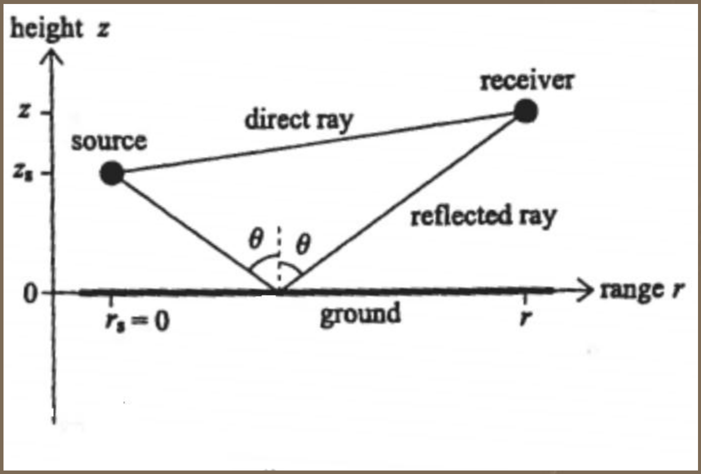
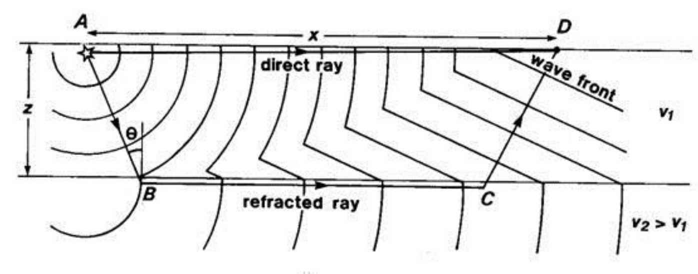
Sound Reflection off Ground



Point Source with Ground

Point Source: $p = \frac{A}{R} e^{-ikR}$



$$p_T = \frac{A}{R_1} e^{-ikR_1} + R_p \frac{A}{R_2} e^{-ikR_2} + (1 - R_p) F \frac{A}{R_2} e^{-ikR_2}$$

Spherical Wave Reflection

$$P_T = \frac{A}{R_1} e^{-ikR_1} + R_p \cdot \frac{A}{R_2} e^{-ikR_2} + (1 - R_p) \cdot F(w) \cdot \frac{A}{R_2} e^{-ikR_2}$$

where

$$F(w) = 1 - i\sqrt{\pi} \cdot w \cdot e^{-w^2} \cdot erfc(i \cdot w)$$

Where

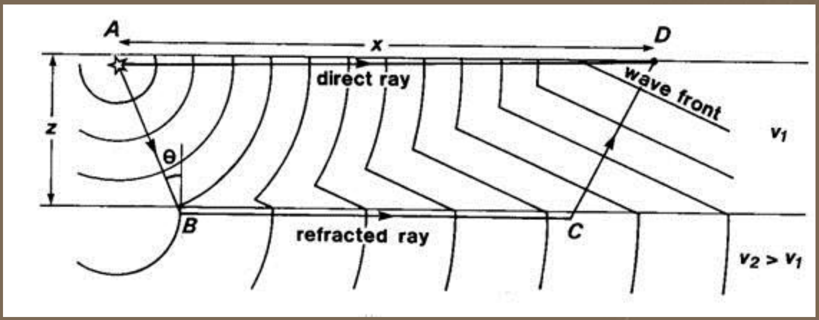
$$w = \frac{1}{2} \cdot (1 - i) \cdot \sqrt{kR_2} \cdot [\cos(\theta) + \beta]$$

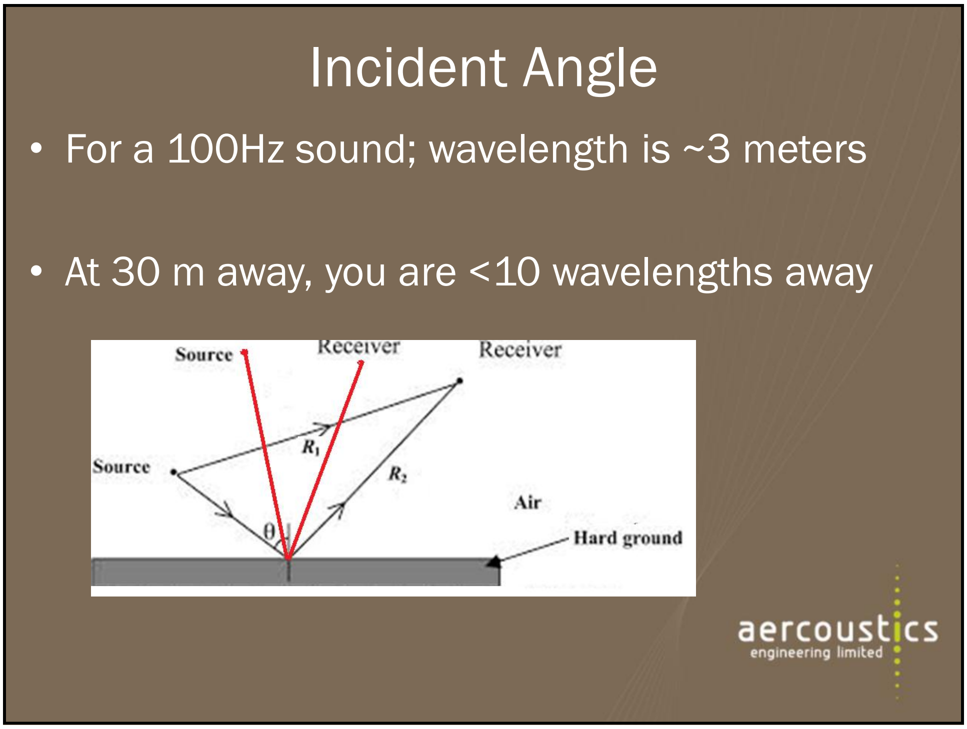
Where

β is the acoustic admittance of the ground

Real World

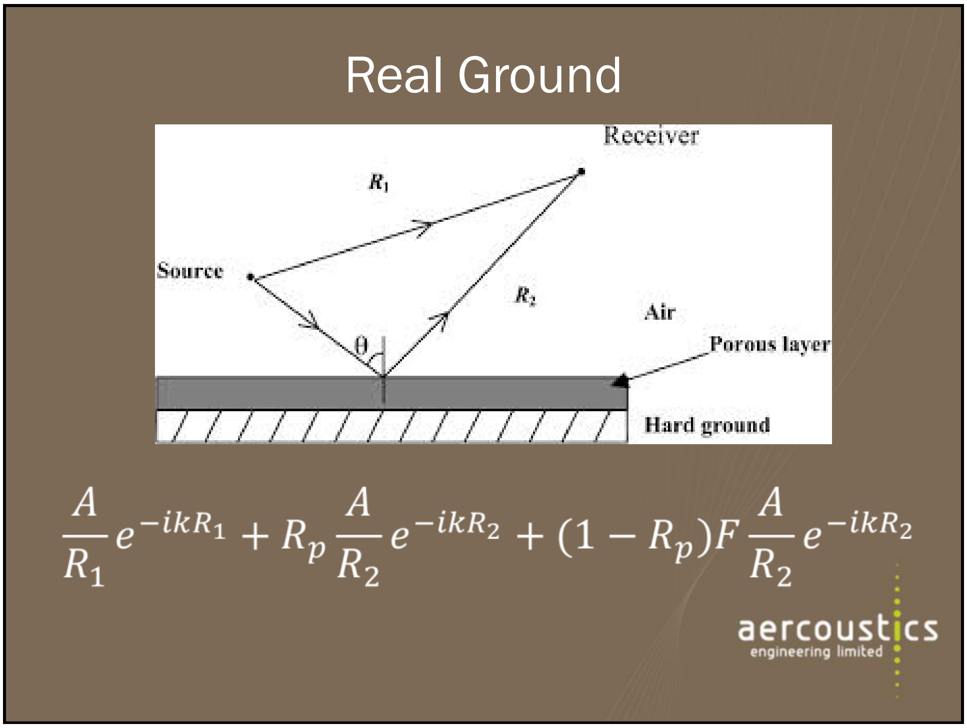
- For a spherical wave, the equations are ***very*** complicated.





Incident Angle

- For a 100Hz sound; wavelength is ~3 meters
- At 30 m away, you are <10 wavelengths away



Real Ground

$$\frac{A}{R_1}e^{-ikR_1} + R_p\frac{A}{R_2}e^{-ikR_2} + (1-R_p)F\frac{A}{R_2}e^{-ikR_2}$$

What do we do?

Currently used?

$L_{PT} = L_{p(direct)} + (1\text{-}G)\ L_{p(ground)}$

- Other empirical methods exist
- Modern algorithms try to take into account flow resistivity.

Real Grounds?

What about ground roughness?

What about ground elasticity?

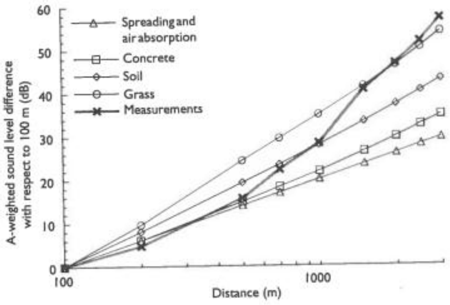
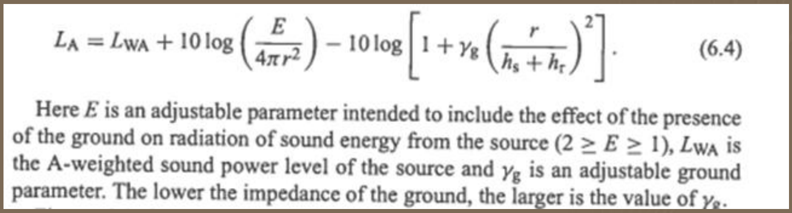


Figure 6.8 Measured differences (joined crosses) between the A-weighted sound level at 100 m and those measured at ranges up to 3 km during an Il-86 aircraft's engine test in the direction of maximum jet noise generation (~ 40° from exhaust axis) and predictions for levels due to a point source at the engine centre height assuming spherical spreading plus air absorption and various types of ground [12]. Reprinted with permission from Elsevier.

Real Grounds?

There are simplified empirical formulae proposed by others e.g.



$$L_A = L_{WA} + 10\log\left(\frac{E}{4\pi r^2}\right) - 10\log\left[1 + \gamma_g\left(\frac{r}{h_s + h_r}\right)^2\right]. \qquad (6.4)$$

Here E is an adjustable parameter intended to include the effect of the presence of the ground on radiation of sound energy from the source ($2 \geq E \geq 1$), L_{WA} is the A-weighted sound power level of the source and γ_g is an adjustable ground parameter. The lower the impedance of the ground, the larger is the value of γ_g.

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Sound Propagation

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Sound Propagation

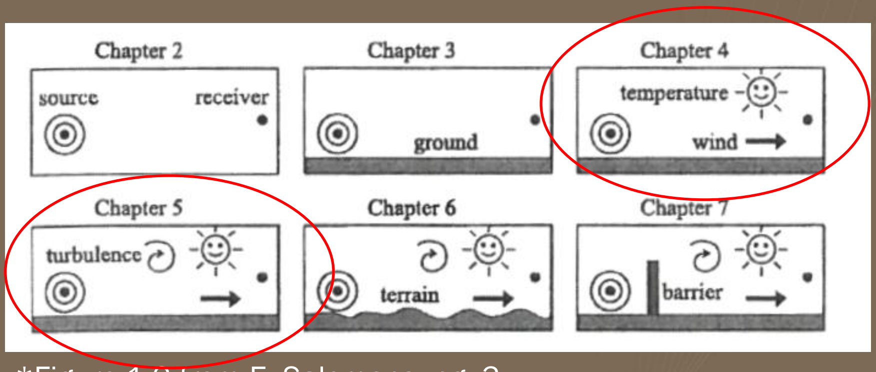

*Figure 1.2 from E. Salomons, pg. 3.

The Atmosphere

There are a number of ways the atmosphere affects sound propagation:

- The air absorbs sound energy
- The air bends/refracts sound waves
- Turbulence changes the phase of sound waves

Absorption

Two mechanisms by which acoustic energy is absorbed by the atmosphere.

1. *Molecular relaxation*
2. *Viscosity effects.*

- High frequencies are absorbed more than low.
- The amount of absorption depends on the temperature and humidity of the atmosphere.

