Physics of the Convective Boundary Layer based on Radar/Lidar Profiler measurements and simulation

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Outline

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• Physics of the Atmospheric Boundary Layer, radar measurements
• Simulation of the RCS in clear air
  – Large Eddy Simulation (LES) of the boundary layer in clear air
  – Radar Cross-section Simulation without rain
• Simulation of the RCS in rain
  – Large Eddy Simulation (LES) of the boundary layer in the presence of rain
  – Radar Cross-section Simulation with rain
• Simulation of the Lidar signal
• Conclusion
Introduction

• UFO project for Improvement of aviation safety
  – Innovative technology developed for Ultra-fast Lidar/X-band Radar wind and EDR monitoring sensors
  – Development of Radar and Lidar simulators based on the same Atmospheric Boundary Layer simulator
  – Development of new design tools for the Radar/Lidar
    • Necessity to understand the impact of the various parameters and to simulate the measured signal
    • Comparison with measurements performed during various campaigns
1. Physics of the atmospheric boundary layer

- The Atmospheric Boundary Layer (ABL) is the part of the atmosphere that is directly influenced by the Earth's surface.
- The ABL responds to the Earth’s surface forcings with a timescale of one hour or less.
- The ABL is generally turbulent during day-time and stably stratified during night-time.
Turbulence is ubiquitous in the ABL

- Much of the ABL turbulence is generated by forcing from the ground (thermals, frictional drag, wakes)
- Turbulence consists of the random superposition of eddies of different scales.
- The size of the large turbulent eddies is 100 - 1000 m typically.
- The small eddies feed on the larger ones (turbulent cascade). The scale of the smaller eddies is ~ 0.1 – 1 cm.
- The distribution of energy of a turbulent flow follows a universal law: \( E(k) = \alpha_k \varepsilon^{2/3} k^{-5/3} \)
- Turbulence is several order of magnitude more efficient at mixing and transporting quantities that is molecular diffusivity.
- It is turbulence that allows the boundary layer to respond to changing surface forcing.
Atmospheric Boundary Layer
Physics and Simulation

- Portrait of the ABL: diurnal cycle
Atmospheric Boundary Layer Physics and Simulation

- Radar observation of the diurnal cycle of the ABL

Structure constant of $n$

$$c_n^2 = \frac{\langle n(r+d) - n(r) \rangle^2}{|\delta|^2/3} \quad [m^{-2/3}]$$

UFO DIssemination April 2015
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- Turbulent Kinetic Energy (TKE) budget

\[
\frac{\partial TKE}{\partial t} = P - B + T - \varepsilon
\]

- \(P\): shear production
- \(B\): Buoyancy (production or sink)
- \(T\): Transport
- \(\varepsilon\): dissipation

Large variability of TKE (several order of magnitude) according to the atmospheric conditions.
A key characteristic of turbulence is space-time intermittency.

The occurrence of intense turbulent patches is much more frequent than expected from normal distribution.

What is the required time and space resolution?
Atmospheric Boundary Layer Physics and Simulation

- Curie X-band radar measurements of turbulence: Rain and dry air echoes
2. Large-Eddy Simulation (LES) of idealized turbulent humid atmosphere

The periodic simulation does not reproduce the whole Atmospheric Boundary Layer, it only intends to simulate the turbulence in a small volume of the atmosphere. The largest of the ABL are not captured. The smallest dissipative scales of size $\eta$ aren’t capture either because of the resolution. The simulation only simulates the turbulence in the inertial part of the spectrum.

$$\eta = \frac{\pi}{k_\eta} \left( \frac{V^3}{\varepsilon} \right)^{\frac{1}{4}} \sim 1 \text{mm}$$

The simulation is performed in a periodic domain. The flow is driven by a random force applied in spectral space at the lowest wavenumbers.

