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Modelling sound propagation in the presence of atmospheric turbulence for the auralization of aircraft noise

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Overview

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1. Aircraft noise and auralization
2. Atmospheric turbulence
3. Calculating time series of amplitude and phase fluctuations
4. Applying fluctuations to a signal
5. Log-amplitude saturation

Introduction

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- Traffic noise pollution in urban areas is a major environmental problem
- Aircraft noise can cause annoyance and sleep disturbance
- Millions of people worldwide are affected by aircraft noise
- We should *predict the audible aircraft sound* and determine the impact of the aircraft sound on people
- Requires a tool for the synthesis or auralization

Development of auralization tool

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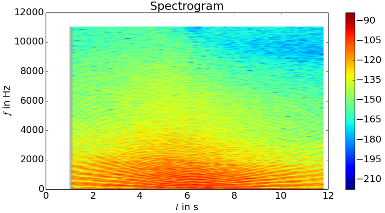
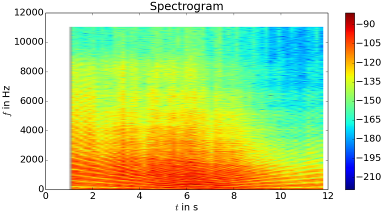
- Support typical urban situations where reflections may play an important role
- Model should be physically correct
- But more importantly, the auralizations should sound plausible
- Implementation:
  - Source synthesiser describes emission from jet, fan, airframe, etc.
  - Propagation model includes spherical spreading, Doppler shift, atmospheric absorption, reflections, fluctuations due to turbulence
- Fluctuations due to turbulence can be heard, and therefore need to be included.

Auralizations with and without turbulence

Without turbulence



With turbulence



Fluctuations at the source are ignored

Atmospheric turbulence

- A *filter* is needed to apply fluctuations due to turbulence
- The wind velocity components and temperature in the turbulent atmosphere are fluctuating both in position and time.
  - Causes fluctuations in refractive-index μ
  - Results in fluctuations of the received signal
- The theory of turbulence is a statistical theory
  - Approximate spectrum of turbulence
- For an auralization instantaneous values of the sound pressure $p(t)$ at the receiver are required
  - Log-amplitude fluctuation $\chi(t) = \log\left(\frac{A}{A_0}\right)$ with $A = |p|$ and $A_0 = \langle A \rangle$
  - Phase fluctuation $S(t) = \phi - \phi_0$ with $\phi = \angle p$ and $\phi_0 = \langle \phi \rangle$
- Model for phase fluctuations by Artnzen, 2013

Modelling atmospheric turbulence

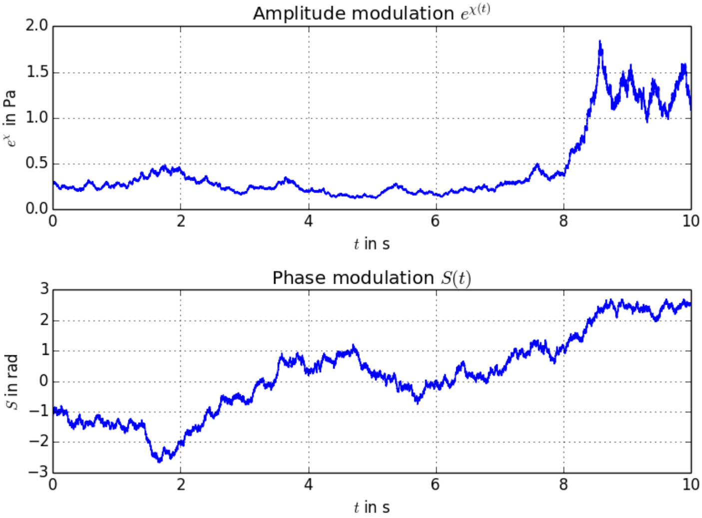
- Gaussian turbulence spectrum
  - Correlation function $B(r) = \langle \mu_1 \mu_2 \rangle = \langle \mu^2 \rangle \exp\left(-r^2/L^2\right)$.
  - Variance of refractive-index $\langle \mu^2 \rangle$, distance r and correlation length L
  - Isotropic and homogeneous.
  - Frozen turbulence
- Variances of fluctuations $\langle \chi^2 \rangle = \langle S^2 \rangle = \frac{\sqrt{\pi}}{2} \langle \mu^2 \rangle k^2 r L$
  - Mean squared log-amplitude fluctuation $\langle \chi^2 \rangle$
  - Mean phase fluctuation $\langle S^2 \rangle$
- Normalized covariances $\frac{B_\chi}{\langle \chi^2 \rangle} = \frac{B_S}{\langle S^2 \rangle} = \frac{\Phi(\rho/L)}{\rho/L}$
  - Spherical waves
  - Valid if Fresnel zone much larger than the correlation length $\sqrt{\lambda r} \gg L$
  - Wavenumber k, spatial separation perpendicular to wave direction ρ and error function Φ