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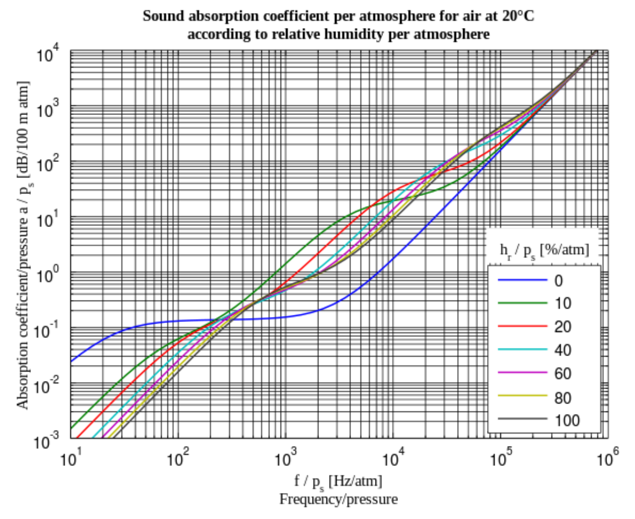
Absorption



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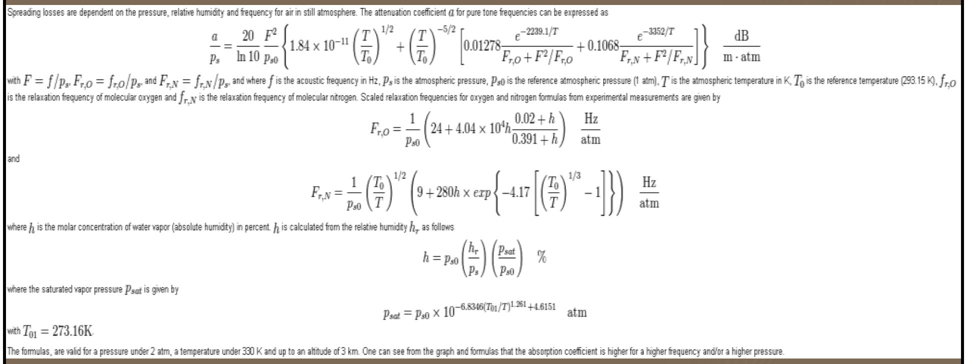
Absorption



Spreading losses are dependent on the pressure, relative humidity and frequency for air in still atmosphere. The attenuation coefficient a for pure tone frequencies can be expressed as

$$\frac{a}{p_s} = \frac{20}{\ln 10}\frac{F^2}{p_{s0}}\left\{1.84\times10^{-11}\left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2}\left[0.01278\frac{e^{-2239.1/T}}{F_{r,O}+F^2/F_{r,O}} + 0.1068\frac{e^{-3352/T}}{F_{r,N}+F^2/F_{r,N}}\right]\right\} \quad \frac{\mathrm{dB}}{\mathrm{m}\cdot\mathrm{atm}}$$

with $F = f/p_s$, $F_{r,O} = f_{r,O}/p_s$, and $F_{r,N} = f_{r,N}/p_s$, and where f is the acoustic frequency in Hz, p_s is the atmospheric pressure, p_{s0} is the reference atmospheric pressure (1 atm), T is the atmospheric temperature in K, T_0 is the reference temperature (293.15 K), $f_{r,O}$ is the relaxation frequency of molecular oxygen and $f_{r,N}$ is the relaxation frequency of molecular nitrogen. Scaled relaxation frequencies for oxygen and nitrogen formulas from experimental measurements are given by

$$F_{r,O} = \frac{1}{p_{s0}}\left(24 + 4.04\times10^4 h\frac{0.02+h}{0.391+h}\right) \quad \frac{\mathrm{Hz}}{\mathrm{atm}}$$

and

$$F_{r,N} = \frac{1}{p_{s0}}\left(\frac{T_0}{T}\right)^{1/2}\left(9 + 280h\times exp\left\{-4.17\left[\left(\frac{T_0}{T}\right)^{1/3} - 1\right]\right\}\right) \quad \frac{\mathrm{Hz}}{\mathrm{atm}}$$

where h is the molar concentration of water vapor (absolute humidity) in percent. h is calculated from the relative humidity h_r as follows

$$h = p_{s0}\left(\frac{h_r}{p_s}\right)\left(\frac{p_{sat}}{p_{s0}}\right) \quad \%$$

where the saturated vapor pressure p_{sat} is given by

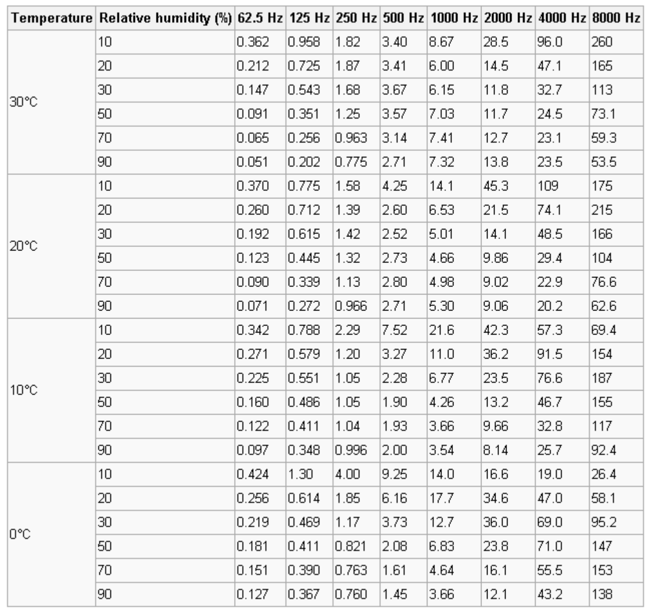
$$p_{sat} = p_{s0}\times10^{-6.8346(T_{01}/T)^{1.261}+4.6151} \quad \mathrm{atm}$$

with $T_{01} = 273.16\mathrm{K}$.

The formulas, are valid for a pressure under 2 atm, a temperature under 330 K and up to an altitude of 3 km. One can see from the graph and formulas that the absorption coefficient is higher for a higher frequency and/or a higher pressure.

http://en.wikibooks.org/wiki/Engineering_Acoustics/Outdoor_Sound_Propagation

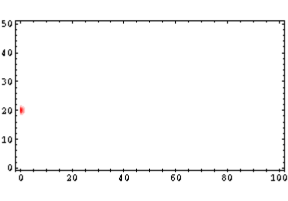
Absorption (dB/km)



Temperature	Relative humidity (%)	62.5 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
30°C	10	0.362	0.958	1.82	3.40	8.67	28.5	96.0	260
	20	0.212	0.725	1.87	3.41	6.00	14.5	47.1	165
	30	0.147	0.543	1.68	3.67	6.15	11.8	32.7	113
	50	0.091	0.351	1.25	3.57	7.03	11.7	24.5	73.1
	70	0.065	0.256	0.963	3.14	7.41	12.7	23.1	59.3
	90	0.051	0.202	0.775	2.71	7.32	13.8	23.5	53.5
20°C	10	0.370	0.775	1.58	4.25	14.1	45.3	109	175
	20	0.260	0.712	1.39	2.60	6.53	21.5	74.1	215
	30	0.192	0.615	1.42	2.52	5.01	14.1	48.5	166
	50	0.123	0.445	1.32	2.73	4.66	9.86	29.4	104
	70	0.090	0.339	1.13	2.80	4.98	9.02	22.9	76.6
	90	0.071	0.272	0.966	2.71	5.30	9.06	20.2	62.6
10°C	10	0.342	0.788	2.29	7.52	21.6	42.3	57.3	69.4
	20	0.271	0.579	1.20	3.27	11.0	36.2	91.5	154
	30	0.225	0.551	1.05	2.28	6.77	23.5	76.6	187
	50	0.160	0.486	1.05	1.90	4.26	13.2	46.7	155
	70	0.122	0.411	1.04	1.93	3.66	9.66	32.8	117
	90	0.097	0.348	0.996	2.00	3.54	8.14	25.7	92.4
0°C	10	0.424	1.30	4.00	9.25	14.0	16.6	19.0	26.4
	20	0.256	0.614	1.85	6.16	17.7	34.6	47.0	58.1
	30	0.219	0.469	1.17	3.73	12.7	36.0	69.0	95.2
	50	0.181	0.411	0.821	2.08	6.83	23.8	71.0	147
	70	0.151	0.390	0.763	1.61	4.64	16.1	55.5	153
	90	0.127	0.367	0.760	1.45	3.66	12.1	43.2	138

Atmospheric Effects

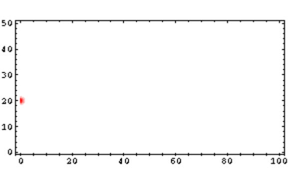
- Atmospheric conditions may have significant effect on the level of noise produced by a distant source.
- Atmospheric conditions affect the speed of sound at various altitudes and directions which are drawn at right angles to the sound wave-front.
- A “**NORMAL**" atmosphere where the sound level steadily in all directions

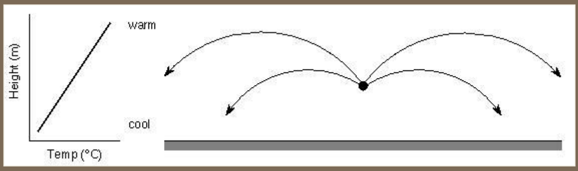


Atmospheric Effects

<u>TEMPERATURE INVERSION</u>

- This shows how a temperature inversion can reflect the rays back towards the ground surface and, as a result, increase the sound level



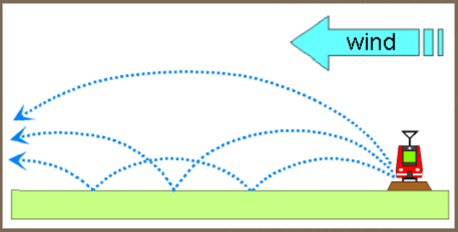


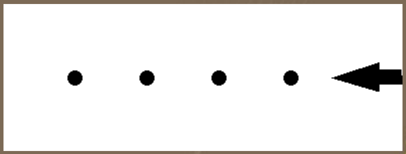
Atmospheric Effects

EFFECT OF WIND

- This shows the most commonly found effect, that of wind

- The sound ray is bent in the direction in which the wind is blowing, resulting in an increased sound pressure level downwind and reduced sound pressure upwind





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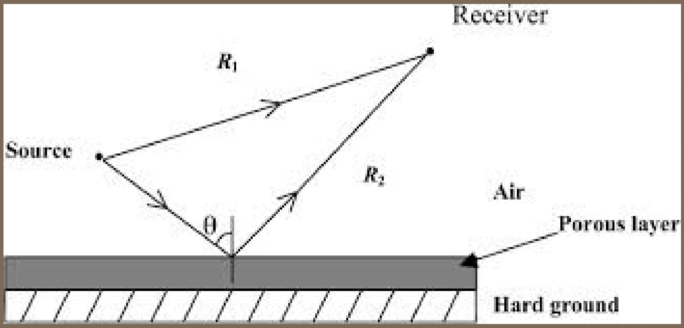
Typical Model



$$\frac{A}{R_1}e^{-ikR_1} + R_p\frac{A}{R_2}e^{-ikR_2} + (1 - R_p)F\frac{A}{R_2}e^{-ikR_2}$$

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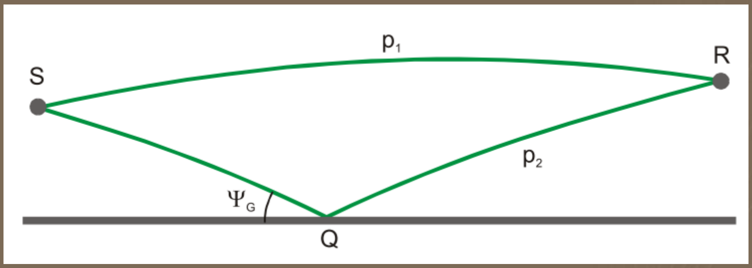
Atmospheric Effects



- How do we now calculate the source to receiver distance?

Atmospheric Effects

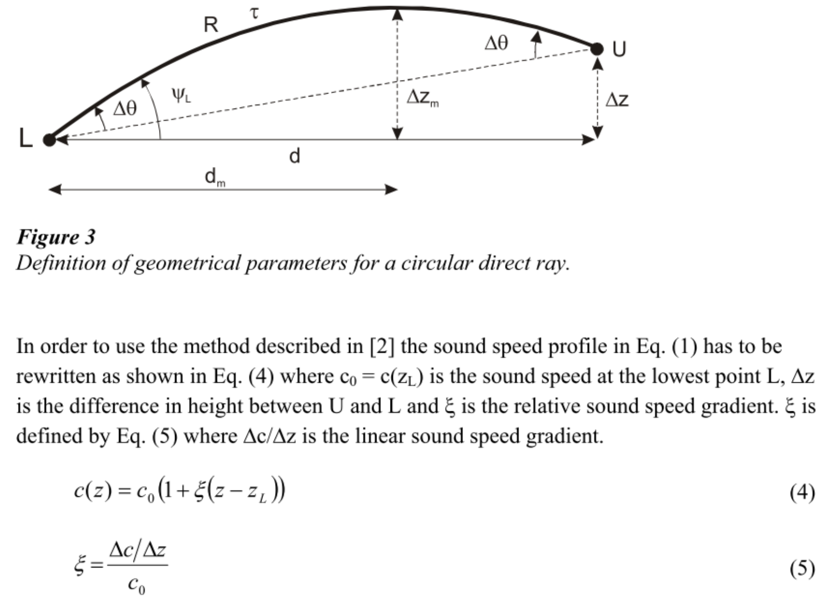


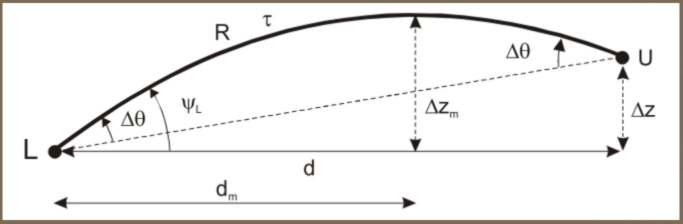
Figure 3
Definition of geometrical parameters for a circular direct ray.

