Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Acoustics I: sound propagation outdoors

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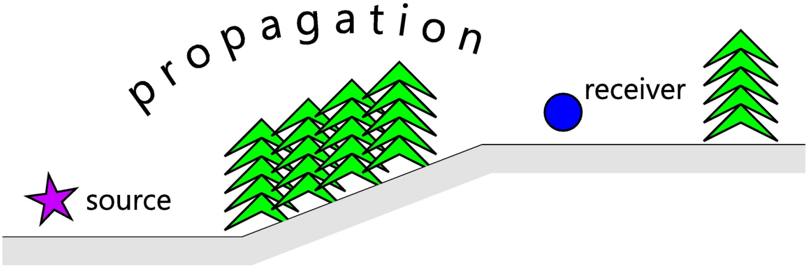
2022-12-12

point-to-point propagation situation



fundamental equation for point-to-point propagation

fundamental equation according to ISO 9613-2

$$L_p(\text{receiver}) = L_W + D - \sum A$$

- L_p: sound pressure level at the receiver
- L_W: sound power level of the source
- D: possible directivity correction of the source
- A: attenuation terms describing propagation effects
  - attenuation terms A are typically frequency dependent $\rightarrow$ calculation in frequency bands (third-octaves or octaves)

directivity of the source

directivity of the source

directivity corrections D for an omnidirectional point source in different arrangements:

source configuration	radiation solid angle	D[dB]
open space	4π	0
next to a surface	2π	$+3$
next to an edge	π	$+6$
next to a corner	$\frac{\pi}{2}$	$+9$

attenuation: geometrical spreading

attenuation: geometrical spreading

- reduction of sound pressure with increasing distance due to the distribution of the radiated sound power over an increasing area
- frequency independent

relation for a point source:

$$I = \frac{W}{4\pi d^2}$$

where
I: intensity in distance d from the source
W: sound power of the source

attenuation: geometrical spreading

for distances larger than a few wavelengths (far field):

$$I = \frac{p^2}{\rho_0 c} \rightarrow p^2 = \frac{W \rho_0 c}{4\pi d^2}$$

$$\frac{p^2}{p_0^2} = \frac{W}{W_0} \cdot \frac{1}{d^2} \cdot \frac{W_0 \rho_0 c}{4\pi p_0^2}$$

$$A_{div} = 20 \log\left(\frac{d}{d_0}\right) + 11 \qquad [\text{dB}]$$

where

d: distance source - receiver [m]

d_0: reference distance $= 1$ m

attenuation: atmospheric absorption

attenuation: atmospheric absorption

- conversion of sound energy into heat
- constant fraction of absorbed energy per unit distance
- depends strongly on frequency
- depends on temperature and humidity

attenuation: atmospheric absorption

$$A_{atm} = \alpha d \qquad [\mathrm{dB}]$$

α in [dB/km]:

T[°C]	H[%]	125	250	500	1k	2k	4k	8k
10	70	0.4	1.0	1.9	3.7	9.7	33	117
20	70	0.3	1.1	2.8	5.0	9.0	23	77
15	50	0.5	1.2	2.2	4.2	11	36	129
15	80	0.3	1.1	2.4	4.1	8.3	24	83

attenuation?: ground effect

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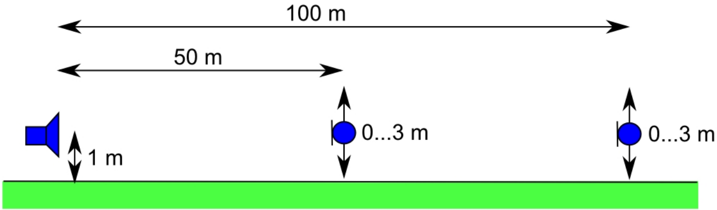
experiment:



recordings:

- noise in 50 m at 3m, 1m, 0.4m, 0.2m, 0.0m
- noise in 100 m at 3m, 1m, 0.4m, 0.2m, 0.0m

attenuation?: ground effect

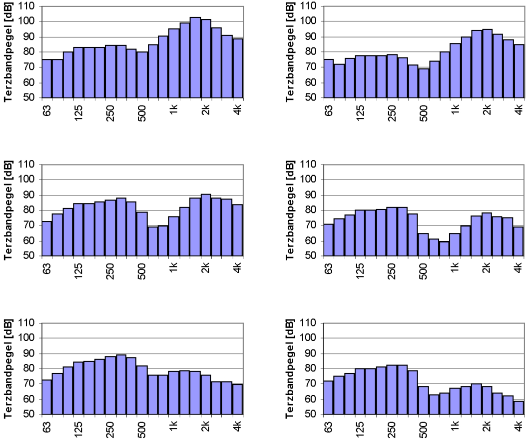
experiment: spectra of the microphone signals

50 m — 100 m

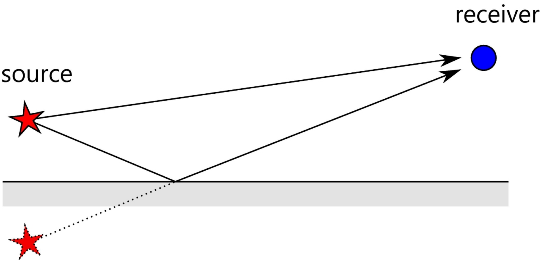
3 m

0.4 m

0.0 m



attenuation?: ground effect



- sound propagation close to the ground $\rightarrow$ significant ground reflection
- constructive and destructive interference with the direct sound

attenuation?: Ground effect

calculation tools available today:

- approximations for octave bands (ISO 9613-2)
- "exact" numerical solution of the interference effect between direct and ground reflected sound for a point source above flat and homogeneous ground
- $\rightarrow$ groundf.exe

attenuation: vegetation

attenuation: vegetation

- attenuation due to vegetation is usually overestimated
- relevant only for depths > 10 m

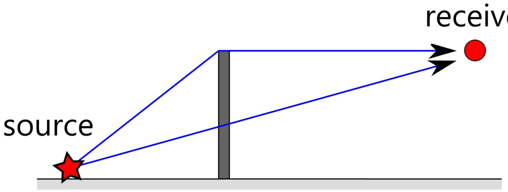
$A_{foliage}$:

depth	250	500	1k	2k
10...20m	1dB	1dB	1dB	1dB
20...200m	0.04dB/m	0.05dB/m	0.06dB/m	0.08dB/m
$>$ 200m	8dB	10dB	12dB	16dB

attenuation: obstacles

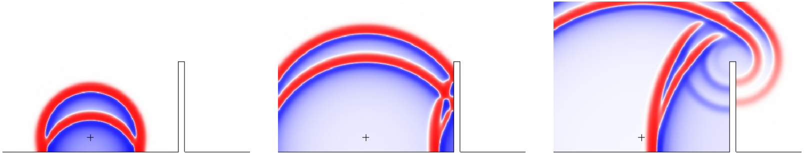
attenuation: obstacles - noise barriers

- noise barriers with specific mass $> 10\ \mathrm{kg/m^2}$
- acoustically relevant if sightline between source and receiver is interrupted



attenuation: obstacles - noise barriers

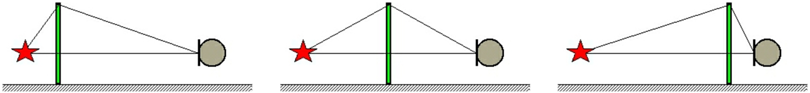
barrier attenuation is determined by effect of diffraction:



attenuation: obstacles - noise barriers

- attenuation is mainly influenced by the path length difference (in wavelengths) introduced by the obstacle

path length difference:



large small large

- increasing attenuation with frequency

attenuation: obstacles - noise barriers

calculation:

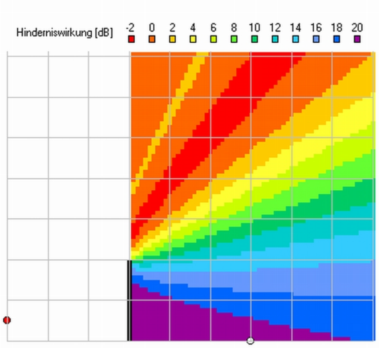
$$A_{screen} = 10 \log \left(3 + C_2 \frac{z}{\lambda} \right) \qquad [\text{dB}]$$

where
$C_2 = 20$
λ: wavelength
z: path length difference

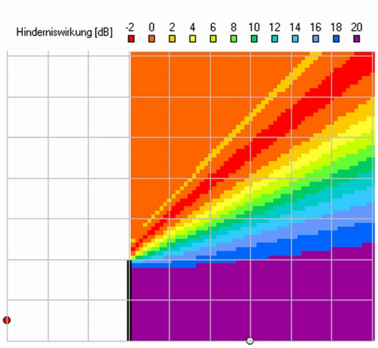
example: $z = 0$: prediction by A_{screen} in comparison to Fresnel zone approach?

attenuation: obstacles - noise barriers

calculation with a wave theoretical model:



500 Hz



2 kHz

amplification: reflections

amplification: reflections

2 type of reflections:

- specular reflections
  - large and smooth surfaces
- diffuse reflections
  - surfaces that are significantly structured in depth (measured in wavelengths)
  - surfaces with inhomogeneous surface properties (impedance)

amplification: reflections: specular

specular reflections:

- e.g. at a smooth facade or noise barrier
- application of mirror source concept $\rightarrow$ energetic superposition
- check, whether point of reflection is on the reflector $\rightarrow$ yes/no
- consider possible attenuation due to absorption

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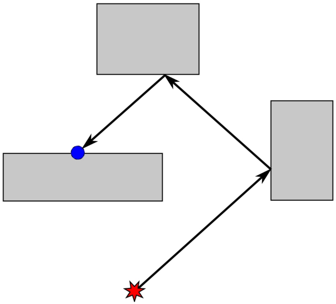
mirror source concept: limitations

- discontinuous transition at border of reflector
- size of reflector has no effect



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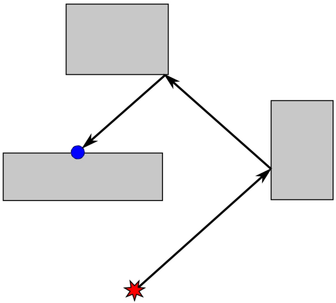

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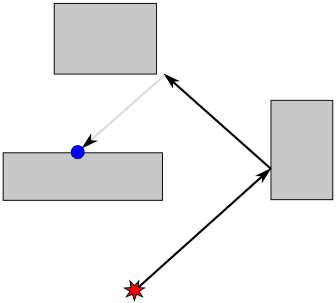

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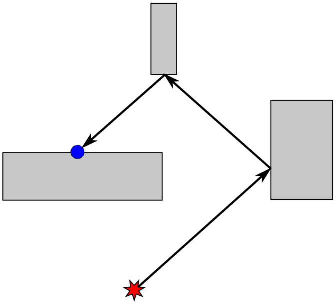

amplification: reflections: diffuse

diffuse reflections:

- e.g. at structured facades, at forest rims, rocks, ...
- handling is less obvious compared to mirror source concept for specular reflection
  - assumption of energy conservation
  - assumption of Lambert directivity

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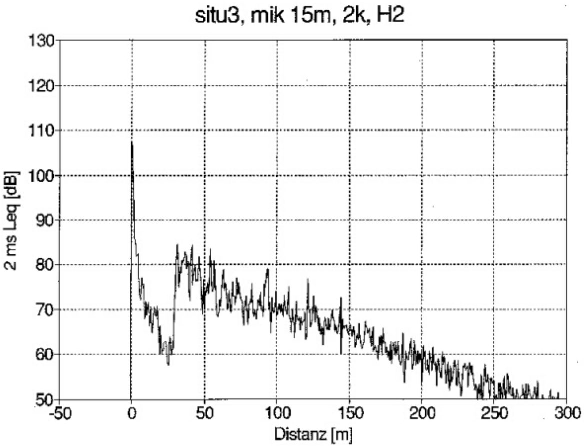
amplification: reflections: diffuse

example: reflections caused by an explosion in front of a forest rim:



meteorological effects on sound propagation

mechanisms

meteorological influences on sound propagation

relevant meteorological parameters:

- temperature and humidity
- vertical gradient of temperature
- vertical gradient of wind speed
- inhomogeneities and turbulences

consequences of temperature and humidity variations for atmospheric absorption

consequences of temperature and humidity variations for atmospheric absorption

- atmospheric absorption depends on the condition of the atmosphere:
  - humidity
  - temperature
- calculation with formulas in ISO 9613-1
- yearly average values for CH:
  - humidity: 76%
  - temperature: 8°C

consequences of temperature gradients

consequences of temperature gradients

temperature dependency of speed of sound:

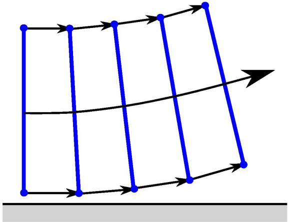
$$c \approx 343.2\sqrt{\frac{T}{293}}$$

c: speed of sound in [m/s]
T: air temperature in Kelvin

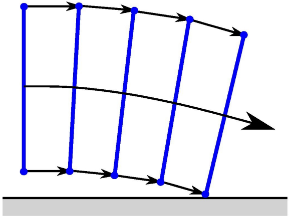
typical +0.6 m/s per degree C

consequences of temperature gradients

tilting of plane wave fronts:



temp. decrease with height

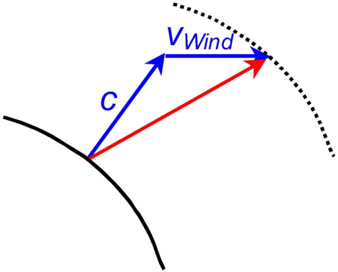


temp. increase with height

consequences of wind

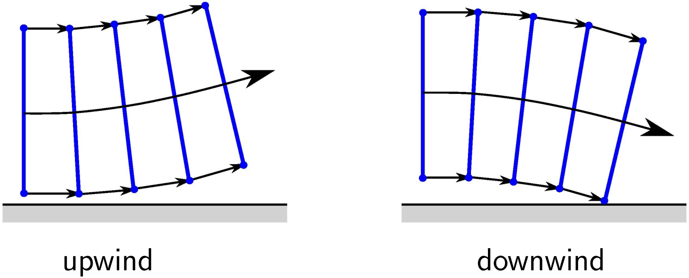
consequences of wind

- stepwise construction of wave fronts in a moving medium
  - given: point of wave front at time t_0
  - to be determined: point of wave front at time t_1



consequences of wind

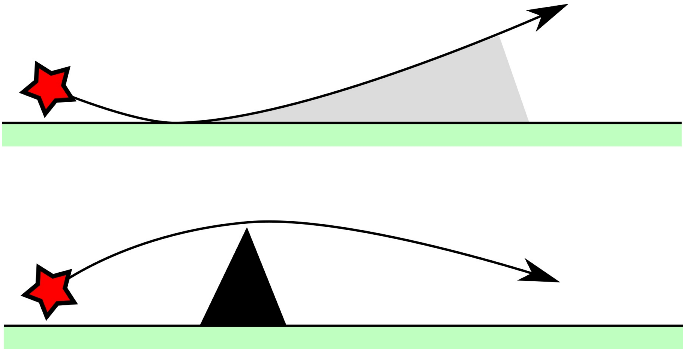
- wind field always exhibits a vertical gradient
- $\rightarrow$ sound propagation speed depends on height above ground
- curved propagation similar to situation with temperature gradients



consequences of curved propagation

consequences of curved propagation

- upwards curvature: formation of shadow zones → substantial attenuation
- downwards curvature: sound wave may rise above barriers, barrier attenuation and ground effect are reduced → amplification



consequences of turbulences

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consequences at a receiver point:

- temporal level fluctuations ($\approx$ energy neutral)
- scattering of sound energy into shadow zones
- coherence loss between different propagation paths

methods to calculate meteorological effects on sound propagation

methods to calculate meteorological effects on sound propagation

- empirical approach to predict barrier attenuation (ISO 9613-2) under favorable propagation conditions
- analytical geometrical approach to handle curved propagation: description with circles
- numerical geometrical approach to handle curved propagation: ray tracing
- numerical solutions of the wave equation:
  - Parabolic Equation (PE)
  - Finite Differences in the Time Domain (FDTD)

empirical extension of barrier attenuation formula

empirical approaches for barrier attenuation

calculation of barrier attenuation according to ISO 9613-2:

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

where

$C_2 = 20$

z : path length difference [m]

$K_{\mathrm{met}} = \exp\left(-\frac{1}{2000}\sqrt{\frac{d_{ss} d_{sr} d}{2z}}\right) < 1.0$

d_{ss}: distance source - barrier [m]

d_{sr}: distance barrier - receiver [m]

d: distance source - receiver [m]

analytical geometrical approach: circular sound rays

analytical geometrical approach: description with circles

- necessary assumption: linear vertical profile of the effective sound speed
  - constant gradients
  - curvature corresponds to circles
- curvature (radius) can be determined analytically
- with help of the circles calculation of modified barrier attenuation and altered ground effect

calculation of the radius of the circle

radius of circles depends on

- vertical gradient of the effective sound speed: $\frac{dc}{dz}$
- elevation angle of emission direction θ
  - for $\theta = 0$ and $\frac{dc}{dz} \approx \pm\, 0.05$ [s^{-1}], $R \approx$ a few kilometers

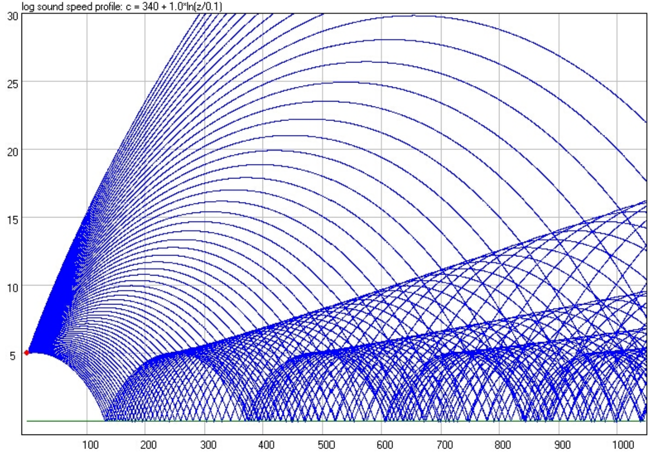
caution: the fundamental assumption of constant gradients is problematic!

numerical geometrical approach: ray tracing

ray tracing

- sound ray: curve in space that describes the propagation of a point on a wave front
- numerical procedure for a stepwise construction
- arbitrary wind and sound speed gradients can be modeled

ray tracing


log sound speed profile: c = 340 + 1.0*ln(z/0.1)
30
25
20
15
10
5
100
200
300
400
500
600
700
800
900
1000

ray tracing

evaluation of the ray tracing process for propagation attenuation calculations:

1. search of all rays that connect source and receiver
2. determination of sound pressure at the receiver by summation of all rays

ray tracing

- advantages:
  - relative fast algorithm
  - empirically extendable for further effects such as reflections
- challenges:
  - singularities (extremely high local ray density)
  - due to its geometrical nature, wave phenomena are ignored
  - unrealistic discontinuous transitions (shadow zones)
  - empirical extensions necessary to handle barriers

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numerical solutions of the wave equation: parabolic Equation

parabolic equation, PE

- originally developed in underwater acoustics, since 50 years in use for outdoor sound predictions
- formulation in the frequency domain (Helmholtz eq.: $\triangle \check{p} + \frac{\omega^2}{c^2}\check{p} = 0$)
- Helmholtz equation in cylindrical coordinates for axial-symmetrical approximation (2D calculation for point source behavior)
- split of the sound field into a slowly varying amplitude information and an oscillation term
- simulation region: 2D grid with mesh size
  - $\approx 0.1\lambda$ horizontally
  - $\approx 10\lambda$ vertically

