Simulation of atmospheric turbulence: Fractal turbulence

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Introduction

A new trend is to observe atmospheric turbulence fields by using scanning Doppler radars and/or lidars. See e.g. Chan (2011) for the retrieval of eddy dissipation rate (EDR) maps at the Hongkong International Airport.

To improve retrievals of turbulence we want to simulate turbulent wind fields.

Simulation of turbulence can be done with increasing complexity. At first instance, we have chosen the most simple approach: a synthetic signal that satisfies the Kolmogorov 5/3 power law.

Features

- Synthetic clean signal
- Direct eddy simulation (DNS)
- Inhomogeneities
- Navier-Stokes equation
- Kolmogorov power spectrum
- Fractal turbulence model
- Advanced world
- More real
- Simpler
- Complex

Models of turbulence in order of complexity

Fractal turbulence model

Here we propose a model of fractal turbulence that satisfies the Kolmogorov 5/3 power law for multiple scales, which is periodic and only needs a few samples as input.

Suppose we have N samples with an EDR of 1 m²/s², then the unaliased continuous velocity signal with an eddy dissipation rate of ɛ on the domain [−∞, ∞] is:

\[ v_n(x) = \varepsilon^{1/3} S_n^{5/6} \sum_{i=0}^{N-1} a_i \Xi(2^{-n}x, i, N), \]

where 2ⁿ is the scale, aᵢ are the samples and Ξ is the periodic Nyquist-Shannon sampling function. The periodic Nyquist-Shannon sampling function is an analytic expression of the sampling function with the assumption that v(x + N) = v(x).

Periodic Nyquist-Shannon sampling. Power spectra of several interpolation methods. Only with periodic Nyquist-Shannon the interpolated samples are unaliased.

To obtain all frequencies in the fractal turbulence model, we add up the signals vᵢ for different scales 2ⁿ. Rescaling is applied for each scale to satisfy the Kolmogorov power law:

\[ v(x) = \sum_n v_n(x) = \varepsilon^{1/3} S_n^{5/6} \sum_{i=0}^{N-1} a_i \Xi(2^{-n}x, i, N), \]

Illustration of the fractal turbulence model. Seven samples are used for the x-direction. For each 2ⁿ scale the samples are reused.

Discussion

- Periodic Nyquist-Shannon sampling provides an unaliased signal.
- The fractal turbulence model is an elegant way to make a realization of a homogeneous isotropic turbulence wind field.
- It is possible to simulate an inhomogeneous EDR field, ɛ(x,y,z).
- With the model the effect of the response function of sonic anemometers and the footprint of radars and lidars can be simulated.

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How does it look?

Illustration of a fractal turbulence building block of 7 x 2 x 2 points. The zonal wind speed is shown in ms⁻¹. In the x-direction the signal satisfies the Kolmogorov 5/3 power law and the second order structure function. In the other directions the zonal wind is slightly correlated.

Validation of the fractal turbulence model. 100 samples are taken with Δx = 3.33 m and ɛ = 1.10⁻³ m² s⁻³. In the figures the power spectrum (left) and second order structure function (right) are shown, with a fitted edr.