In order to use the method described in [2] the sound speed profile in Eq. (1) has to be rewritten as shown in Eq. (4) where $c_0 = c(z_L)$ is the sound speed at the lowest point L, Δz is the difference in height between U and L and ξ is the relative sound speed gradient. ξ is defined by Eq. (5) where Δc/Δz is the linear sound speed gradient.

$$c(z) = c_0\left(1 + \xi\left(z - z_L\right)\right) \tag{4}$$

$$\xi = \frac{\Delta c/\Delta z}{c_0} \tag{5}$$

Atmospheric Effects



$$R(\Delta z) = \frac{1}{\xi \cos(\psi_L)} \left(\arcsin\left((1 + \xi\,\Delta z) \cos(\psi_L) \right) - \frac{\pi}{2} + \psi_L \right)$$

Atmospheric Effects

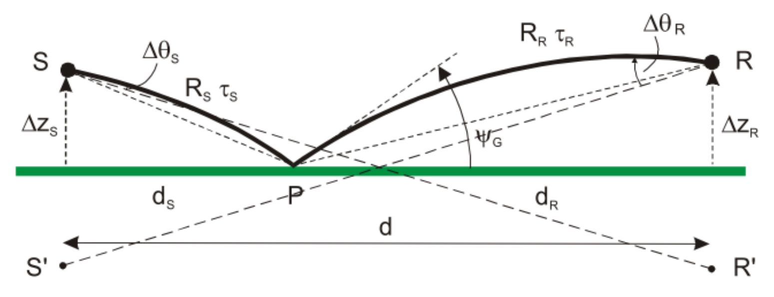
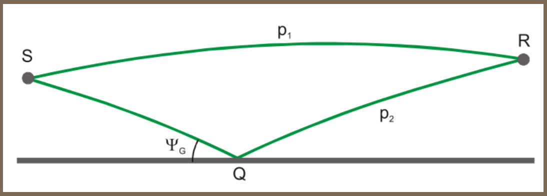


Figure 4
Definition of geometrical parameters for a circular reflected ray.

Atmospheric Effects



$$R(\Delta z) = \frac{1}{\xi \cos(\psi_L)} \left(\arcsin\left((1 + \xi \Delta z) \cos(\psi_L) \right) - \frac{\pi}{2} + \psi_L \right)$$

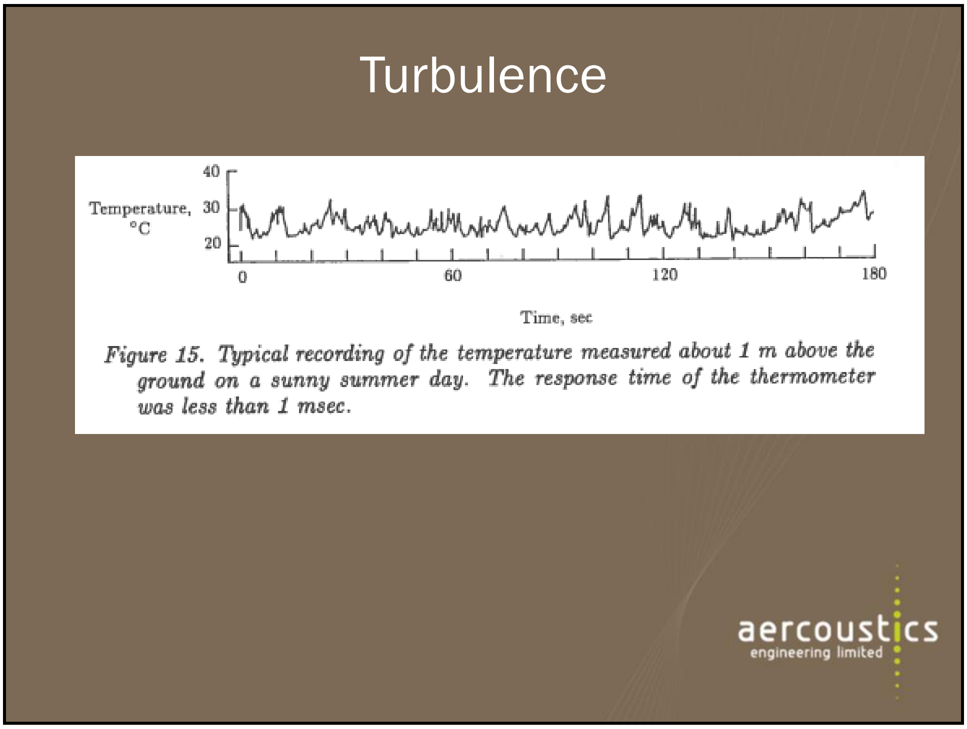
$$\frac{A}{R_1} e^{-ikR_1} + R_p \frac{A}{R_2} e^{-ikR_2} + (1 - R_p) F \frac{A}{R_2} e^{-ikR_2}$$

What do we do?

Currently used?

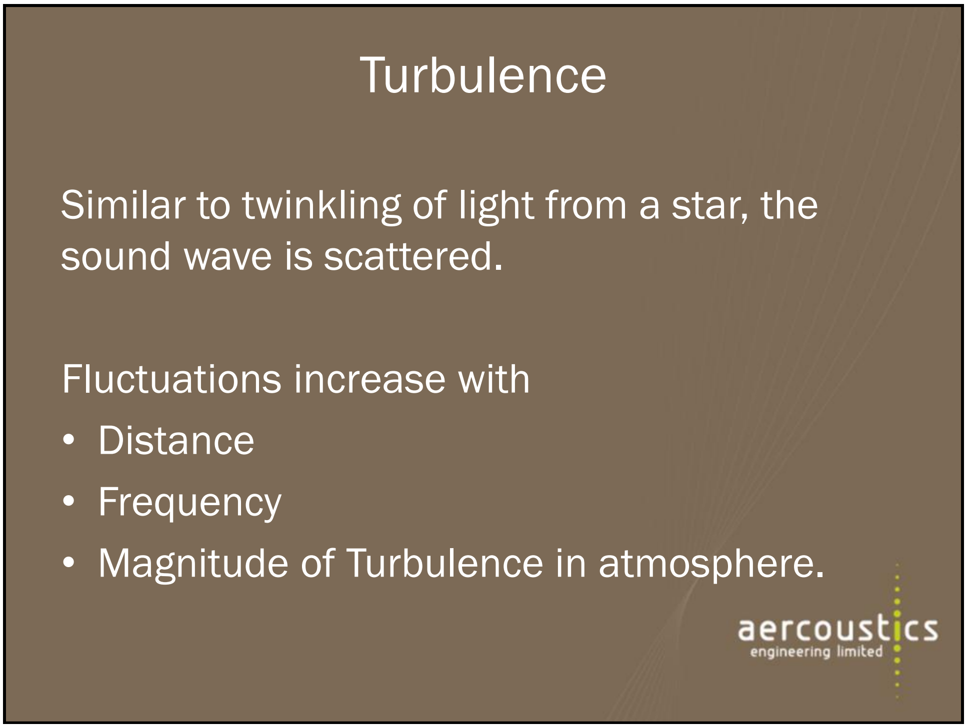
- A correction factor!

Newer models today (e.g. Nord2000) do consider these effects and equations.



Turbulence

Figure 15. Typical recording of the temperature measured about 1 m above the ground on a sunny summer day. The response time of the thermometer was less than 1 msec.



Turbulence

Similar to twinkling of light from a star, the sound wave is scattered.

Fluctuations increase with

- Distance
- Frequency
- Magnitude of Turbulence in atmosphere.

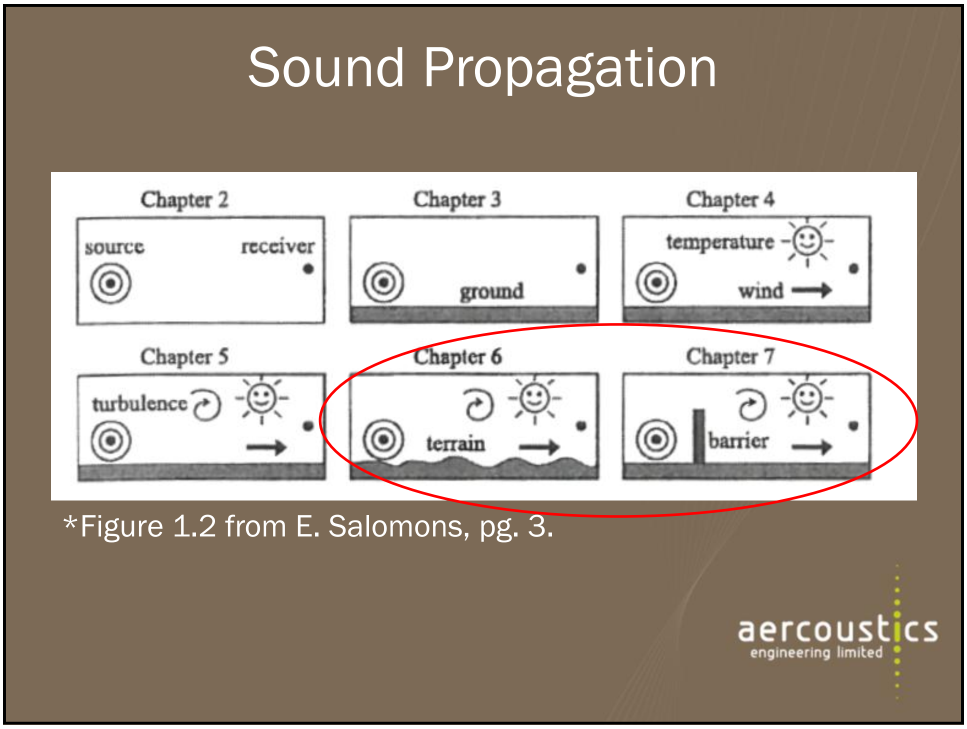
Turbulence

- Random turbulence tends to average out over the mean level.
- Other phenomena are more strongly affected by the atmosphere.
- Was evoked in the past to account for many phenomena which we now understand is something else.

Sound Propagation

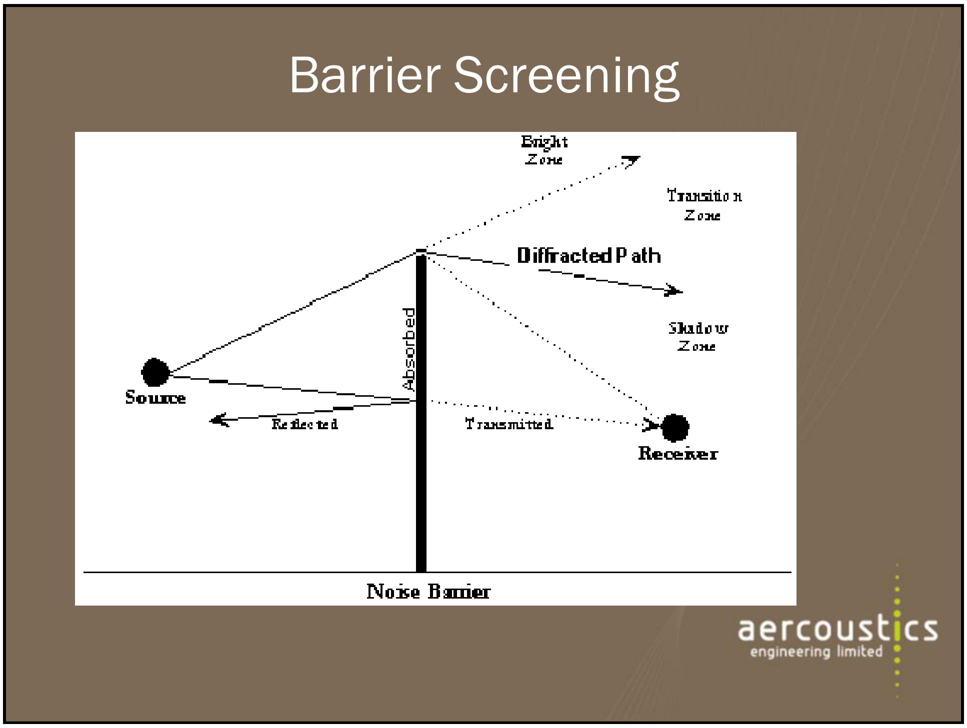
Outdoor sound is attenuated by

- distance,
- interaction with the ground,
- atmospheric effects
- and Topography/barriers,

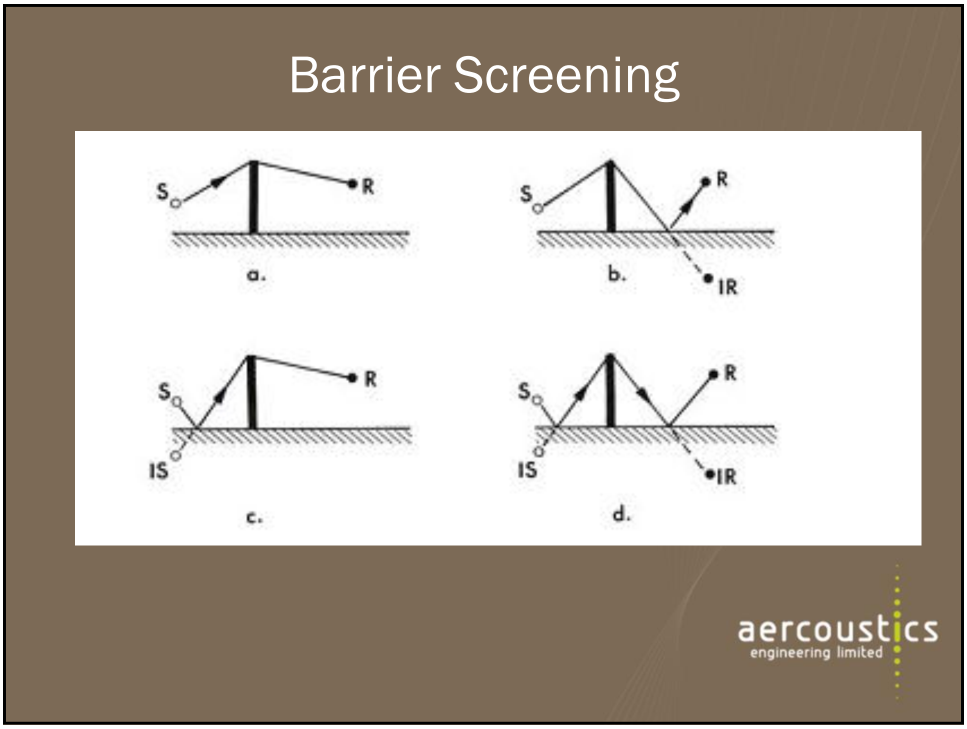


Sound Propagation

*Figure 1.2 from E. Salomons, pg. 3.