Grid size:

$$h = \frac{\pi}{k_c} \sim 1 \text{m}$$

Box size:

$$\frac{L}{h} = \frac{k_c}{k_L} = N = 256$$
Simulation of the ABL: clear air ambient turbulence with stable stratification

Large-Eddy Simulation of idealized stably stratified atmosphere

Parameters of the simulations (N is the Brunt-Vaisala frequency):

<table>
<thead>
<tr>
<th>EDR [m²/s³]</th>
<th>N [1/s]</th>
<th>2.546 x 10⁻³</th>
<th>8.913 x 10⁻³</th>
<th>1.273 x 10⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻²</td>
<td>✔ Case 3</td>
<td>(~ -9.5 K/km)</td>
<td>(~ -7.5 K/km)</td>
<td>(~ -5.2 K/km)</td>
</tr>
<tr>
<td>5 x 10⁻⁴</td>
<td>✔ Case 2</td>
<td>✔ Case 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>✔ Case 1</td>
<td>✔ Case 4</td>
<td>✔ Case 6</td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric Boundary Layer Physics and Simulation

- Boundary layer parameters – UCL LES simulation

- **Atmospheric data:**
  - Strongly stratified atmosphere starting at 400 m of altitude.
  - Clear air, no cloud, no rain and no mean wind.
  - Duration: 1 hour with time step of 1 s.
  - Dimension: 400 m in each direction.
  - Res: 0.78 m in each direction.

\[ C_n^2 = \frac{\langle (n_{(r+d)} - n_{(r)})^2 \rangle}{|\delta|^{2/3}} \quad [m^{-2/3}] \]

Typical values of turbulence:
\[ 10^{-15} < C_n^2 < 10^{-10} \quad [m^{-2/3}] \]

**In this case:**
\[ Cn^2 \sim 10^{-14} -> \text{weak turbulence} \]
Atmospheric Boundary Layer Physics and Simulation

- Boundary layer parameters— ISL LES simulation

- **Atmospheric volume:**
  - Generated by LES model
  - **Place:** Virtual flat ground
  - **Weather:** Summer day, no cloud, no rain, no mean wind
  - **Duration:** 1 hour with time steps of 20 s
  - **Dimension:** 5 km horizontally and 1.5 km in height
3. Simulation of radar cross-section in clear air

- Various methods have been proposed for the calculation of oscillating integrals:

\[
\sigma_r = 4\pi|x_r|^2 \frac{P_r(x_r)}{P_{i,\text{max}}} = \frac{\omega^2 \varepsilon_0 \mu_0 k^2_0}{4\pi} |I|^2 = \frac{k^4_0}{4\pi} |I|^2
\]

\[
I = \iiint (\varepsilon_r(x) - 1)f(x, y, z)e^{-2jk_0\xi}dV
\]

- asymptotic methods whose accuracy improves when the frequency increases
- quadrature methods proposed by Levin and improved by Li for improving the robustness for an ill-conditioned system.
- an alternative method proposed by Muchinski (using $C_n^2$) has been implemented and compared with the method of Li ($W_p$ is antenna radiation pattern and $V_p$ are the sub-volumes of LES)

\[
I(t) = A\sqrt{0.0330}k^{-11/3} \sum W_p \sqrt{\left[C_n^2\right]_p} V_p e^{-j\phi_p(t)}
\]
Atmospheric Boundary Layer
Physics and Simulation

Simulation of radar cross-section in clear air - Example

Using ISL LES data (clear sky and turbulent atmosphere)

Using UCL LES data (clear sky and stable atmosphere)
Atmospheric Boundary Layer
Physics and Simulation

- Wind retrieval in Doppler spectrum, in clear air
Atmospheric Boundary Layer Physics and Simulation

- EDR retrieval in Doppler spectrum, in clear air (ISL LES)
4. LES in the presence of rain

- Large-Eddy Simulation of idealized stably stratified atmosphere with tracking of falling raindrops
- Preliminary case for a rain rate of 5 mm/h with $256^3$ raindrops in a low EDR ($EDR = 10^{-5} \text{ m}^2/\text{s}^3$) and low stratification ($N = 2.546 \times 10^{-3}$) turbulence (Case 1)

![Raindrop size distribution](image1)