Calculating time series of fluctuations

Consider a single propagation path and a pure tone:

1. Sample the covariance $B_\chi(\rho) = B_S(\rho) = \frac{\sqrt{\pi}}{2}\langle\mu^2\rangle k^2 r L \frac{\Phi(\rho/L)}{\rho/L}$
2. Determine spatial impulse response $h(\rho)$ from $B_\chi(\rho) = B_S(\rho)$
3. Generate two series of random numbers, for amplitude and phase
4. Convolution of $h(\rho)$ with random numbers results in fluctuations $\chi(t)$ and $S(t)$

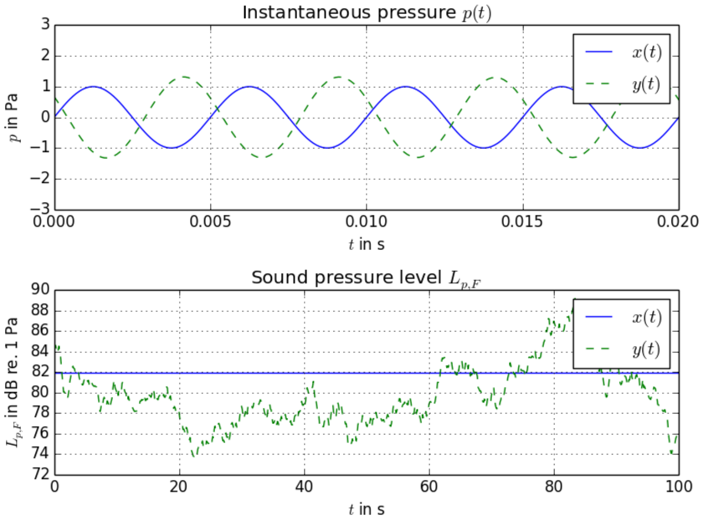
Time series of fluctuations



Applying fluctuations to signal

- Apply the fluctuations $\chi(t, f)$ and $S(t, f)$ to a signal $x(t)$ resulting in modulated signal $y(t)$:
- Two methods:
  - Slow method:
    1. Decompose $x(t)$ in pure tones using DFT and apply (unique) modulation to each tone
    2. $y(t) = \sum_{f=0}^{N} \left\{ |X(f)| \cdot e^{\chi(t,f)} \cdot \sin\left(2\pi f t + \angle X(f) + S(t, f)\right) \right\}$
  - Faster method, but different operation:
    1. Decompose $x(t)$ using bandpass filters
    2. Convert phase in radians to delay in seconds: $d = \frac{\phi}{2\pi f}$
    3. Use a variable delay line to apply the phase modulation and a simple multiplication for the amplitude modulations
- Methods are different, but both give a plausible result

Example: Signal affected by turbulence



Log-amplitude saturation

- For longer path lengths and stronger turbulence, the amplitude fluctuations gradually level off.
- Saturation can be observed when measuring aircraft noise at distances of over a few kilometers.
- The standard deviation of the fluctuating sound pressure levels is then limited to approximately 6 dB.
- Can be accounted for by multiplying $\chi(t, f)$ with $\sqrt{\frac{1}{1+r/r_s}}$.
  - With saturation distance $r_s(f)$ according to Wenzel, 1976.
  - $r_s = \frac{1}{2\langle\mu^2\rangle k^2 L}$