Barrier Screening



Barrier Screening

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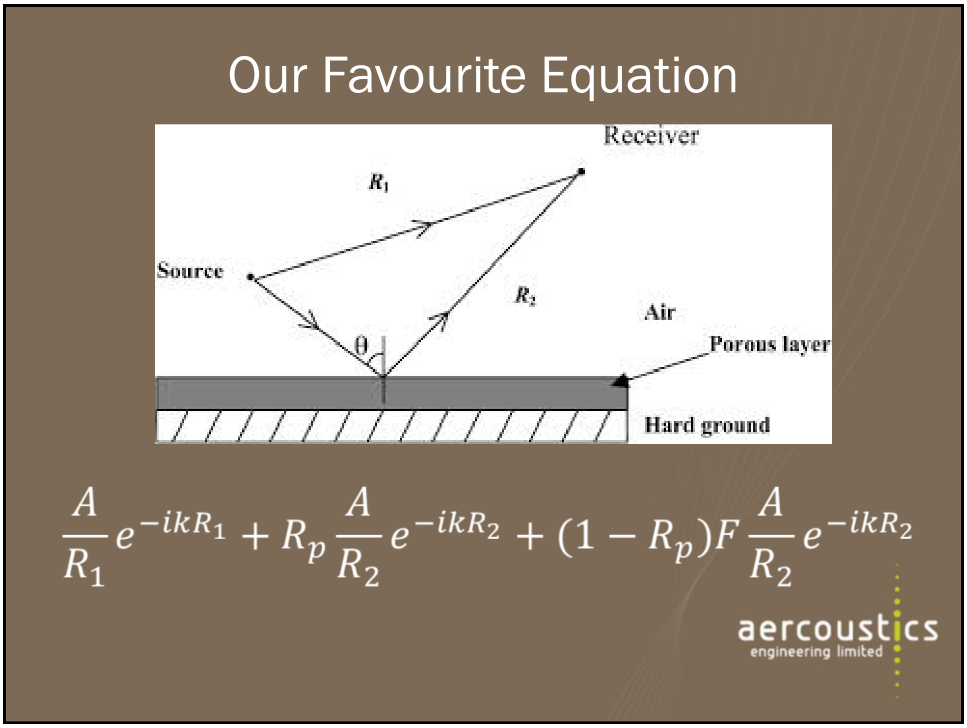

Our Favourite Equation

$$\frac{A}{R_1}e^{-ikR_1} + R_p\frac{A}{R_2}e^{-ikR_2} + (1-R_p)F\frac{A}{R_2}e^{-ikR_2}$$

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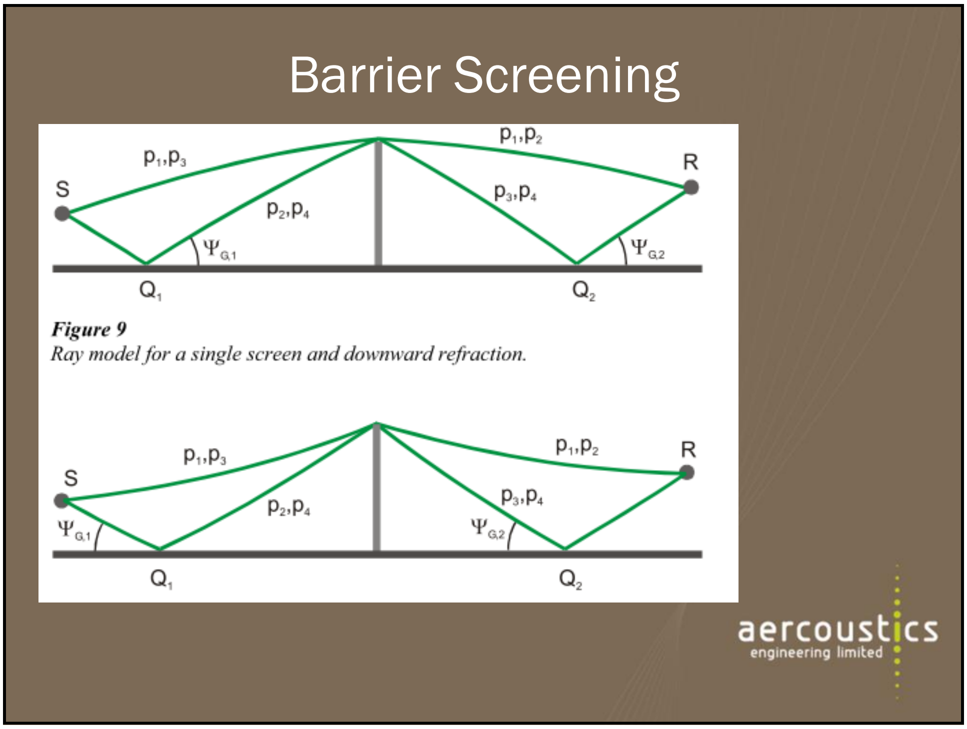
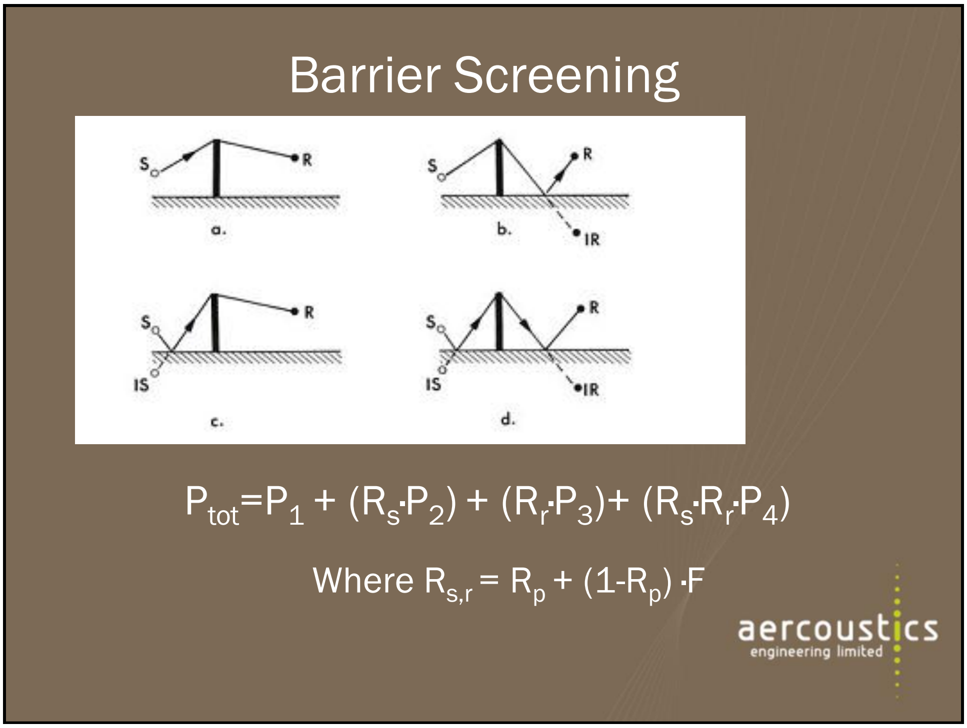


Barrier Screening

Figure 9
Ray model for a single screen and downward refraction.

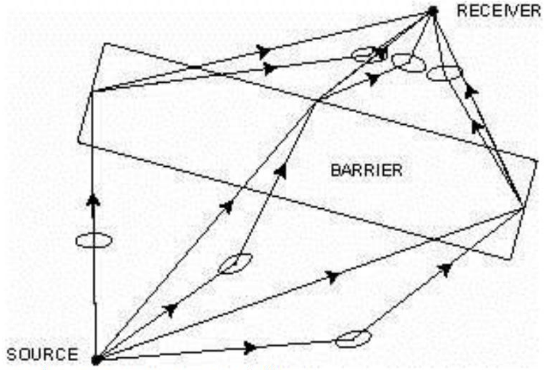


Barrier Screening

$$P_{tot}=P_1 + (R_s \cdot P_2) + (R_r \cdot P_3) + (R_s \cdot R_r \cdot P_4)$$

Where $R_{s,r} = R_p + (1-R_p) \cdot F$

Edges



The total pressure at the receiver is given as follows:

$$P_{TOT} = P_1 + Q_S \cdot P_2 + Q_R \cdot P_3 + Q_S \cdot Q_R \cdot P_4 + P_5 + Q_R \cdot P_6 + P_7 + Q_R \cdot P_8$$

What do we do?

Use an empirical formulae that looks at the **Path Length Difference**

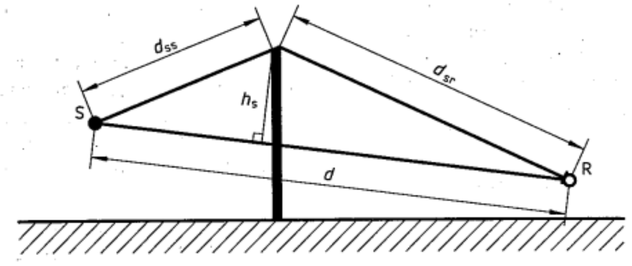
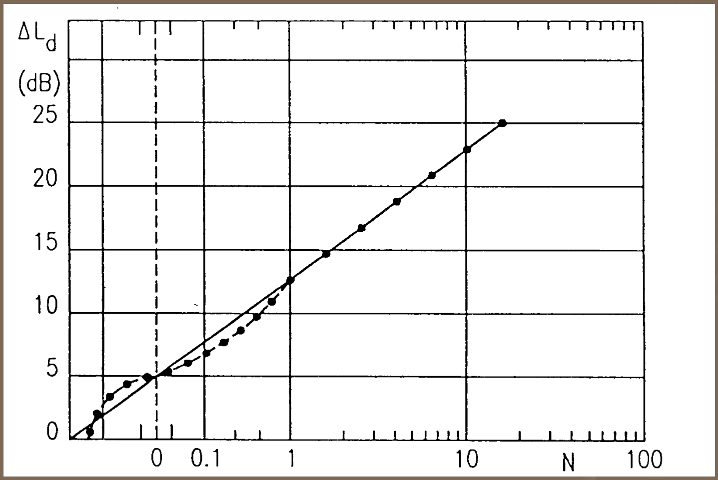
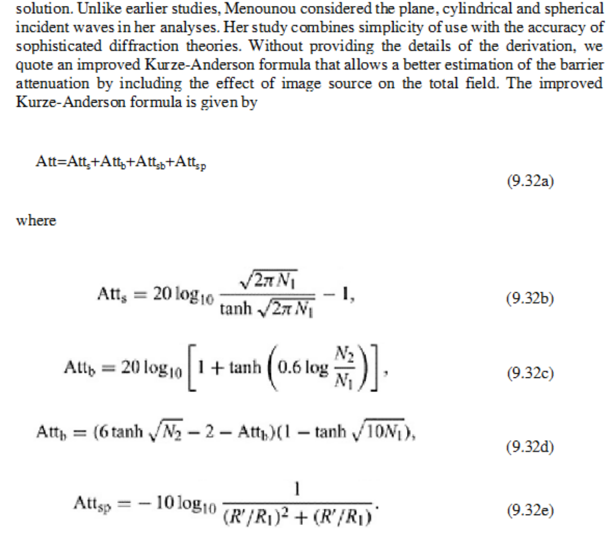


Figure 6 — Geometrical quantities for determining the pathlength difference for single diffraction

What do we do?