Raindrop size distribution in the simulation for $R = 5 \text{ mm/h}$

![Example of raindrop trajectories](image2)

Example of raindrop trajectories
Raindrops are modeled as point particles of mass \( M = \rho_{\text{water}} \frac{\pi}{6} D^3 \). Their equations of motion are:

\[
\begin{align*}
\dot{x} &= v \\
\dot{v} &= \frac{1}{M} F
\end{align*}
\]

The forces acting on the raindrops are their weight and their drag:

\[
\frac{1}{M} F = \frac{g}{V_T^2} |\delta v| \delta v - g e_z
\]

where

\[
\Delta v = v_{\text{air}} - v
\]

It is assumed that there is no interaction between the particles, no deformation of the raindrops, and no evaporation/condensation. The domain is periodic so that the number of particle is constant (no injection, no removal).
LES simulations

- The terminal velocity of the raindrops is given by
  \[ V_T = (\alpha_1 - \alpha_2 \exp(-\alpha_3 D)) \left( \frac{\rho_0}{\rho} \right)^{0.4} \]
  \[ \alpha_1 = 9.65 \text{ m/s }, \alpha_2 = 10.3 \text{ m/s }, \alpha_1 = 0.6 \text{ 1/mm} \]

- The raindrop size varies with the rain rate R according to the distribution
  \[ N = N_0 D^2 \exp(-\Lambda D) \]
  \[ N_0 = 64500 R^{-0.5} \text{ [m}^{-3}\text{mm}^{-3}] \]
  \[ \Lambda = 7.09 R^{-0.27} \text{ [mm}^{-1}] \]

- Small particles with small \( V_T \) are considered as purely Lagrangian
5. RCS simulation in rain

- 2 methods are used in each radar cell:
  - The radar signal is obtained by the backscattering of each single particle. The Doppler spectrum is calculated by taking the FFT of the signal.
  - The Doppler spectrum is calculated in each velocity bin by the power scattered by all the raindrops having a radial velocity in that bin.
  - Parameters of the simulation: \( f = 10 \text{ GHz}, 38 \text{ dB antenna gain}, 3^\circ \text{ antenna aperture} \)
Atmospheric Boundary Layer Physics and Simulation

- Example

No mean wind in LES
6. Simulation of the Lidar signal

- The simplified expression of the SNR measured by the Lidar is:

\[
SNR(z) = \frac{\eta_0 U_L}{\hbar \nu B_w} K^2(z) \beta(z) C(z)
\]

- \( U_L \) is the LASER pulse energy, \( K \) is the extinction component, \( \beta \) is the backscatter coefficient and \( C \) is the term due to the influence of the telescope lenses, transmitted beam size and refractive turbulence.

- The simulation of SNR necessitates an in depth knowledge of the LIDAR parameters. A possible way to solve the problem is to use SNR curves measured by the LIDAR so that the real SNR curves of the instrument are used. In this case, the term \( C \) is not modelled in the simulator, and its contribution is directly considered in the used SNR curves.

- The instrument SNR curves vary with respect to the tropospheric status.
Atmospheric Boundary Layer
Physics and Simulation

- Retrieved wind radial velocity in the clear air LES

Radial wind in the frame of the Lidar for the LES case 1 ($\varepsilon_f=10^{-5}$ and $N=2.55 \times 10^{-3}$) [m/s]

- Next step: SNR in presence of rain.
Atmospheric Boundary Layer
Physics and Simulation

Conclusion

• The Radar and Lidar simulators have been developed to calculate the Radar Cross-Section and Lidar SNR on Large Eddy Simulation of turbulent atmospheric boundary layer.
  - Based on the same LES simulation
  - Enable retrieval of wind speed

• The Lidar simulation needs tropospheric measurements in order to further assess the effect of the tropospheric parameters on the SNR and to calibrate the coefficients.

• The tools developed will enable a comparison between the sensors in the presence of rain

• The main limitations are the stratification for the LES simulation and the computer time/memory for the LES.
THANK YOU FOR YOUR ATTENTION