Variances of fluctuations

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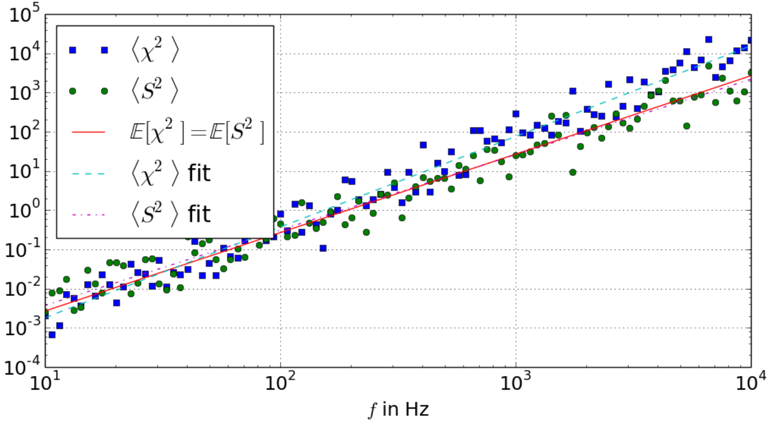
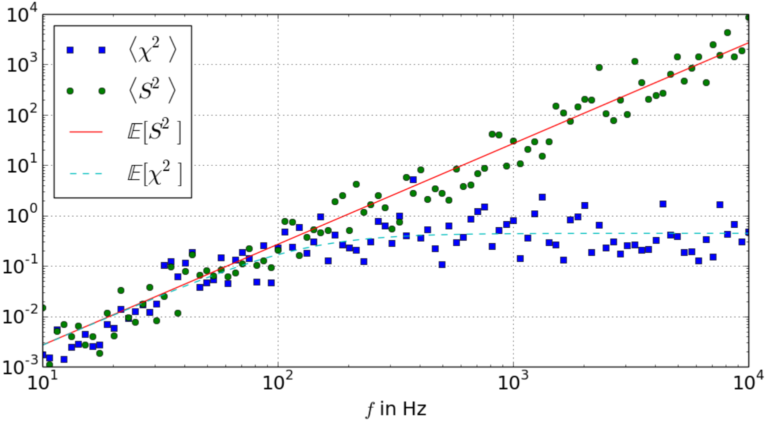


$$\mathbb{E}\left[\chi^2\right] = \mathbb{E}\left[S^2\right] = \frac{\sqrt{\pi}}{2}\langle\mu^2\rangle k^2 rL$$

Variances of fluctuations including saturation



$$\mathbb{E}\left[S^2\right] = \frac{\sqrt{\pi}}{2}\langle\mu^2\rangle k^2 rL \qquad \mathbb{E}\left[\chi^2\right] = \frac{\sqrt{\pi}}{2}\langle\mu^2\rangle k^2 rL \cdot \frac{1}{1+r/r_s}$$

Example: Auralization of aircraft noise

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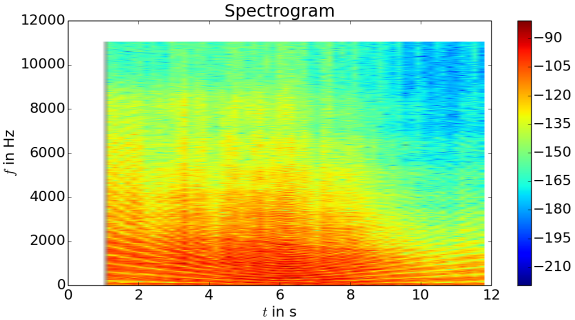
- Unique time series of fluctuations applied to each third-octave band.



Auralization

Conclusion

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- Possible to generate time series of amplitude and phase fluctuations due to propagation in a turbulent atmosphere
- Use common parameters
  - Outer length scale of turbulence L
  - Mean squared refractive-index $\langle \mu^2 \rangle$, which is based on variances in windspeed and temperature
- Results in more realistic auralizations

Future work:

- Replace Gaussian spectrum with Von Karman spectrum (Ostashev, 1998)
- Height-dependent correlation length
- Validation
  - Compare fluctuations with measurements
  - Listening tests

Questions?

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