Barrier Screening


solution. Unlike earlier studies, Menounou considered the plane, cylindrical and spherical incident waves in her analyses. Her study combines simplicity of use with the accuracy of sophisticated diffraction theories. Without providing the details of the derivation, we quote an improved Kurze-Anderson formula that allows a better estimation of the barrier attenuation by including the effect of image source on the total field. The improved Kurze-Anderson formula is given by

$$\mathrm{Att}=\mathrm{Att}_s+\mathrm{Att}_b+\mathrm{Att}_{sb}+\mathrm{Att}_{sp} \tag{9.32a}$$

where

$$\mathrm{Att}_s = 20\log_{10}\frac{\sqrt{2\pi N_1}}{\tanh\sqrt{2\pi N_1}} - 1, \tag{9.32b}$$

$$\mathrm{Att}_b = 20\log_{10}\left[1+\tanh\left(0.6\log\frac{N_2}{N_1}\right)\right], \tag{9.32c}$$

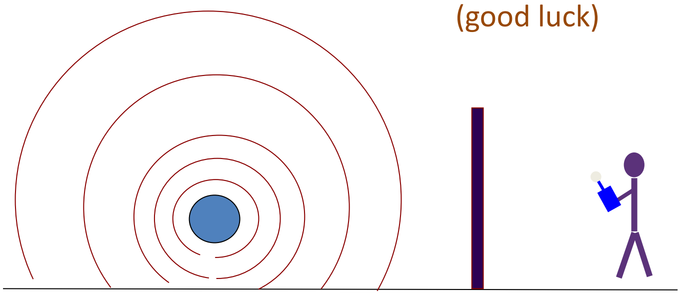
$$\mathrm{Att}_b = (6\tanh\sqrt{N_2} - 2 - \mathrm{Att}_b)(1-\tanh\sqrt{10N_1}), \tag{9.32d}$$

$$\mathrm{Att}_{sp} = -10\log_{10}\frac{1}{(R'/R_1)^2+(R'/R_1)}. \tag{9.32e}$$

Barrier Screening

- Solve Wave Equation with a source, atmosphere, and a barrier, and applicable boundary conditions

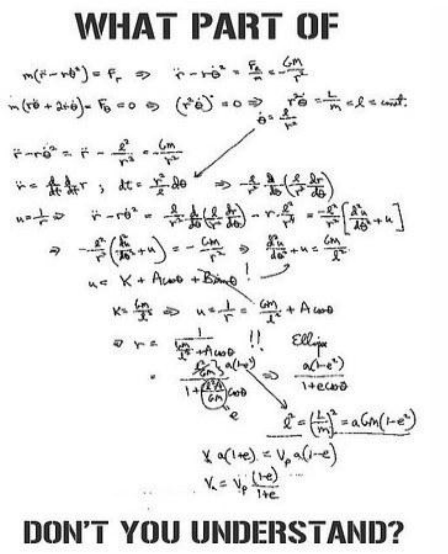
(good luck)



Sound Propagation

Outdoor sound is attenuated by

- distance,
- interaction with the ground,
- atmospheric effects
- and Topography/barriers,



How about a Break?

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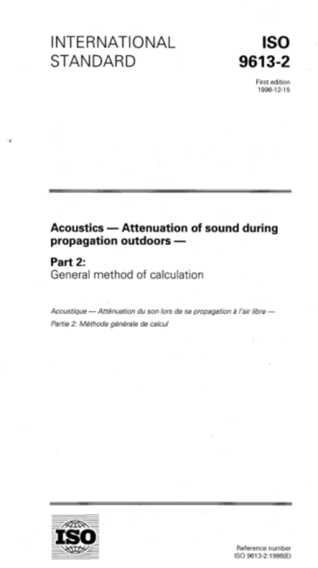
References


INTERNATIONAL STANDARD

ISO
9613-2

First edition
1996-12-15

Acoustics — Attenuation of sound during propagation outdoors —

Part 2:
General method of calculation

Acoustique — Atténuation du son lors de sa propagation à l'air libre — Partie 2: Méthode générale de calcul

Reference number
ISO 9613-2:1996(E)

ISO 9613-2

- Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculations

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ISO 9613-2

Outdoor sound is attenuated by

- distance, A_{div}
- interaction with the ground, A_{gr}
- atmospheric effects, A_{atm}
- Topography/barriers, A_{screen}
- and with other stuff, A_{trees}, A_{misc}, etc.

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ISO 9613-2

"The method described in this part of the ISO 9613 is general in the sense that it may be applied to a wide variety of noise sources, and covers most of the major mechanisms of attenuation.

There are, however, constraints on its use [...]"

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ISO 9613-2

- Inversion conditions over water sources are not covered
- Predicts a long-term average A-weighted sound pressure level
- Not applicable to aircraft in flight or blast waves.

Definitions

- A – Attenuation
- D - distance from point to receiver
- G – ground factor
- H – height of source or receiver
- L – sound pressure/power level
- λ – Wavelength
- N – Fresnel Number
- D_c – Directivity Correction

Basic Equation

$L_{fT}(DW) = L_W + D_c - A$

Downwind Sound Pressure Level at Receiver =

- Sound Power +
- Directivity Correction -
- Attenuation

Attenuation

Attenuation (A) consists of:

- $A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{Misc}$

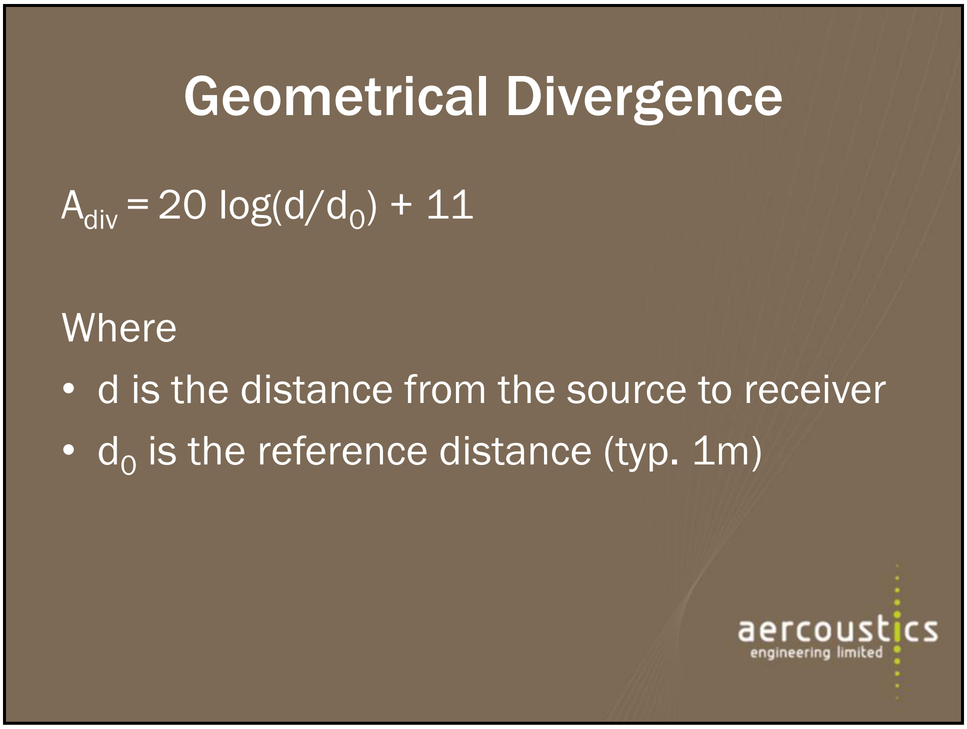
Divergence

Atmospheric

Ground Absorption

Barrier Screening

Miscellaneous

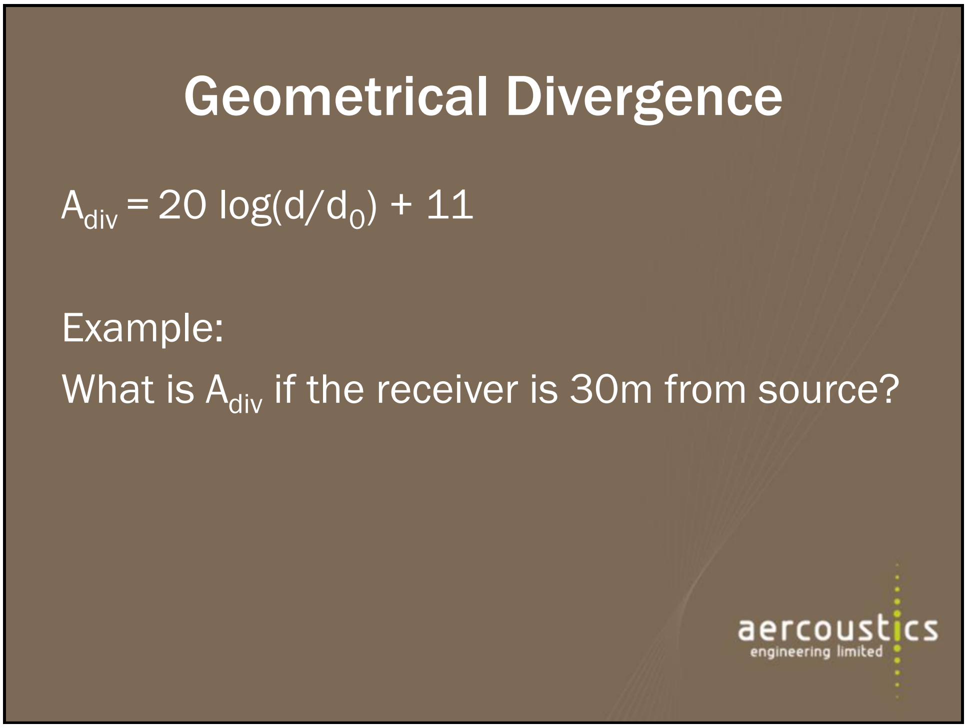


Geometrical Divergence

$A_{div} = 20 \log(d/d_0) + 11$

Where

- d is the distance from the source to receiver
- d_0 is the reference distance (typ. 1m)



Geometrical Divergence

$A_{div} = 20 \log(d/d_0) + 11$

Example:

What is A_{div} if the receiver is 30m from source?

Atmospheric Absorption

$A_{atm} = \alpha d/1000$

Where

- d is the distance from the source to receiver
- α is the atmospheric attenuation coefficient, in dB, per kilometer, in each octave band.

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Atmospheric Absorption

$A_{atm} = \alpha d/1000$

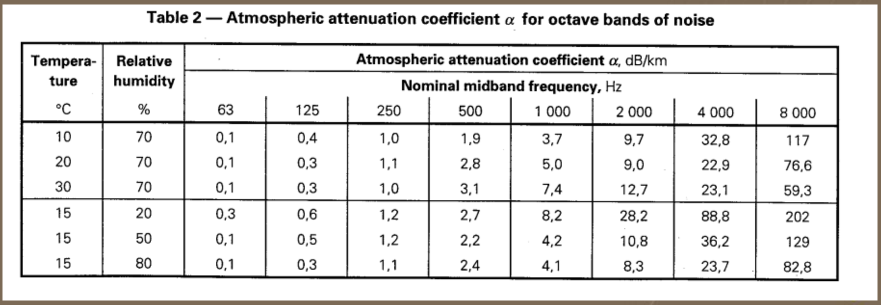

Table 2 — Atmospheric attenuation coefficient *α* for octave bands of noise

Temperature	**Relative humidity**	**Atmospheric attenuation coefficient *α*, dB/km**							
		Nominal midband frequency, Hz							
°C	%	63	125	250	500	1 000	2 000	4 000	8 000
10	70	0,1	0,4	1,0	1,9	3,7	9,7	32,8	117
20	70	0,1	0,3	1,1	2,8	5,0	9,0	22,9	76,6
30	70	0,1	0,3	1,0	3,1	7,4	12,7	23,1	59,3
15	20	0,3	0,6	1,2	2,7	8,2	28,2	88,8	202
15	50	0,1	0,5	1,2	2,2	4,2	10,8	36,2	129
15	80	0,1	0,3	1,1	2,4	4,1	8,3	23,7	82,8

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Ground Effect

To determine ground effect, the path between the source and receive is split into three sections:

1. The Source region
2. The middle region
3. The receiver region.

α

Each may be assigned a different ground type.

$A_{gr} = A_s + A_m + A_r$

Ground Effect

A_s & A_r α *30x* the source/receiver height

A_m is what's left

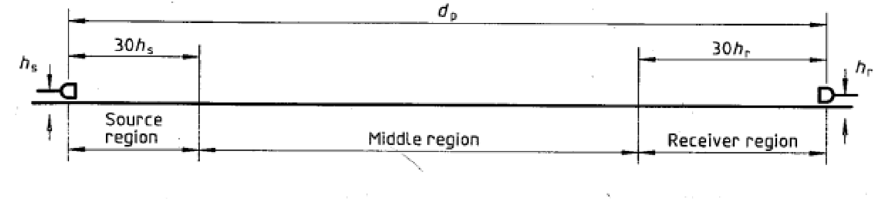

Figure 1 — Three distinct regions for determination of ground attenuation

Ground Effect

- Hard Ground – paved ground, water, ice, concrete, tamped soil, G=0
- Porous Ground – grass covered, trees, vegetation, farm-land, G=1
- Mixed ground - Somewhere in-between ???, 0 < G < 1

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Ground Effect

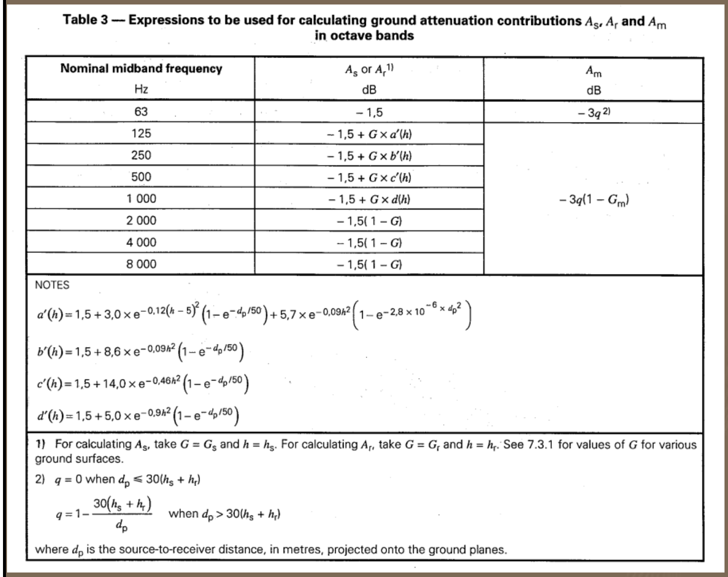

Table 3 — Expressions to be used for calculating ground attenuation contributions A_s, A_r and A_m in octave bands

Nominal midband frequency Hz	A_s or A_r [1) dB	A_m dB
63	$-1,5$	$-3q$ [2)
125	$-1,5 + G \times a'(h)$	$-3q(1-G_m)$
250	$-1,5 + G \times b'(h)$	
500	$-1,5 + G \times c'(h)$	
1 000	$-1,5 + G \times d(h)$	
2 000	$-1,5(1-G)$	
4 000	$-1,5(1-G)$	
8 000	$-1,5(1-G)$	

NOTES

$$a'(h) = 1,5 + 3,0 \times e^{-0,12(h-5)^2}\left(1 - e^{-d_p/50}\right) + 5,7 \times e^{-0,09h^2}\left(1 - e^{-2,8 \times 10^{-6} \times d_p^2}\right)$$

$$b'(h) = 1,5 + 8,6 \times e^{-0,09h^2}\left(1 - e^{-d_p/50}\right)$$

$$c'(h) = 1,5 + 14,0 \times e^{-0,46h^2}\left(1 - e^{-d_p/50}\right)$$

$$d'(h) = 1,5 + 5,0 \times e^{-0,9h^2}\left(1 - e^{-d_p/50}\right)$$

1) For calculating A_s, take $G = G_s$ and $h = h_s$. For calculating A_r, take $G = G_r$ and $h = h_r$. See 7.3.1 for values of G for various ground surfaces.