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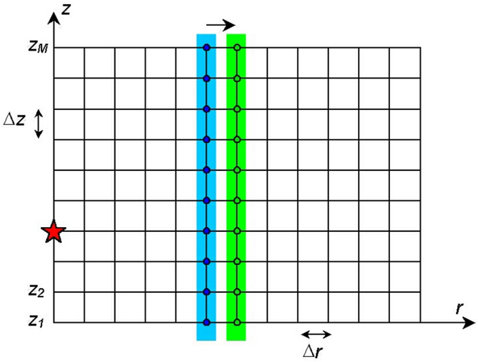
parabolic equation, PE

- advantage compared to FE: stepwise solution $p(r,z) \rightarrow p(r+\Delta r, z)$ $\Rightarrow$ only a system of equations with M variables has to be solved (M: number of elements in height)



parabolic equation, PE

challenges:

- strictly speaking only applicable for flat ground
- however, approximations available for undulating ground
- abrupt changes in topography (e.g. barriers) are difficult to handle
- high computational effort

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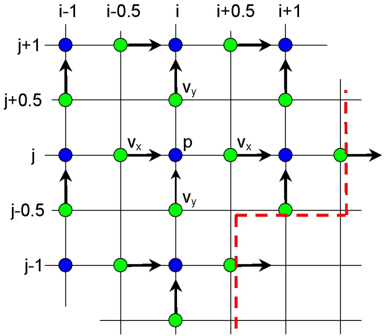
numerical solution of the wave equation: finite differences in the time domain (FDTD)

finite differences in the time domain (FDTD)

- basic equations:
  - $grad(p) = -\rho \frac{\partial \vec{v}}{\partial t}$
  - $-\frac{\partial p}{\partial t} = \kappa P_0 \mathrm{div}(\vec{v})$
- simulation region: 2/3D grid with mesh size $\approx 0.1\lambda$
- calculation by step-wise updating of the sound field variables
- advantage:
  - no system of equations has to be solved
  - result is an impulse response (containing all frequencies)

finite differences in the time domain (FDTD)



$$v_x^{\text{new}} = v_x^{\text{old}} - \alpha \left(p_{\text{right}} - p_{\text{left}} \right)$$

$$p^{\text{new}} = p^{\text{old}} - \beta \left(v_{x\text{right}} - v_{x\text{left}} \right) - \beta \left(v_{y\text{top}} - v_{y\text{bottom}} \right)$$

finite differences in the time domain (FDTD)

difficulties:

- approximation of ground impedance in the time domain is delicate
- high computational effort

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- today meteorological effects on sound propagation can be predicted with sophisticated calculation tools
- current meteorological models offer sufficiently fine local resolution (example. COSMO2 Meteo Schweiz, 2.1 km mesh size) that can be used as input

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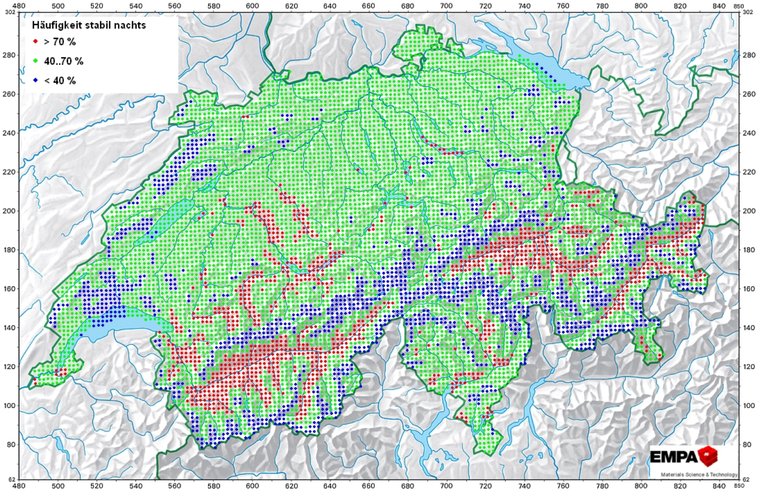
Example: COSMO2 evaluation of probability of near ground inversion



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