2) $q = 0$ when $d_p \leqslant 30(h_s + h_r)$

$$q = 1 - \frac{30(h_s + h_r)}{d_p} \quad \text{when } d_p > 30(h_s + h_r)$$

where d_p is the source-to-receiver distance, in metres, projected onto the ground planes.

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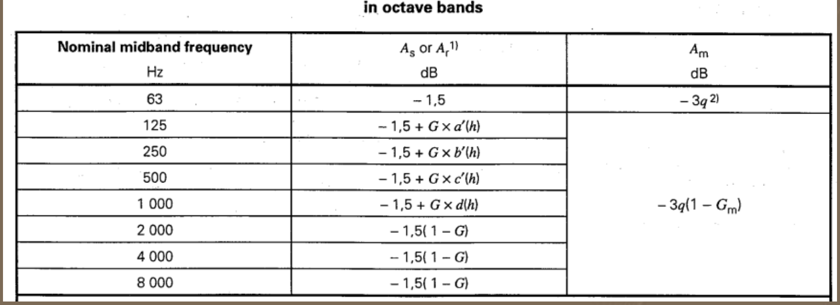
Ground Effect

What is A_{gr} when G=0 and no middle ground?



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250	$-1,5 + G \times b'(h)$	
500	$-1,5 + G \times c'(h)$	
1 000	$-1,5 + G \times d(h)$	
2 000	$-1,5(1-G)$	
4 000	$-1,5(1-G)$	
8 000	$-1,5(1-G)$	

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Example

Attenuation (A) consists of:

$A = A_{div} + A_{gr}$

$= 20 \log(d/d_0) + 11 + (A_s + A_m + A_r)$

Now what happens if we have hard ground?

Hemispherical spreading

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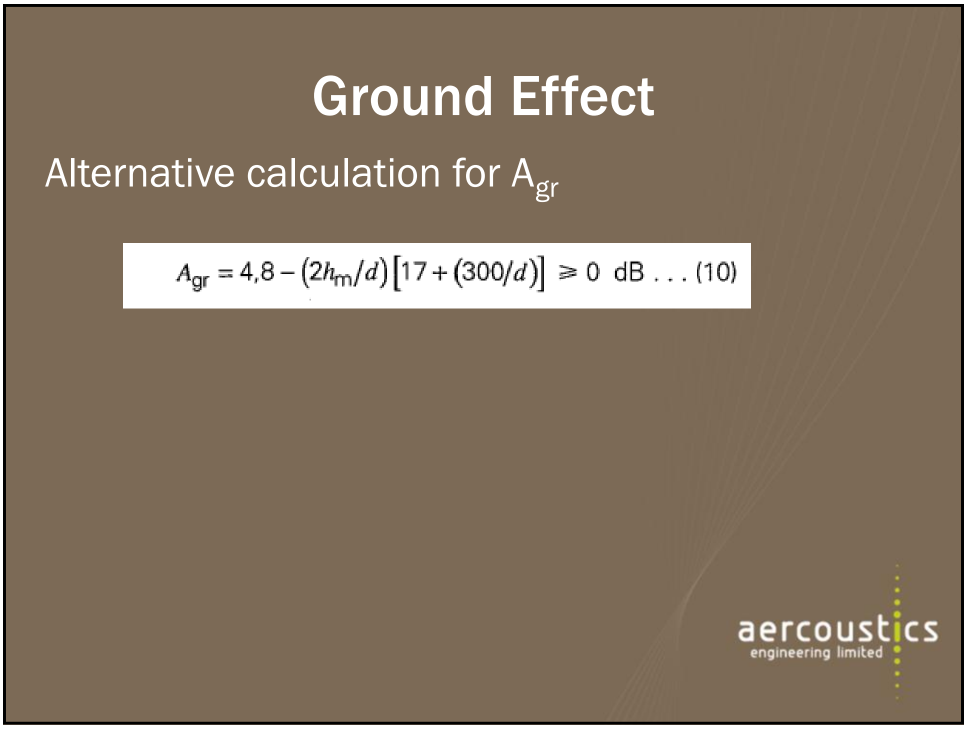
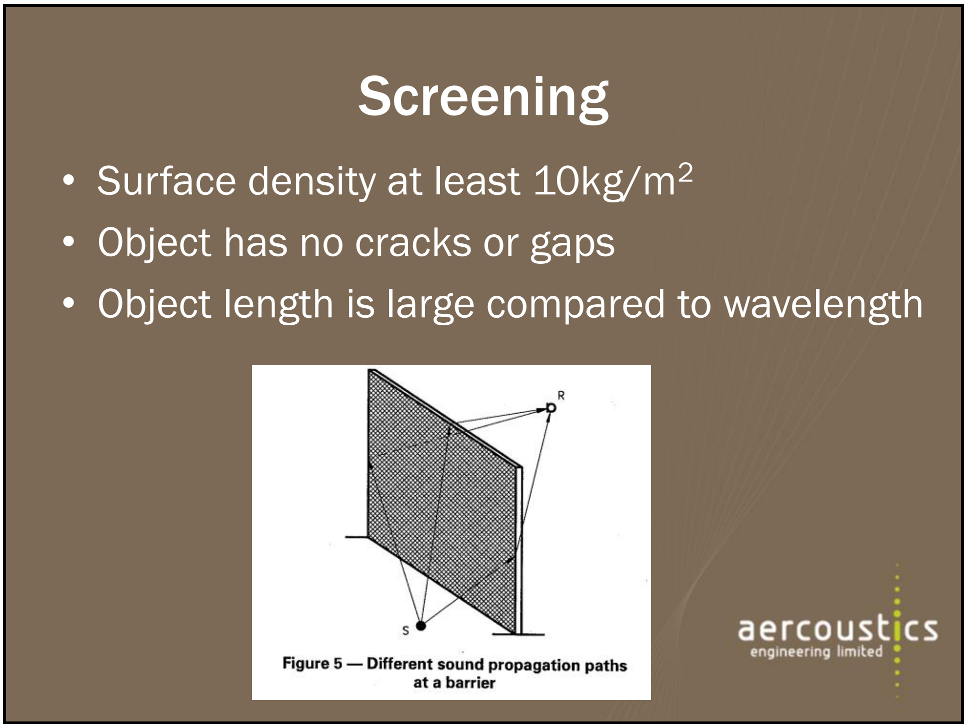


Ground Effect

Alternative calculation for A_{gr}

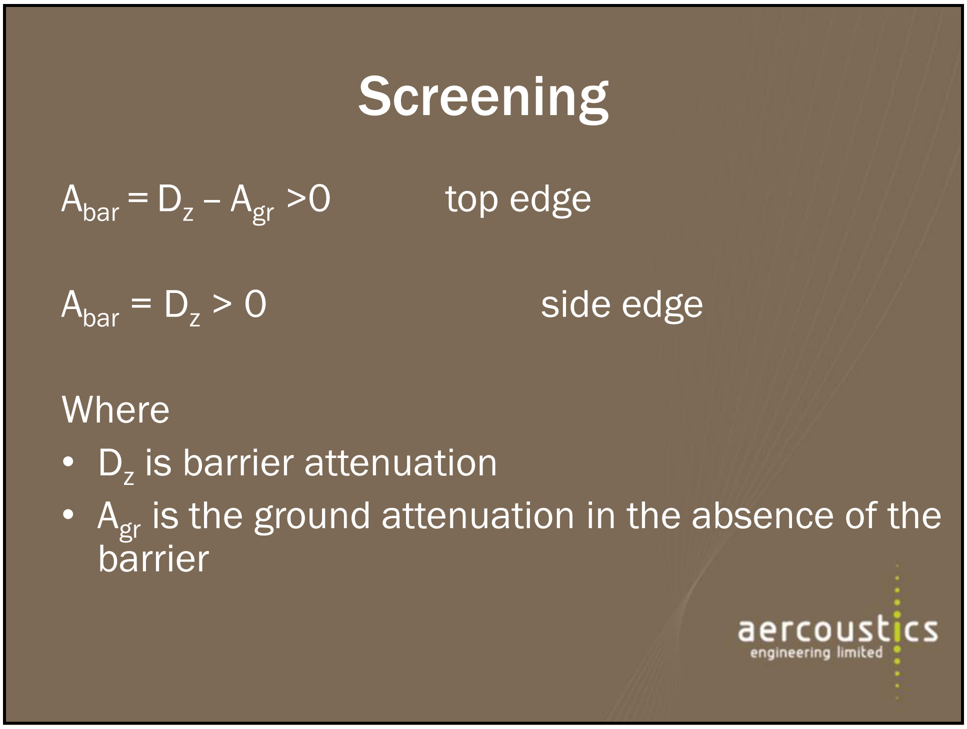
$$A_{gr} = 4{,}8 - (2h_m/d)\left[17 + (300/d)\right] \geqslant 0 \text{ dB} \ldots (10)$$



Screening

- Surface density at least 10kg/m^2
- Object has no cracks or gaps
- Object length is large compared to wavelength

Figure 5 — Different sound propagation paths at a barrier



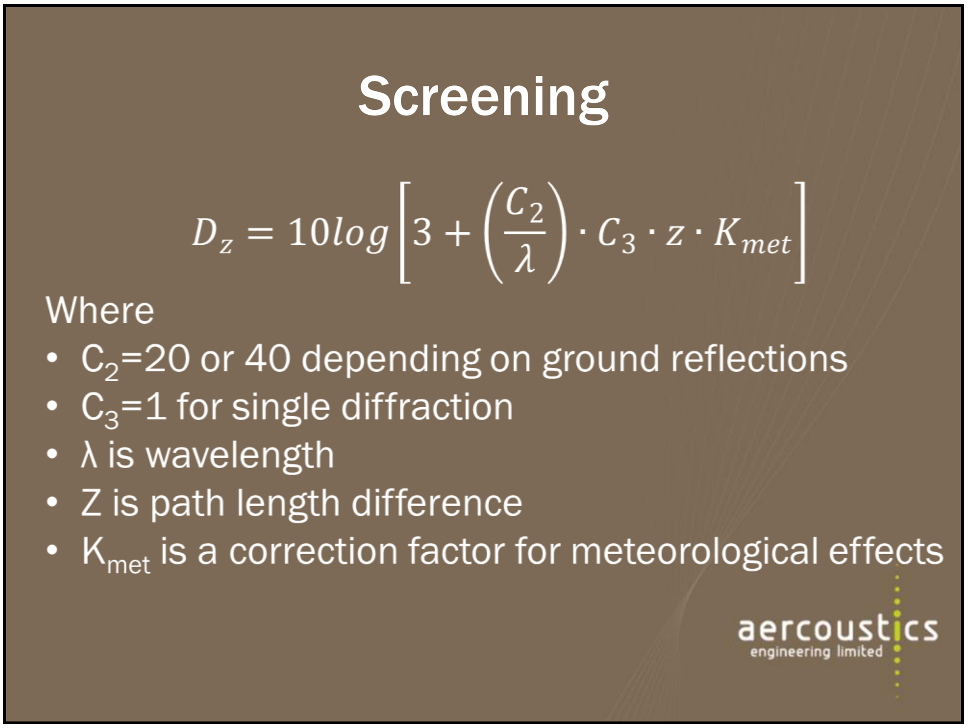
Screening

$A_{bar} = D_z - A_{gr} > 0$ top edge

$A_{bar} = D_z > 0$ side edge

Where

- D_z is barrier attenuation
- A_{gr} is the ground attenuation in the absence of the barrier

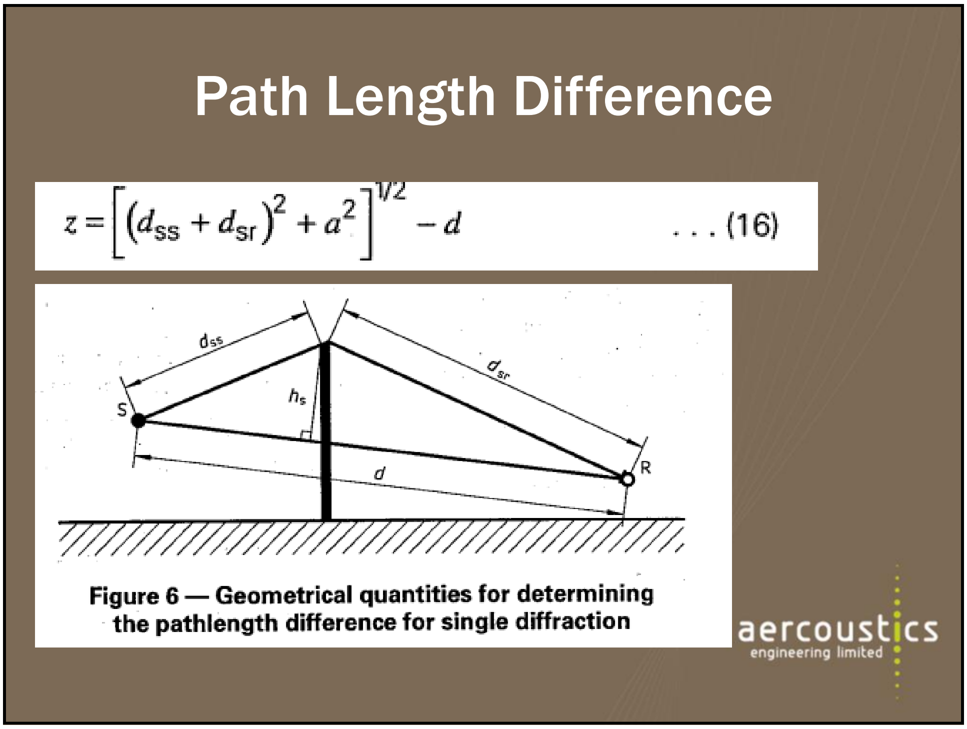


Screening

$$D_z = 10log\left[3 + \left(\frac{C_2}{\lambda}\right) \cdot C_3 \cdot z \cdot K_{met}\right]$$

Where

- C_2=20 or 40 depending on ground reflections
- C_3=1 for single diffraction
- λ is wavelength
- Z is path length difference
- K_{met} is a correction factor for meteorological effects



Path Length Difference

$$z = \left[\left(d_{ss} + d_{sr} \right)^2 + a^2 \right]^{1/2} - d \qquad \ldots (16)$$

Figure 6 — Geometrical quantities for determining the pathlength difference for single diffraction

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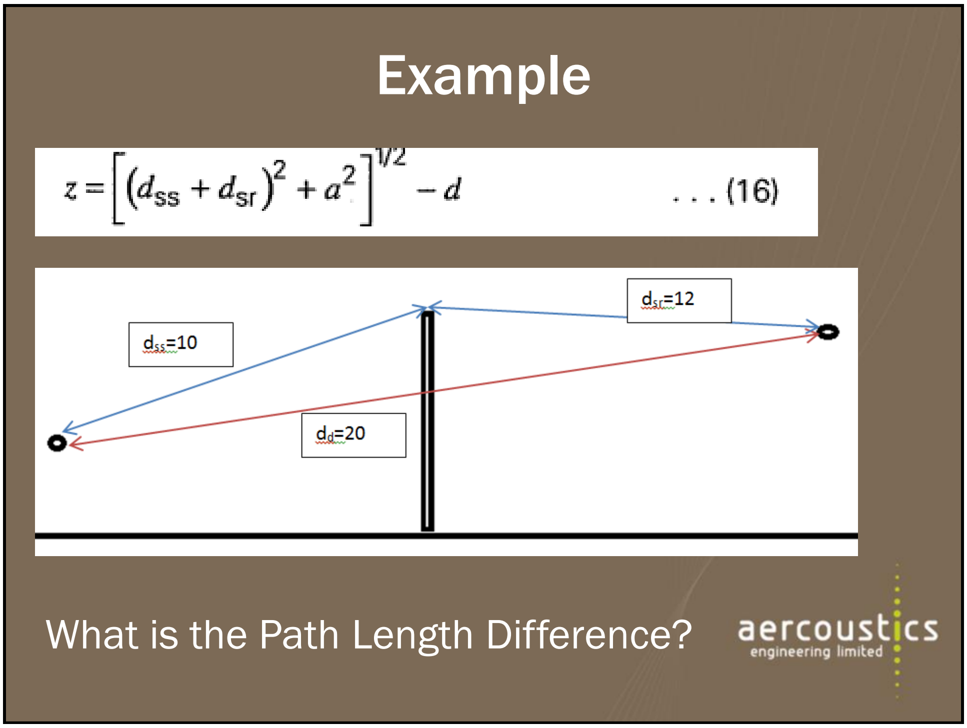

Example

$$z = \left[\left(d_{ss} + d_{sr} \right)^2 + a^2 \right]^{1/2} - d \qquad \ldots (16)$$

What is the Path Length Difference?

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Screening

Calculate D_z

- C_2=20, C_3=1, λ =100, & K_{met} =1
- Z is calculated before (e.g. 2 or 12)

$$D_z = 10log\left[3 + \left(\frac{20}{100}\right) \cdot 1 \cdot z \cdot 1\right]$$

What if Z=0?

Screening

Fresnel Number:

A dimensionless number that gives you an idea of the amount of screening.

N=2z/λ

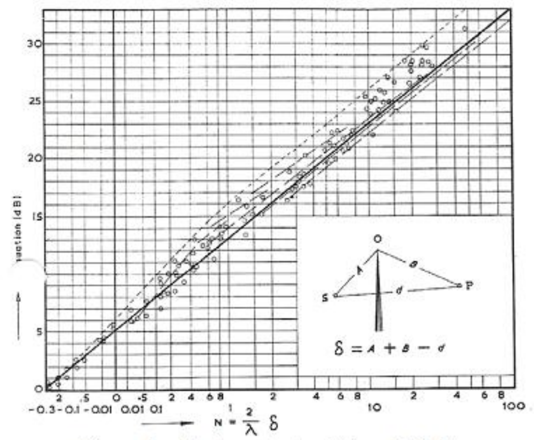
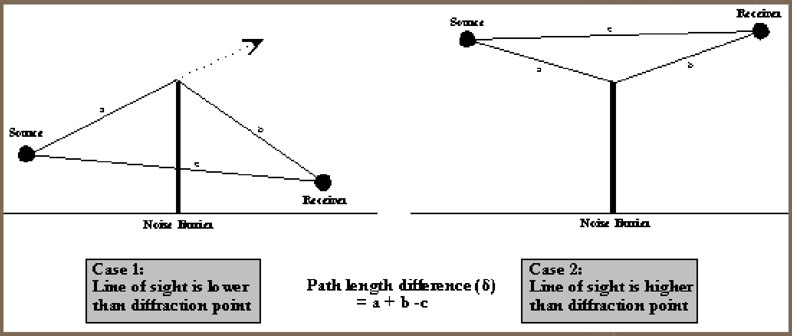


Figure 2 – Maekawa's chart (from Ref. 2)

Screening

What happens if the barrier does not block line of sight?



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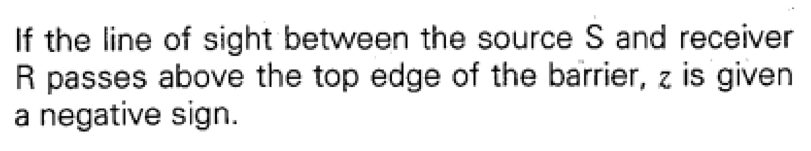
Screening

What does ISO 9613-2 say?

Page 10:



If the line of sight between the source S and receiver R passes above the top edge of the barrier, z is given a negative sign.

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Screening

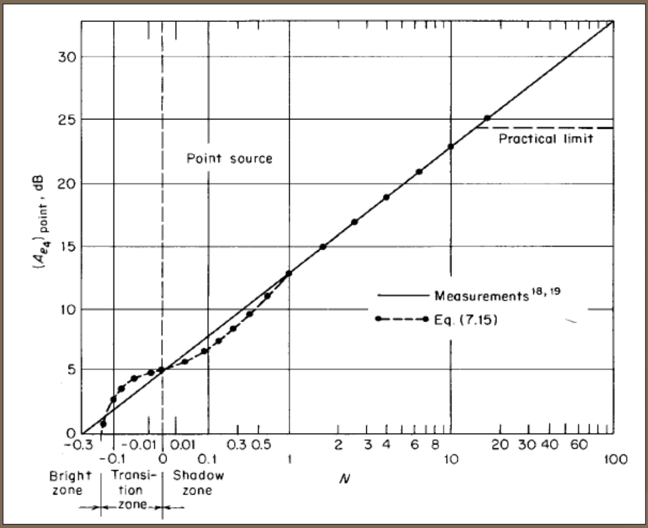
What happens if the barrier is below the screen?

$$D_z = 10log\left[3 + \left(\frac{C_2}{\lambda}\right) \cdot C_3 \cdot z \cdot K_{met}\right]$$

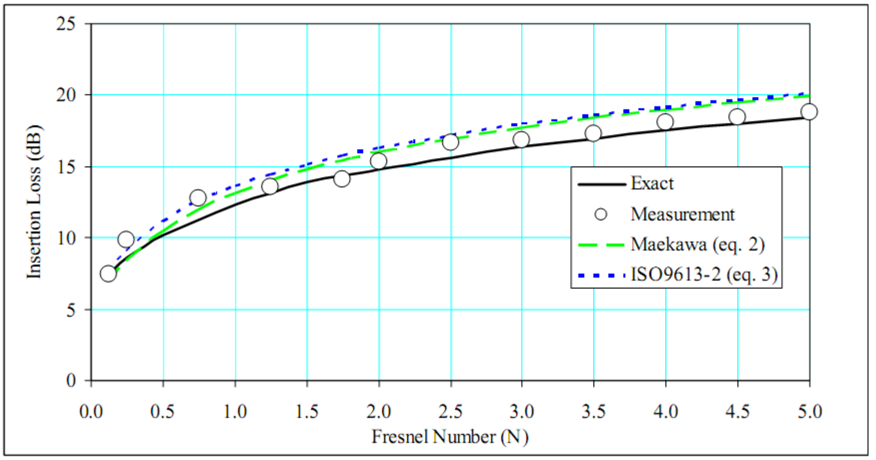
Where

- C_2=20 or 40 depending on ground reflections
- C_3=1 for single diffraction
- λ is wavelength
- Z is path length difference
- K_{met} is a correction factor for meteorological effects

Screening



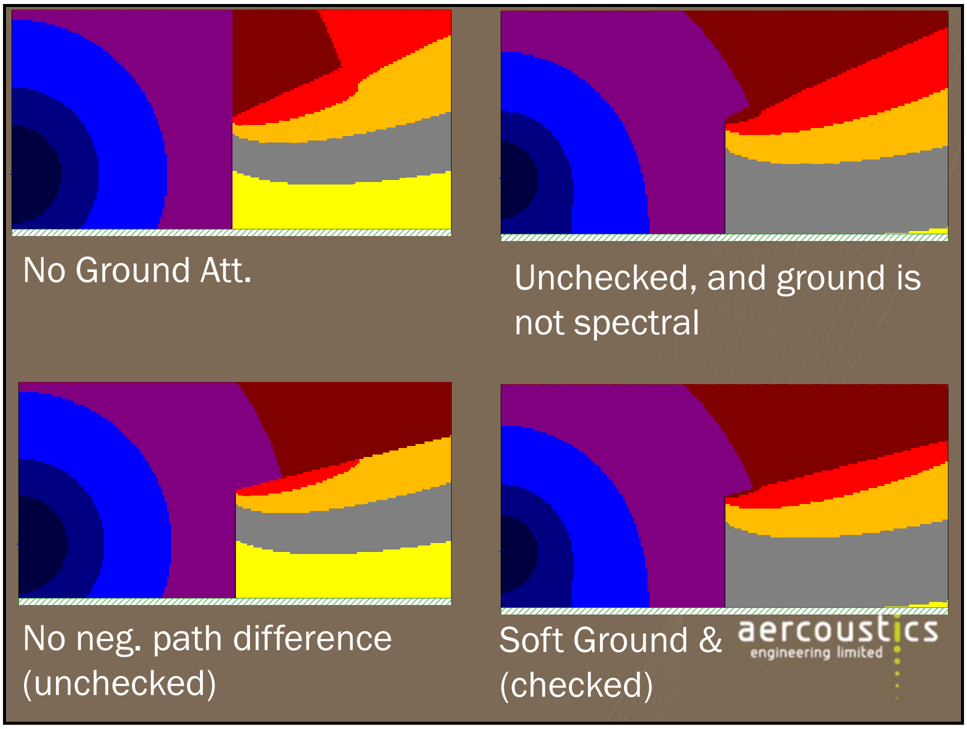
Screening



Screening

$A_{bar} = D_z - A_{gr} > 0$ top edge

How is A_{bar} affected if the ground is hard vs. soft?

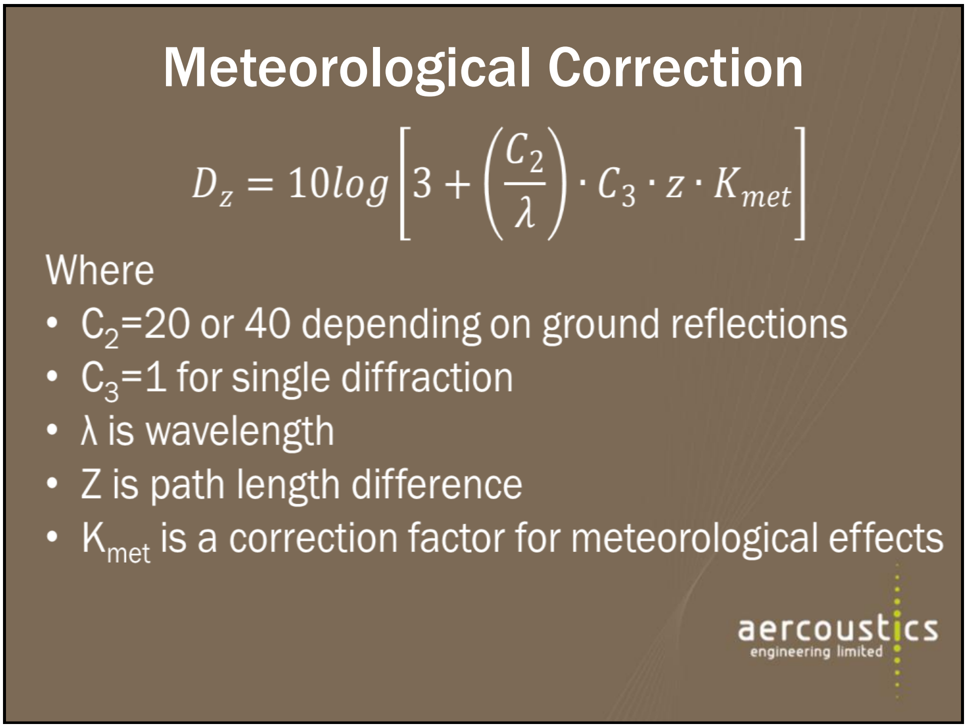


No Ground Att.

Unchecked, and ground is not spectral

No neg. path difference (unchecked)

Soft Ground & (checked)



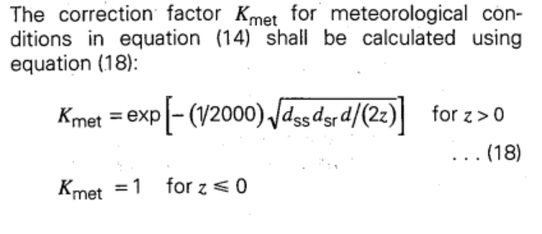
Meteorological Correction

$$D_z = 10log\left[3 + \left(\frac{C_2}{\lambda}\right) \cdot C_3 \cdot z \cdot K_{met}\right]$$

Where

- C_2=20 or 40 depending on ground reflections
- C_3=1 for single diffraction
- λ is wavelength
- Z is path length difference
- K_{met} is a correction factor for meteorological effects

Meteorological Correction



The correction factor K_{met} for meteorological conditions in equation (14) shall be calculated using equation (18):

$$K_{\text{met}} = \exp\left[-(1/2000)\sqrt{d_{ss}\,d_{sr}\,d/(2z)}\right] \quad \text{for } z > 0 \qquad \ldots (18)$$

$$K_{\text{met}} = 1 \quad \text{for } z \leqslant 0$$

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Long Term vs. Down Wind

Long term average A-weighted sound pressure level includes a variety of meteorological conditions.

Covered in Section 6 of IS 9613-2

- $L_{AT}(LT) = L_{AT}(DW) - C_{met}$
  - $C_{met}=0$ if $d_p \leq 10(h_s+h_r)$
  - $C_{met}=C_0(1-[10(h_s+h_r]/d_p)$
    - Dp is distance between source and receiver

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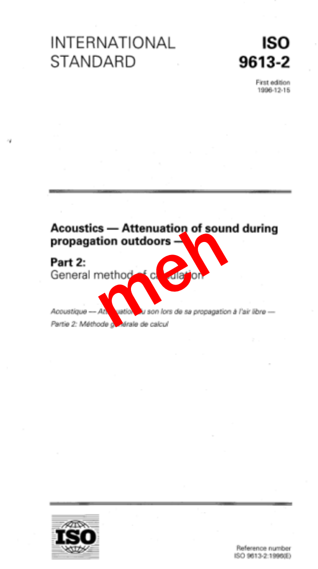
What else then?



INTERNATIONAL STANDARD

ISO 9613-2

First edition
1996-12-15

Acoustics — Attenuation of sound during propagation outdoors —

Part 2:
General method of calculation

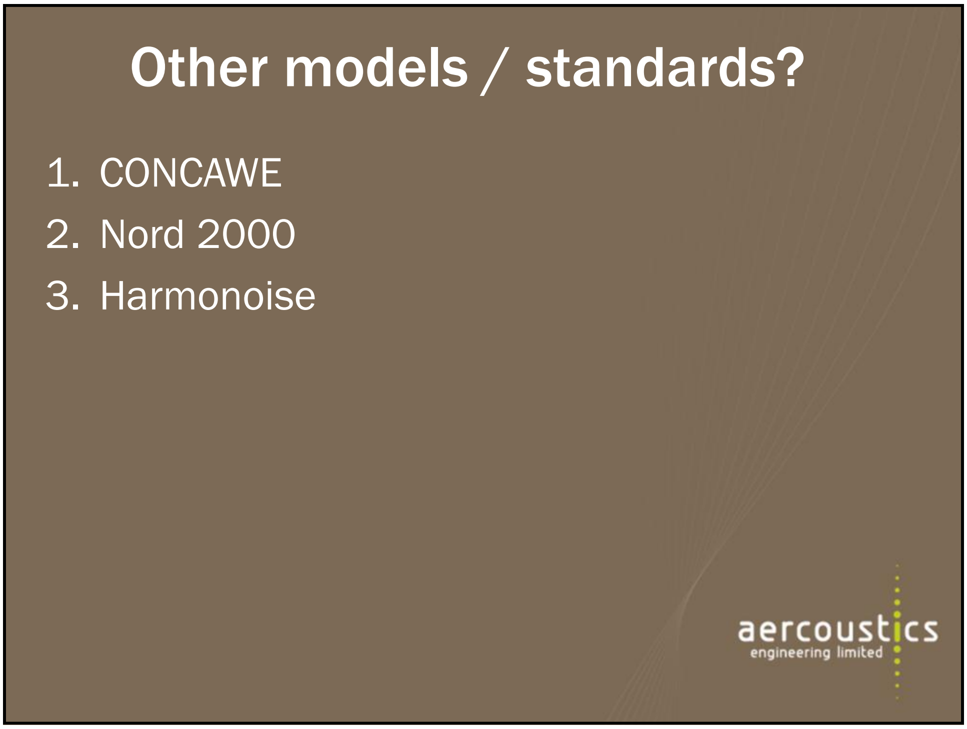
Acoustique — Atténuation du son lors de sa propagation à l'air libre —
Partie 2: Méthode générale de calcul

Reference number
ISO 9613-2:1996(E)

So if ISO 9613-2 isn't great, what do we do?

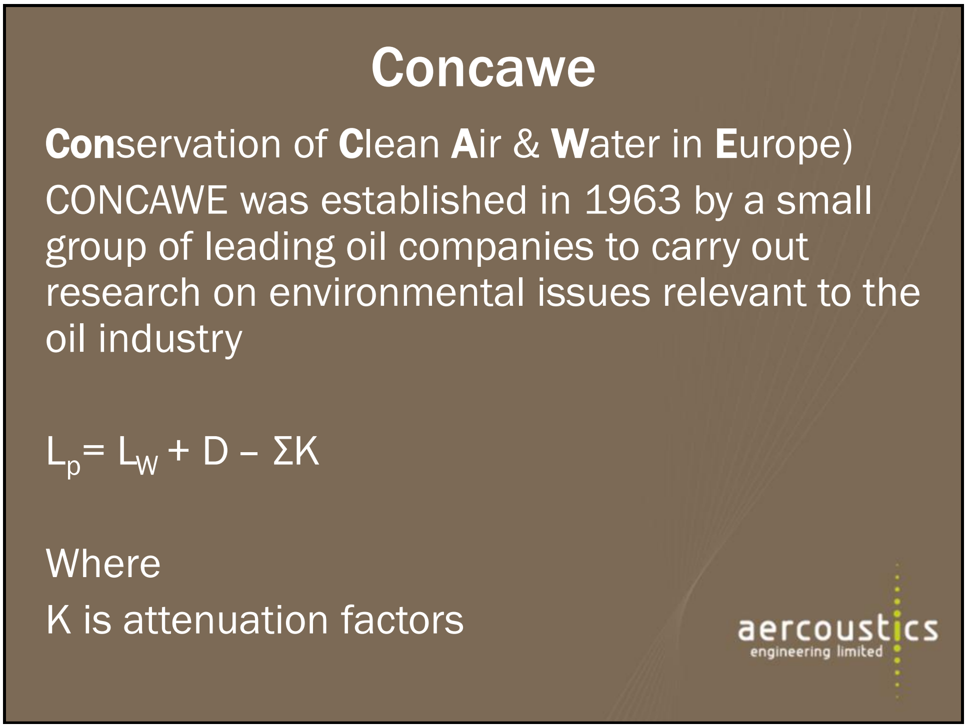
"The need for standardisation cannot be disputed since standards are set up by organisations to provide the methodology by which independent investigations ought to derive the same conclusions.

The down side of this need is that sometimes standardisation is being perceived by society as a dogma, beyond which one should not investigate matters deeper."



Other models / standards?

1. CONCAWE
2. Nord 2000
3. Harmonoise



Concawe

Conservation of **C**lean **A**ir & **W**ater in **E**urope)

CONCAWE was established in 1963 by a small group of leading oil companies to carry out research on environmental issues relevant to the oil industry

$L_p = L_W + D - \Sigma K$

Where

K is attenuation factors

Concawe

$L_p = L_W + D - \Sigma K$

Primary differences are:

- Atmospheric Absorption i.e. factors stability classes
- Ground attenuation is a function of distance and frequency

Nord 2000

The Nord2000 method was developed in the period 1996-2001 in the Nordic countries. The Nord2000 method was revised in 2005-2006 and is the most up-to-date well-establish model today.

Nord 2000

Primary notes:

- 1/3 Octave band calculations
- Able to take into account complex atmosphere data
- Able to consider aerodynamic roughness length of the ground
- Screening takes into account geometrical theory of diffraction
- Atmospheric refraction taken into account with curved rays

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Harmonoise

The Harmonoise has been around for more than 15 years, and is used to take into account complex meteorological conditions.

Not that dissimilar to ISO 9613-2.

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Harmonoise

Primary notes:

- Barrier Shielding slightly different, more modern than Maekawa
- Ground attenuation more complex, based on ground impedance & flow resistivity
- Refraction somewhat addressed (by curving the ground, not adjusting the sound ray/wave)
- Two turbulence effects can be considered.

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Others…

- The **OTL – Terrain** calculation engine is based on the work of Salomons who applies a ray model using analytical solutions.
- Spherical wave diffraction coefficients are given by Hadden and Pierce.
- Spherical wave reflection coefficients are based on the work of Chessel and Embleton, while ground impedance is based on the Delany and Basley model.
- Finite size reflectors Fresnel zones contribution is taken into account by applying the work of Clay.
- The atmospheric turbulence model used is based on Harmonise

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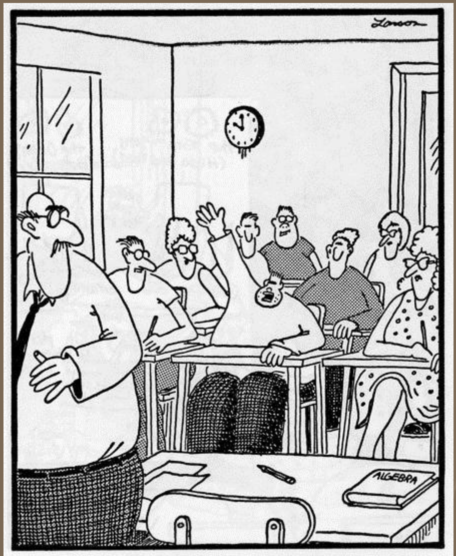
Conclusion



"Mr. Osborne, may I be excused? My brain is full."

What did we learn?

Factors affecting outdoor sound propagation are pretty complicated!

A wave in the atmosphere changes with:

- distance,
- interaction with the ground,
- atmospheric effects
- and Topography/barriers,

Objectives

1. To understand the mechanisms affecting outdoor sound propagation. ✓
2. To understand the current ray tracing models used today. ✓
3. To understand the modern numerical models. ✓

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Conclusion

We haven’t touched on:

- Sources other than “point” sources
- Ministry policy
- “Worst-case” emissions
- Determining source sound levels
- Human perception of hearing

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Modelling Sound in the Atmosphere

Presented by:

Nicholas Sylvestre-Williams

Aercoustics Engineering Ltd.

October 21, 2013

AIR & WASTE MANAGEMENT ASSOCIATION
ONTARIO SECTION